NASA/CR—2016–219272

Model Based Mission Assurance in a Model Based Systems Engineering (MBSE) Framework

State-of-the-Art Assessment

Steven L. Cornford
Jet Propulsion Laboratory, Pasadena, California

Martin S. Feather
Jet Propulsion Laboratory, Pasadena, California

August 2016

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/CR—2016–219272

Model Based Mission Assurance in a Model Based Systems Engineering (MBSE) Framework

State-of-the-Art Assessment

Steven L. Cornford
Jet Propulsion Laboratory, Pasadena, California

Martin S. Feather
Jet Propulsion Laboratory, Pasadena, California

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
Pasadena, CA 91109-8099

August 2016

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

We thank Frank Groen and John Evans of NASA OSMA for their vision and their support of our task to create this report, and Steve Jenkins of JPL for the interactions we had with him during the early days of his promotion of MBSE within JPL.

Finally, we thank all the people we talked with, whether during our "interviews" or otherwise, for their feedback and insights on the subject of this report.

Level of Review: This material has been technically reviewed by technical management.

Reprinted figures

The figures in this document are reprinted from other sources, as follows:

- **Figure 1 – Attendees' organizations list from 2015 NASA/JPL Symposium and Workshop on MBSE.** Reprinted from C. Lin, R. Fradet & D. Dvorak, "NASA/JPL Symposium & Workshop on Model-Based Systems Engineering," January 2015, with the permission of the authors. (The workshop's presentations are available from https://drive.google.com/drive/folders/0B3hsmXWocH2JZVpTSzdzaUxYQzA)
- **Figure 2 – Structure of a logical space system model.** © 2015 IEEE. Reprinted, with permission, from D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani & R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status," *2015 IEEE Aerospace Conference*, 2015, pp. 1-16.

  Figure 3 – Top level of the Reliability and Maintainability Objectives Hierarchy. Reprinted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.
- **Figure 4 – Standards, models, engineering activities and safety/assurance cases.** © 2016 IEEE. Reprinted, with permission, from J. Evans, S. Cornford & M.S. Feather, "Model based mission assurance: NASA's assurance future," *2016 Annual Reliability and Maintainability Symposium (RAMS)*, 2016, pp. 1-7.
- The following five figures:
  - **Figure 5 – Where areas 1 & 2 support the R&M Objectives Hierarchy.**
  - **Figure 6 – Where area 3 supports the R&M Objectives Hierarchy.**
  - **Figure 7 – Where areas 4 & 5 support the R&M Objectives Hierarchy.**
  - **Figure 8 – Where some area 6 activities support the R&M Objectives Hierarchy.**

- **Figure 9 – Where some more area 6 activities support the R&M Objectives Hierarchy**

  Are adapted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

- **Figure 10 – Model-based IRD/ICD interface review process.** Reprinted from M. Aguilar, K. Bonanne, J.A. Favretto, M.M. Jackson, S.L. Jones, R.M. Mackey, M.A. Sarrel & K.A. Simpson, *Review of Ground Systems Development and Operations (GSDO) Tools for Verifying Command and Control Software*, NASA/TM-2014-218278, June 2014, with permission of the authors.

- **Figure 11 – Various analyses and the data they ingest.** Reprinted from *Reliability Engineering and System Safety, 111*, R. Cressent, P. David, V. Idasiak & F. Kratz, "Designing the database for a reliability aware Model-Based System Engineering process," 171-182, copyright 2013, with permission from Elsevier.

- **Figure 12 – Class diagram for FMEA artifacts.** © IEEE. Reprinted, with permission, from F. Mhenni, J-Y. Choley & N. Nguyen, "SysML Safety Profile for Mechatronics," in *Mecatronics (MECATRONICS), 2014 10th France-Japan / 8th Europe-Asia Congress on*, 2014, pp. 29-34.

- **Figure 13 – Safety profile diagram.** © IEEE. Reprinted, with permission, from F. Mhenni, J-Y. Choley & N. Nguyen, "SysML Safety Profile for Mechatronics," in *Mecatronics (MECATRONICS), 2014 10th France-Japan / 8th Europe-Asia Congress on*, 2014, pp. 29-34.

- **Figure 14 – Profile elements relating to hazardous events.** *Springer Journal of Software and Systems Modeling*, "A profile and tool for modelling safety information with design information in SysML," 15(1), 2016, 147-178, G. Biggs, T. Sakamoto & T. Kotoku, © 2016. With permission of Springer.

- **Figure 15 – An information model for Requirements, Verification Planning and Test Cases.** Reprinted from B.M. Selvy, C. Claver & G. Angeli, "Using SysML for Verification and Validation Planning on the Large Synoptic Survey Telescope (LSST)," *SPIE Astronomical Telescopes + Instrumentation*, pp. 91500N-91500N. International Society for Optics and Photonics, 2014, copyright SPIE. With permission from SPIE and the authors.

- **Figure 16 – An information model for test activities and events.** Reprinted from R. Kratzke, "MBSE for System Testing," *Systems Engineering Conference (SEDC2014), 2014*. Reprinted with permission of Vitech Corporation. Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-9_Model-based-System-Engineering-MBSE-for.pptx

- **Figure 17 – An information model for system integration and test.** Reprinted from *INCOSE International Symposium, Vol. 23, No. 1*, A. Salado, "Efficient and Effective Systems Integration and Verification Planning Using a Model-Centric Environment," 1159-1173, copyright 2013, with permission from John Wiley and Sons.

- **Figure 18 – An information model for verification.** Reprinted from *Acta Astronautica, 115*, D.R. Wibben & F. Furfaro, "Model-Based Systems Engineering approach for the development of the science processing and operations center of the NASA OSIRIS-REx asteroid sample return mission," 147-159, copyright 2015, with permission from Elsevier.

- **Figure 19 – An N2 diagram of system interfaces.** Reprinted from "'Top-10' MBSE Tool Inspections to Analyze System Design Quality," P. Montgomery, *Systems Engineering Conference, 2014 (SEDC2014),* copyright 2014 Paul R. Montgomery, with the permission of the author**.** Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-1_Top-10-MBSE-Tool-Inspections.ppt
- **Figure 20 – CubeSat stakeholders.** © 2015 IEEE. Reprinted, with permission, from D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani & R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status," *2015 IEEE Aerospace Conference*, 2015, pp. 1-16.
- The five figures in appendix B:
    - R&M Objectives Hierarchy – Top Level
    - R&M Hierarchy Sub – Obj. 1
    - R&M Hierarchy Sub – Obj. 2
    - R&M Hierarchy Sub – Obj. 3
    - R&M Hierarchy Sub – Obj. 4

  are from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

Available from

NASA STI Support Services
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
757-864-9658

National Technical Information Service
5301 Shawnee Rd.
Alexandria, VA 22312
webmail@ntis.gov
703-605-6000

This report is also available in electronic form at
http://ntrs.nasa.gov

Table of Contents

Executive Summary

NASA's Safety and Mission Assurance (S&MA) organizations assure the safety and enhance the success of all NASA activities. The purpose of this report is to explore how S&MA can adjust to a fundamental shift occurring in many areas of Systems Engineering (SE), the shift to "Model Based Systems Engineering" (MBSE). In this shift, much of the information that underpins SE is being organized and represented in models: carefully crafted rigorous computer-based representations of information, which collectively make SE activities easier to perform, less error prone, and scalable. Motivating this is the need to deal with ever larger and more complex systems. MBSE is perceived as key if these systems are to be developed in a cost-effective manner without sacrificing performance, reliability and safety. This shift is especially pertinent to NASA, given its ambitious mission expectations driving the need for novel and increasingly complex systems with very small production volumes.

As SE practices shift to MBSE, S&MA practices must adjust accordingly – hence the term "Model Based Mission Assurance (MBMA)." To understand the adjustments that will be needed, this report turns to OSMA's recently developed "Objective Structure Hierarchies." As stated on the OSMA web page [NASA OSMA, 2014] introducing them:

> *"…the hierarchies provide a consistent way to describe the technical considerations behind existing standards in a consistent manner. By focusing on objectives, OSMA hopes that the new standards will be more flexible, agile and cost-effective, and will allow more ingenuity to achieve objectives. It will serve as a guide to help programs and projects plan how they will meet their objectives, instead of dictating what they must do to via prescriptive requirements."*

The standards' objectives will remain constant, while the S&MA practices (activities, processes, tools) to achieve those objectives are subject to change as the shift to MBSE takes place. Some existing practices may become less relevant or even obsolete; some may become much easier, faster, and/or increasingly applicable; some may require adjustment to most effectively operate; in addition, some new S&MA practices may become necessary to develop and apply.

Brief introductory material on MBSE is provided for readers unfamiliar with the topic, to provide them context sufficient for them to appreciate the remainder of the document. As MBSE is an emerging technology, there are a variety of disparate efforts underway at various organizations. A significant emphasis of this study was to identify these efforts and possible implications for NASA's future MBMA efforts. The bulk of the report presents insights derived from literature studies and interviews:

- Literature studies were focused on published reports and presentations drawn from, predominantly, space-related applications of MBSE. They were examined for what they had to say on MBSE's implications for assurance. Included herein are summaries of these points, illustrated with fragments from, and references to, the literature sources.
- Interviews and discussions were conducted with knowledgeable S&MA and MBSE personnel. Again, the focus was to discover their concerns and ideas for MBSE's implications for assurance. Many of the interviews were with people involved, or soon to be involved, with the ongoing application of MBSE techniques on NASA's Europa Clipper pre-project, the first large-scale NASA flight project to take this approach to SE.

Preliminary findings and observations are presented on the state of practice of S&MA with respect to MBSE, how it is already changing, and how it is likely to change further. Finally, recommendations on how to foster the evolution of MBMA (S&MA in an MBSE world) are provided.

1 Introduction

1.1 The emergence of MBSE

NASA has developed the ability to successfully accomplish very difficult missions in hazardous conditions with high reliability, typically with very small production volumes (often 1). This stands as one of NASA's great accomplishments and contributions to the aerospace industry. It has been achieved through the use of a variety of processes, standards, reviews and other checkpoints. Recognition of the need for many of these activities, and the artifacts they require in the course of project development, resulted from (often) painful lessons learned along the way. Even the Systems Engineering V developed in the 1960s (for a history of the model, see Appendix B, "The V-Model" in [Weilkiens et al., 2015]) was motivated by the need to better organize the process of design and development. Over time NASA has honed its systems engineering processes to produce and use a cross-referenced set of documents. These documents both guide the system's development, and inform S&MA assessments of that development. However, some of these processes can be imperfect. Thus, yet more documents and processes are used to keep track of some of the original data, and document trees are established to ensure that each process is using data from the latest set of documents. Unfortunately, these processes become quite laborious, and errors creep in and sometimes escape detection despite them. When one document references information in another (or even duplicates that information), change management is difficult, error-prone and costly. Reviews often must scrutinize consistency within and among documents to attempt to eradicate errors. In an effort to improve upon this situation, various Information Technology solutions have been deployed, using documents, spreadsheets and databases at their heart to store and track information. In the late 1990s this led to various requirements tools; these were, at their core, electronic document-based systems. NASA projects and programs currently use a mix of paper, spreadsheets and other products, all carefully managed through PDMS/CM systems. This approach (mostly) works but it is unclear whether and how it will scale to future missions and their ever more complex systems.

Systems Engineers have been at the center of this challenging situation, and many have job functions primarily focused on data consistency. They were thus, in hindsight, naturally the first to see the value of Model-Based System Engineering (MBSE) approaches. Data itself must be both consistent and used in a consistent manner if the products derived from that data are in turn to be consistent. MBSE addresses this. **MBSE is at its heart about data and relationships.** For example, when one team wants the mass of a component, another wants the power draw of that component, and yet another wants the name of the vendor who supplied the component, there is no need to make three separate documents to capture that information. Instead in MBSE there is one underlying source of data (the model) and various users can interrogate that model to extract the subset of information that they need. They do this by establishing *viewpoints* and *views* tailored to their particular needs:

> *"A viewpoint describes the point of view of a set of stakeholders by framing their concerns along with the method for constructing an artifact (e.g., a set of slides in PowerPoint, a PDF file, a Word document, a web viewable format, etc.) that addresses those concerns. The view specifies the model content that is to be presented to the stakeholder in the artifact."* [Friedenthal et al., 2015]

Because all these viewpoints are looking at the same underlying data model, the information they extract is self-consistent. Many of our historical engineering problems would have been solved by just this breakthrough alone, but MBSE has much more to offer than just a single source of data. MBSE seeks to organize and model *all* of the information pertaining to a system and its development. To do so, an MBSE model includes objects, properties of those objects, and relationships among objects. This desire is easy to state, but in practice this is where careful preparations are necessary. To pave the way for modeling, it is necessary to establish clear common definitions of terms and notions, the properties or relationships they have, and how they connect.

MBSE's model (which may be structured as a coordinated federation of models that together behave as one) is now the single authoritative source of data. References to data are explicit, so when it is changed, all the places that reference it see that change. Relationships between data are explicit, which reduces errors and enables automated checking of models to detect (and so prompt the correction of) many of the errors to which document-based engineering are prone.

Interest in and adoption of MBSE spans many engineering sectors. This is evident from the variety of organizations listed in Figure 1, below, taken from opening remarks at the NASA/JPL Symposium & Workshop on Model-Based Systems Engineering.

Figure 1 – Attendees' organizations list from 2015 NASA/JPL Symposium and Workshop on MBSE. Reprinted from C. Lin, R. Fradet & D. Dvorak, "NASA/JPL Symposium & Workshop on Model-Based Systems Engineering," January 2015, with the permission of the authors. (The workshop's presentations are available from https://drive.google.com/drive/folders/0B3hsmXWocH2JZVpTSzdzaUxYQzA)

1.2 Mission Assurance and MBSE

This document focuses on integrating the roles and disciplines of mission assurance into the practice of MBSE for NASA's space mission purposes. The same factors that drive NASA's interest in MBSE in general – the need to manage and execute the design, development and operation of ever-more complex mission-critical systems – clearly apply to the Aerospace and Defense arena and the commercial entities in the industrial sectors that support them. What distinguishes NASA's space activities from most (admittedly not all) of those other areas is NASA's need to do one-of-a-kind missions in relatively unexplored and unknown environments. Furthermore, in many of its missions NASA is involved throughout the lifecycle, from establishing the science requirements and mission concepts that will achieve them all the way through to operation and decommissioning. It is in this challenging context that NASA's mission assurance practices take place. The high visibility of NASA's endeavors places a premium on mission assurance, not only with the safety of NASA's astronauts and workforce, but also with the successful accomplishment of mission objectives by billion+ dollar assets.

1.3 Organization of this report

From here on the report is organized as follows:

Section 2 “**MBSE and MBMA – key factors**” first summarizes the area of knowledge representation that forms the foundation of MBSE: the notion of an “ontology” is explained, its realization in the widely adopted systems engineering language SysML is discussed, and the (non-trivial) organization and development of an ontology for space systems engineering is outlined. This section then goes on to summarize OSMA’s “Objective Hierarchies”, introduced to become guidance to help OSMA practitioners focus on the “what” they are trying to achieve without having the “how” dictated. The Reliability and Maintainability (R&M) Objective Hierarchy in particular is used in this report to organize and show where MBSE contributes to various areas of Mission Assurance.

Section 3 “**MBSE’s implications for MBMA**” introduces and summarizes seven areas of MBSE influences on Mission Assurance. These were derived from a survey of the MBSE literature, with a particular focus on how MBSE might affect Mission Assurance of space systems. This section uses the aforementioned R&M Objectives Hierarchy to show the nature of those influences.

Section 4 “**MBMA details found in the MBSE literature**” presents the detailed results of our literature survey. Numerous references to MBSE applications of space systems engineering are provided. The key points are illustrated with example portions taken from the literature.

Section 5 “

Observations derived from stakeholder interviews" covers those insights that arose from interviews with stakeholders in the MBSE and S&MA communities.

Section 6 "**Primary findings / observations**" distills the aforementioned details and observations into the primary findings related to S&MA.

Section 7 "**Recommendations**" follows.

"**Appendixes**" conclude this report, covering Stakeholder Interviews, The Reliability and Maintainability Objectives Hierarchy, Acronyms, and References.

2 MBSE and MBMA – key factors

2.1 Information representation in MBSE

One of the cornerstones to achieving MBSE's goals is the development of a complete and correct way of representing information in models. This provides the semantic underpinnings of models. Done right, it enables much of the power of computer science to be applicable, including automated checking of models to determine whether various elements are complete, inconsistent or ambiguous. It also enables reasoning and sophisticated searches ("queries" in the lexicon of computer science). Machines can traverse the model to answer questions such as:

Show all functions performed by components that consume power made by vendor X.
Check that there are no functions lacking a corresponding component to perform them.

As updates are made to models, they can be checked for simple well-formedness criteria. Comprehensive checks of the model as a whole may take significant time to execute. For large models with many objects and relationships, as would be the case for complex engineering projects, a good approach would be to run these overnight on a snapshot of the model. The results would then be relevant the next morning (on the assumption that little or no change to the model occurs overnight).

. **Ontology** is the most appropriate term for this kind of information representation:

*"In computer science and information science, an **ontology** is a formal naming and definition of the types, properties, and interrelationships of the entities that really or fundamentally exist for a particular domain of discourse." [Wikipedia: Ontology (Information Science)]*

Thus, a well-crafted ontology not only enables one to capture the various objects (e.g., components, functions, requirements, schedule elements), it also enables one to: express relationships between them (e.g., performed by, delivered by, identified by); apply additional constraints (e.g., total system mass shall be less than the margined available payload manifest mass); setup user-oriented views of the underlying model/ontology; and do reasoning upon this model. It is this precision of information that enables many of the MBSE benefits. As an alternative to "ontology," the related term "meta-model" is seen in some of the MBSE literature.

Note the potential for an unfortunate misunderstanding of the word "ontology". This may stem from confusion caused by an alternate online definition (one *not* specific to computer and information science), namely:

"Ontology is the philosophical study of the nature of being, becoming, existence, or reality, as well as the basic categories of being and their relations." [Wikipedia: Ontology]

This definition sounds very esoteric and open-ended, and frankly useless for engineers! The notion of *relationships* as distinct from the *objects being related* is also key to understanding MBSE. For example:

- *Components* (objects) *perform* (relationship) *Functions* (objects). Furthermore, this "*perform*" relationship is an object in its own right and may have properties of its own. The reverse "*performed by*" relationship relates Functions to Components.
- Components can be "*delivered by"* a Responsible party, but Functions do <u>not</u> have the "*delivered by"* relationship to Responsible parties as it would not make sense.

Thus, models can be automatically checked for missing relationships, for misconnected relationships, and for other well-formedness properties. As mentioned earlier, some checking can be run incrementally, and whole-model checks run in overnight batch mode.

More fundamentally, the ontology itself can be checked for axioms of completeness, consistency and rules of good practice. Advances in the field of knowledge representation, for example the Web Ontology Language (OWL) – see https://www.w3.org/2001/sw/wiki/OWL – and associated toolsets, provide support for this kind of checking. This need only be done if and when the ontology itself is changed.

2.2 SysML

A significant portion of the MBSE community has coalesced around a common standard for information modeling, the Systems Modeling Language (SysML™) [SysML]. In the early years it was nurtured by individual heroics of a few, and support from volunteer organizations such as INCOSE and OMG™. In recent years, support for SysML has blossomed. There are a number of books (e.g., [Friedenthal et al., 2015]) and introductory courses for achieving familiarity and competence with SysML, and software tools that support development of models in the SysML language.

The SysML language is designed for representing *systems* engineering information. It is an outgrowth of an earlier language, the Unified Modeling Language (UML), which was developed to be a standard language for *software* engineering. SysML adds constructs appropriate to systems engineering not already found in UML.

SysML is designed to be a *general-purpose* systems engineering language, but in order to accommodate domain-specific needs, SysML is *extensible* (in fact, SysML is itself is an extension of UML). This capability is key. Concepts appropriate for a particular engineering discipline can, and should, be defined. These allow the ideal representation of information in that engineering discipline. For example, space systems engineering concepts of "mission", "science objective", "work package" etc. are not present in out-of-the-box SysML, but can be defined using its extension mechanism. SysML thus gives us the means to represent an ontology – its terminology, and associated properties and relationships. Done well, this will permit succinct and intuitive representation of information, while preventing misuse of properties and relationships. For example, in the context of space missions it makes sense for science objectives to be directly related to a mission, but not to a work package.

2.3 Developing an ontology for space systems engineering

Most pilot applications of MBSE across NASA have adopted SysML as the modeling language they use. They all then have the same need to develop an ontology appropriate for space systems engineering. This is critical if NASA is to effectively apply MBSE.

Ontology development is inevitably done in an evolutionary manner, using discussions with experts and experiences of applying it to space systems' engineering information to guide its expansion and revision (as and when found to be necessary). Significant efforts towards this end are underway within JPL and in the broader INCOSE community:

- JPL: Around 2011, JPL stood up the Integrated Model-Centric Engineering (IMCE) office. For the first several years (with modest funding) this office began the task of developing an ontology for space systems engineering. A series of pilot efforts were performed to explore the application of these ontological elements to some of the engineering disciplines. The success of this phase contributed to the adoption of MBSE as the methodology for Systems Engineering of the formulation phase on the Europa Clipper pre-project [Cooke, 2015].
- INCOSE: As reported in [Kaslow et al., 2015]: "The International Council on Systems Engineering (INCOSE) Space Systems Working Group (SSWG) established the Space Systems MBSE Challenge team in 2007. The SSWG Challenge team has been investigating the applicability of MBSE for designing CubeSats since 2011." This is heading towards development of a "Reference Model" for a typical space-ground system, one that can be used as a starting point for a mission-specific CubeSat model.

Much of the work of developing an appropriate space systems engineering ontology is in clarifying language use within that domain. In the past one may have been ambiguous about whether a spacecraft's "mass" refers to its wet mass (fully fueled) or dry mass (without fuel), leaving it to the intelligence of the reader to infer which it is from context. But for MBSE models it is important to have clearly distinct notions for mass (wet) and mass (dry). Furthermore, when the scope of modeling encompasses the design and development phases as well as the operational phase, there are additional variations of "mass" to represent: allocated mass, estimated mass (t), allocated + reserve mass, etc. It is this careful capture of terminology appropriate to space systems engineering that is both an initial disincentive (by forcing making explicitly making distinctions previously left implicit) and an eventual enabler.

An ontology need not be, nor should be, a monolithic entity. Just as SysML is a layer on top of (most of) UML, a space systems engineering ontology will ideally be built on top of SysML in several more levels. This is the case for JPL's ontology, which first adds to SysML a "Base" layer containing several fundamental concepts (e.g., that of an "IdentifiedElement" for any model element with an identifier and/or name(s)). Subsequent layers sit on top of that "Base" and thus are able to make use of its concepts. For example, in JPL's ontology on top of the "Base" there's a Mission portion (containing concepts such as Objectives, Components and Environments). In turn there is a Flight System portion that specializes mission concepts. Similarly, a layer itself need not be, nor necessarily should be, a monolithic entity. It can be compartmentalized into several portions, siblings with one another at the same level. For example, JPL has identified (and already developed some of) discipline-specific portions, such as "Navigation," "Propulsion," and "Telecommunications" to name but a few.

In a similar manner, Figure 2, below, shows the structure of a Logical Space System Model.

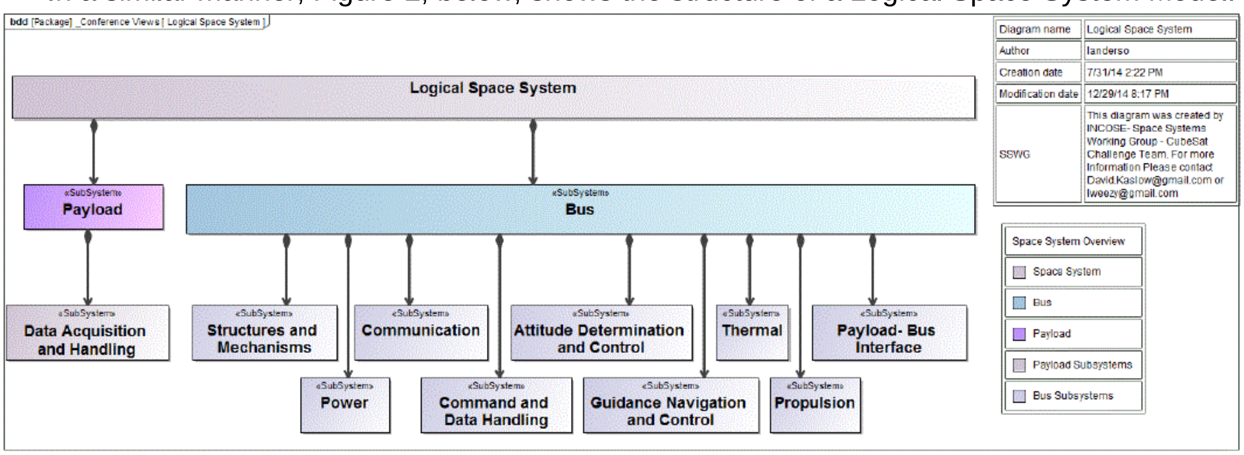


Figure 2 – Structure of a logical space system model. © 2015 IEEE. Reprinted, with permission, from D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani & R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status," *2015 IEEE Aerospace Conference*, 2015, pp. 1-16.

Note that this is just part of what needs to be represented – in addition there is the Ground System, the Environment in which the mission takes place, the project planning and development phases including V&V. It should be apparent that a space systems engineering ontology must encompass a wide range of considerations, and its development will take time and effort. At JPL this is occurring as the Europa Clipper pre-project extends its modeling to include information from additional engineering disciplines (e.g., trajectory, thermal control). Similarly, the INCOSE CubeSat effort is following a staged process – the first phase dealt with the logical and physical architecture of a reference model and its application to a specific CubeSat; the second phase introduced behaviors; the third phase improved upon the behavioral aspects of the second phase, and also began development of a generic model. At the time of writing of [Kaslow et al., 2015] the fourth phase was underway to model system development, and expansion of the model scope to all lifecycle stages (including V&V) and all phases of operation (including degraded as well as normal).

As an ontology is extended, some modifications merely require adding a property to an existing object (e.g., adding the property “Requires inspection?” to a component or to a status object that references the component). These will have few ripple effects on the remainder of the ontology and the infrastructure built around it. Conversely, some modifications will have more far-reaching ramifications. Consider a reliability factor that needs the number of Operating hours on a piece of Flight hardware. This requires connection of Operating hours to components of type Flight hardware. The Components are in turn related to Test (V&V) objects that capture (via a new property) the Number of Hours Operated. This simple example illustrates that the introduction of a new quantity (Operating Hours) will require ontology modifications to the part of the ontology defining Component and to the part of the ontology defining V&V concepts (Tests, so that they incur and track Operating Hours). The point is that this will require coordination and agreement among the developers and users of different parts of the ontology. Modifications that are especially cross-cutting in nature, such as integrating the notion of risk, may have even farther reaching implications. If risks were merely items to track in 5x5 matrices, their addition to an ontology would not be difficult. However, NASA’s risk management practices involve identification of risk scenarios, likelihoods and consequences, and the processes for dealing with risks (accepting, watching, mitigating etc.) Properly accommodating the notion of risk into a space systems engineering ontology will need to be done with care.

2.4 Mission Assurance

The previous subsections provided a brief description of some of the key ideas and notions of MBSE. MBSE’s emergence provides an opportunity for Mission Assurance to move from document-centric approaches, which often hinder the contribution and timely conduct of assurance activities, to objective-based products that are embedded within, and compatible with, the modeling used in an MBSE setting. To realize this improvement, mission assurance products and processes need to be able to fit within this framework. For example, safety and reliability engineers must be closely linked to the development taking place in the MBSE framework, from requirements definition through analysis, to support trade studies and design analyses that assure the required reliability and safety. The MBSE framework may demand that reliability and safety analysis and related products take on a new shape. Overall, this new environment presents an unprecedented opportunity to improve effectiveness of the reliability and safety communities. This subsection summarizes developments within NASA’s OSMA that are conducive to this end.

Contemporaneously with the advent of MBSE, NASA’s OSMA has begun the development and promulgation of a new objectives-based approach to standards. As stated in [Groen et al., 2015] (emphasis added):

> *“…NASA OSMA has developed an approach…to provide for flexibility … while focusing on a vision that is rooted in technical objectives rather than specifying specific products and processes. This approach uses the development of objectives hierarchies with supporting strategies for implementation. The results promise the potential of improved effectiveness, flexibility, and **compatibility with Model Based Systems Engineering (MBSE)**…”*

The objectives-driven approach starts with a single top-level objective of a successful project. This is then broken down into sub-objectives much like the development of any systems engineering hierarchy. Integral to this structure, however, is the use of *Strategies* to convey information about satisfying objectives. The strategy or strategies that couple with it identify non-process specific methodologies for satisfying the objective. For example, Figure 3 shows the top level of OSMA’s Reliability and Maintainability (R&M) Objectives Hierarchy [NASA OSMA R&M].

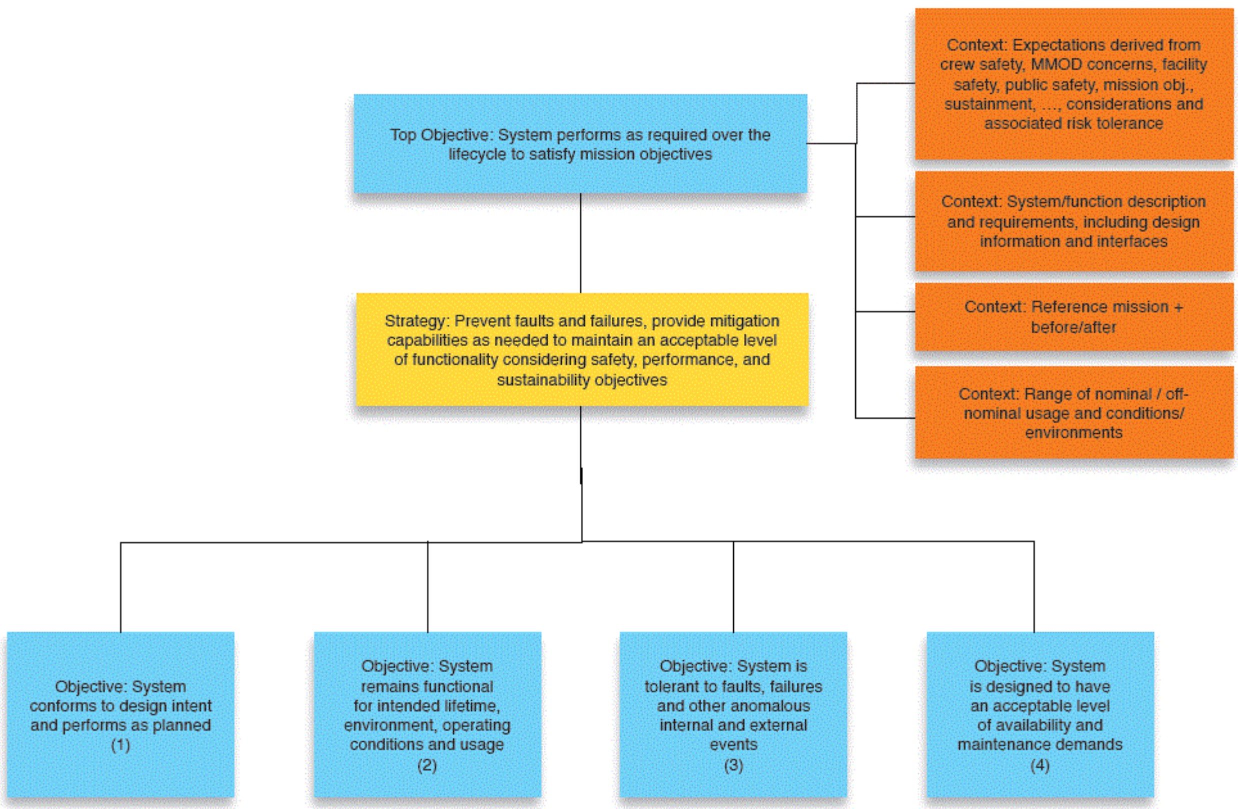


Figure 3 – Top level of the Reliability and Maintainability Objectives Hierarchy.
Reprinted from "Reliability and Maintainability Objectives Hierarchy"
https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4
Unlimited distribution of Government document; no re-use statement required.

This notation follows the style of the Goal Structuring Notation [Kelly & Weaver, 2004]. As used here, the top-level objective (the topmost blue rectangle) is decomposed into four sub-objectives (the four blue rectangles at the bottom). The strategy for this decomposition is stated in the intermediary yellow box, and the context for all this is stated in the several orange rectangles to the right. Each objective block is coupled with at least one strategy that is used to facilitate accomplishment of the objective. The four objectives at the bottom of Figure 3 are in turn decomposed into more detailed objectives. The R&M hierarchy was developed by a team that represented a significant cross section of the R&M expertise within NASA. The complete hierarchy is shown at the end of this document in the appendix.

To date OSMA has developed Objectives Hierarchies for the following areas:

- Reliability and Maintainability
- Software Assurance
- ELV Payload
- Range Safety
- Quality Assurance

For background information and the first four of these, see [NASA OSMA, 2014]. It may be that ultimately there will be a single integrated hierarchy for all of the OSMA disciplines.

The fundamental tenet of the objectives-driven approach is to define the technical objectives and strategies that constitute the assurance considerations for a system, as derived from a top-level objective. This decomposition is intended to help OSMA practitioners focus on the "what" they are trying to achieve without having the "how" dictated. It is an integral part of OSMA's shift towards use of a Risk Informed Safety Case (RISC) as the means by which to convey the argument for why a system is adequately safe [Dezfuli et al., 2014]. This shift applies to systems whether engineered by traditional means, or by using MBSE techniques. As emphasized in the quote earlier, its flexibility permits compatibility with, and utilization of, MBSE.

This is notionally indicated in Figure 4, to the right, where layers from bottom to top are as follows:

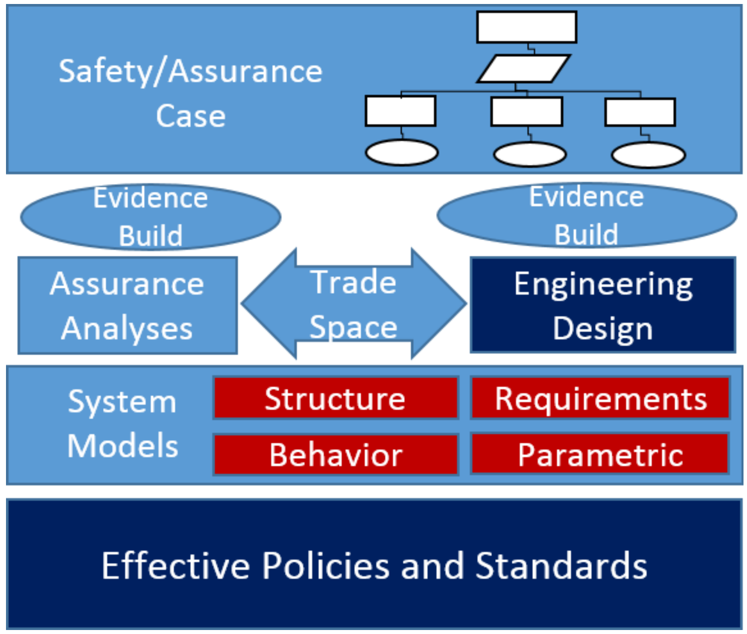


Figure 4 – Standards, models, engineering activities and safety/assurance cases.

- The bottom layer, "Effective Policies and Standards," is based on Objective Hierarchies.
- The layer above indicates that for systems that employ MBSE, much of their information is captured in models. For SysML in particular, models are conveyed through diagrams that fall into one or more of the areas shown in red, the four "pillars" of SysML (from the names "Structure", "Requirements" and "Behavior" it is obvious the areas they cover; in SysML, "Parametrics" *"represents constraints on system property values such as performance, reliability, and mass properties, and serves as a means to integrate the specification and design models with engineering analysis models"* [SysML].
- A system's MBSE models are used to inform the activities of Engineering Design and Assurance Analyses. Many of those activities will explore options in a trade space of design alternatives. Selections among these alternatives will be informed by the results of analyses performed on the designs (e.g., various forms of reliability analysis).
- As development takes place, evidence is accumulated from the design process (e.g., analyses, tests, inspections, and relevant historical data).
- In the vision espoused in [Dezfuli et al., 2014] this evidence is organized into the form of a Risk Informed Safety Case (RISC), or more generally, a Risk Informed Safety and Mission Success Case to cover both safety and mission success criteria. The system-independent Objective Hierarchies that informed the policies and standards can be used as templates to guide the development of the system-specific RISC – for an illustration, see [Witulski et al., 2016].

3 MBSE's implications for MBMA

To understand MBSE's implications for Mission Assurance, the future of which we're calling MBMA, a survey of MBSE literature addressing space mission engineering concerns was conducted. The objective was to find how MBSE approaches are being (or could be) applied to support assurance needs. The detailed survey results are in the following section, are organized into seven areas. This section gives a summary of those seven areas, and to give them context, relates them to OSMA's R&M Objectives Hierarchy.

1. *Representation and management of systems engineering information.* Rigorous model-based representation (i.e., with a semantic underpinning that ensures a shared, unambiguous understanding) of systems engineering information is the hallmark of MBSE. This rigorous foundation helps ensure consistency and some aspects of completeness of the systems engineering information. The desirable qualities have obvious relevance and benefit to the entire R&M Objectives Hierarchy to the extent that MBSE is carried through the mission lifecycle. May provide specific benefit in 1.B.1.A (Test, inspect, and demonstrate to an acceptable level to ensure that issues are found) through heading off subtle and hard to detect problems that stem from misinterpretations prevalent when less rigorous documentation is the norm.
2. *Support of the contractual interface between acquirer and potential suppliers.* One purpose of using NASA's Objectives Hierarchies is for it to be the means for a developer or service provider to communicate assurance information to NASA. In the R&M Objectives Hierarchy the conveyance of much of this information from acquirer to provider is indicated in the four context descriptions accompanying the top objective of the R&M hierarchy.

These first two areas related to the R&M Objectives Hierarchy as shown in the Figure 5, below.

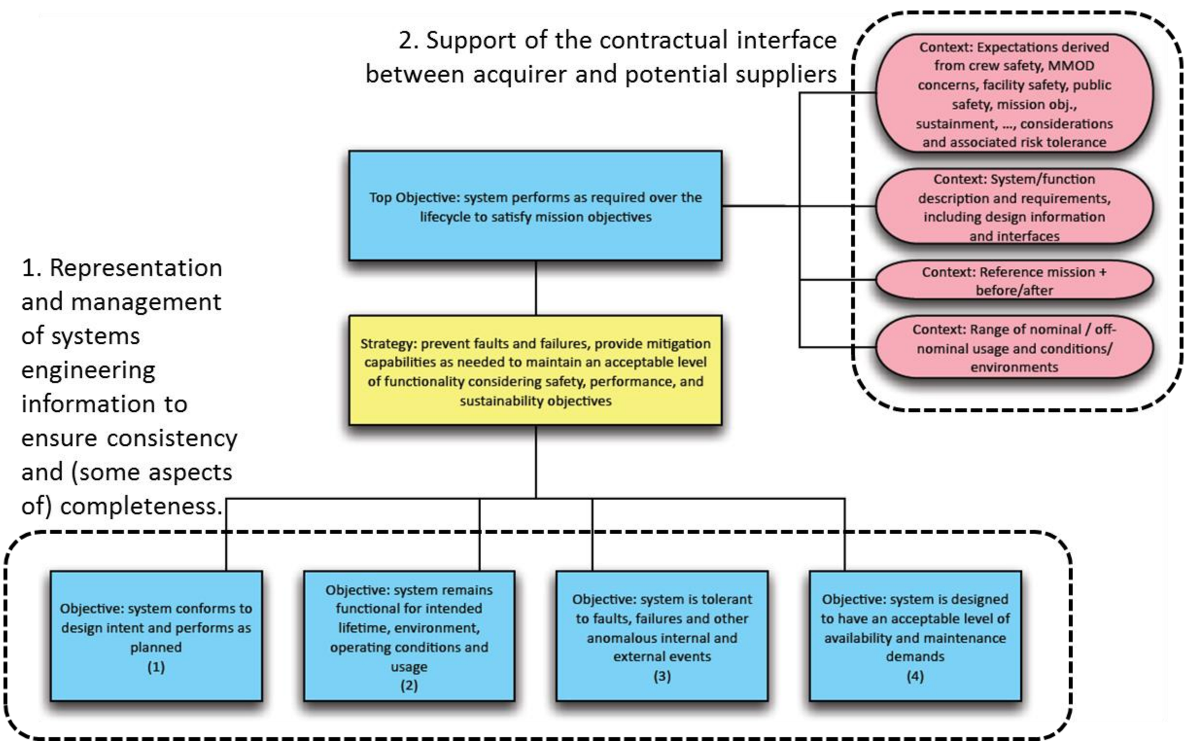


Figure 5 – Where areas 1 & 2 support the R&M Objectives Hierarchy. Adapted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

3. *Generation of review documentation from the shared MBSE system model.* Preliminary results from ongoing NASA applications show evidence of benefits to R&M Hierarchy 1.A.1.A (Demonstrate to an acceptable level that the functionality of the system meets the design intent). Traditional review materials (text and tabular documents) are being *generated* from the system models rather than hand-composed, ensuring those materials reflect the consistency of MBSE's "single authoritative source of truth." This has potential to benefit reviews and evaluations between acquirer and provider at any Key Decision Point (KDP) provided MBSE covers that stage in the system's lifecycle. Figure 6, below, thus suggests the universal scope of this with respect to the R&M Objectives Hierarchy.

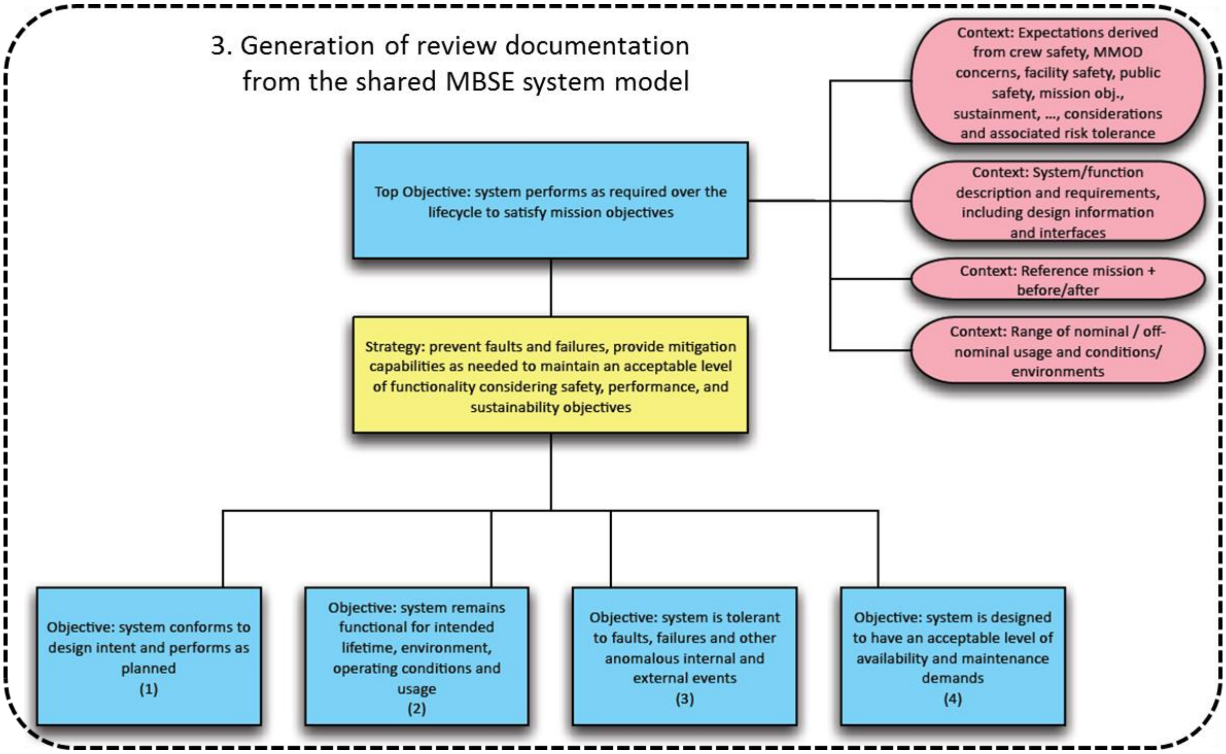


Figure 6 – Where area 3 supports the R&M Objectives Hierarchy. Adapted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

4. *Automated assistance for generating reliability artifacts (FMECAs, Fault Trees, etc.).* Relevant to sub-objectives 2 (System remains functional for intended lifetime, environment, operating conditions and usage), 3 (System is tolerant to faults, failures and other anomalous internal and external events), and to a lesser extent so far, 4 (System is designed to have an acceptable level of availability and maintenance demands). Generally, applications to date have been during design. It remains to be seen how MBSE will affect the later phases of development, most especially operations.

5. *Representation of and reasoning about off-nominal states and behaviors.* This is a fundamental capability supporting the previous area (reliability artifacts), therefore likewise relevant to sub-objectives 2, 3 and 4. Several efforts have focused on developing automated assistance, using its needs to drive the initial development of the representation.

These two areas relate to the R&M Objectives Hierarchy as shown in Figure 7, next page.

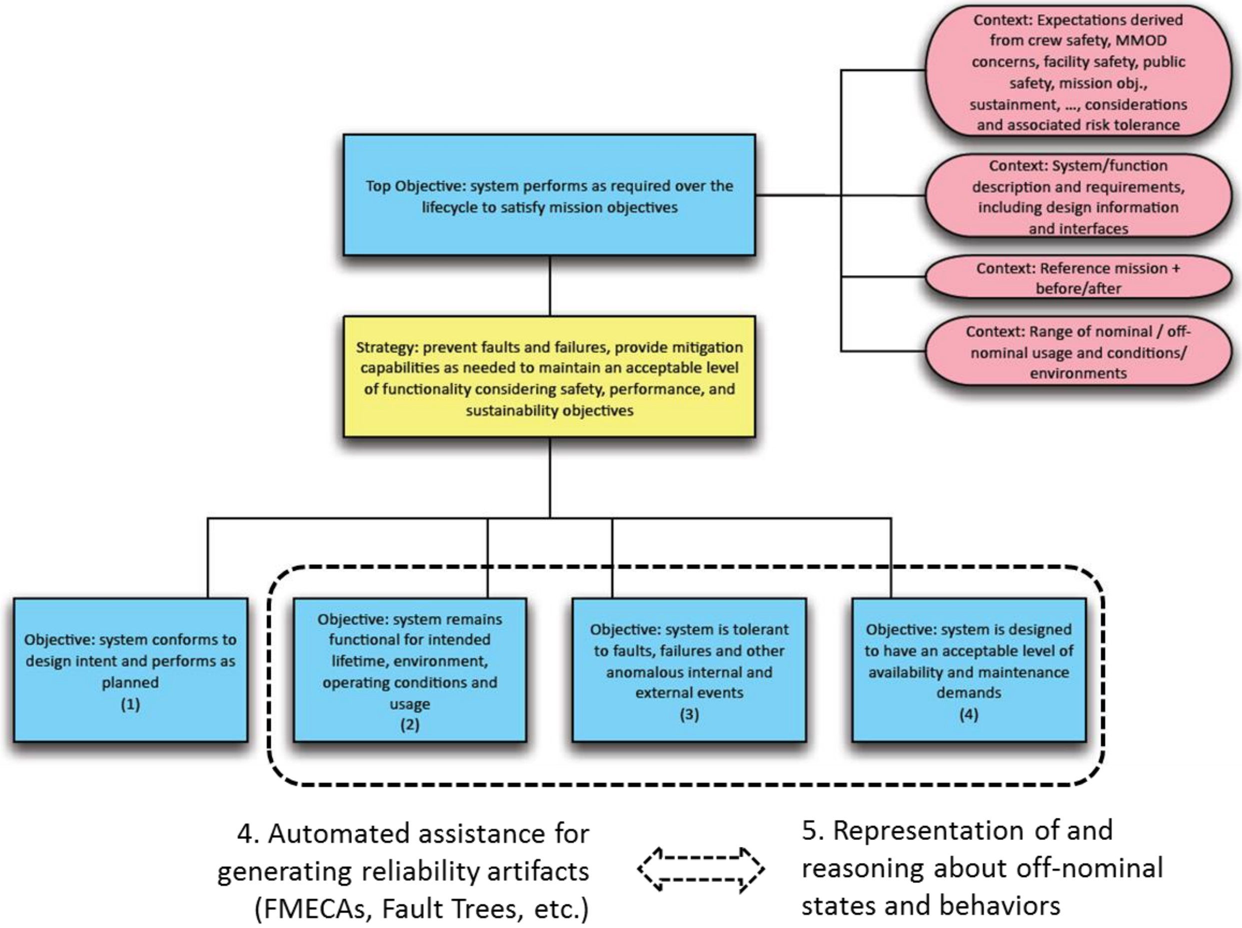


Figure 7 – Where areas 4 & 5 support the R&M Objectives Hierarchy. Adapted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

6. *Support for activities post-design.* While most of the MBSE literature focuses on the design stage, some address later activities, notably testing. Planning for and managing the testing activities could potentially benefit from the same MBSE principles of capturing the pertinent information in a formal representation, relevant to: 1.B.1.A, 2.A.1.D (Perform qualification testing and life demonstration to verify design for intended use), 2.B.1.D (Plan and perform life testing), 4.A.1.G (Provide demonstration testing to verify 'detect, diagnose, isolate' capability of systems and confirm corrective and preventive maintenance task actions and analysis) and 1.C.1.D (Screening, proof testing and acceptance testing). In the software arena there are instances of software being automatically generated from models, thus contributing to 1.C (Achieve high level of process reliability), and of software being extensively tested against computer simulations of the system and its operating conditions.

Figure 8, next page, shows these specific R&M Objective areas in the hierarchy for sub-objective 1, and Figure 9, page after, for the hierarchy for sub-objective 2.

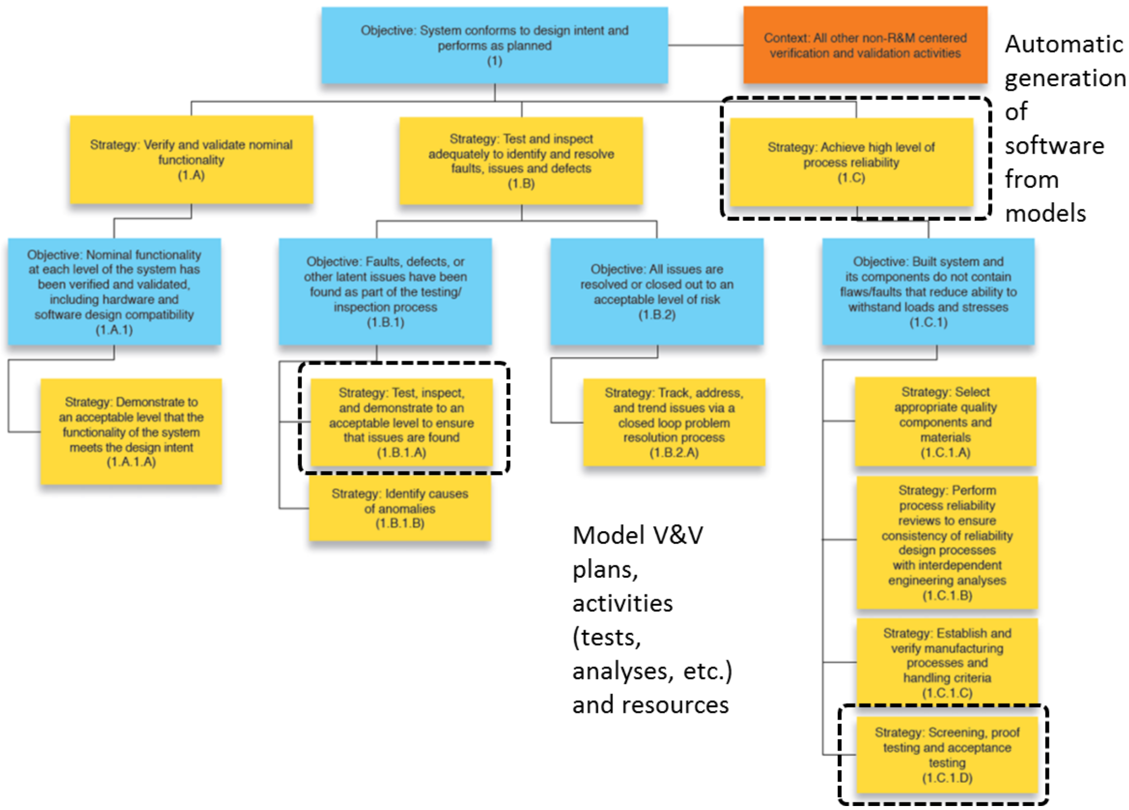


Figure 8 – Where some area 6 activities support the R&M Objectives Hierarchy. Adapted from "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 Unlimited distribution of Government document; no re-use statement required.

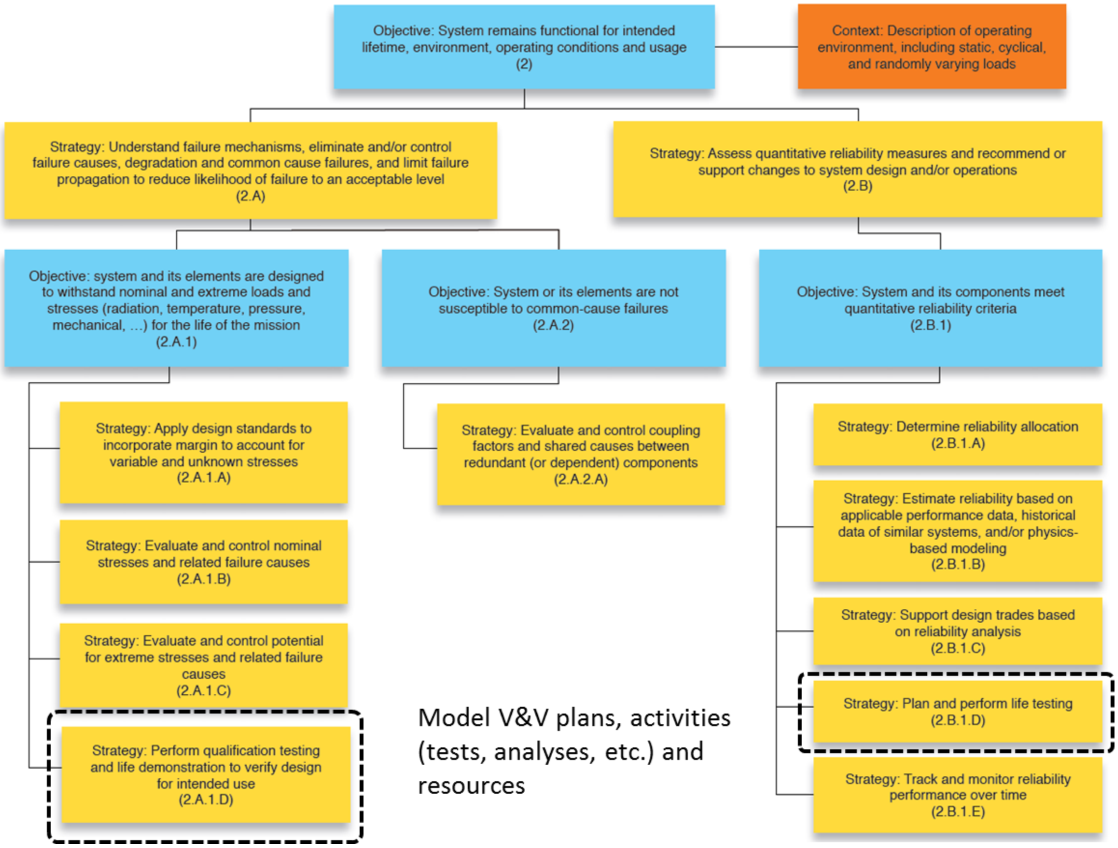


Figure 9 – Where some more area 6 activities support the R&M Objectives Hierarchy.
Adapted from "Reliability and Maintainability Objectives Hierarchy"
https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4
Unlimited distribution of Government document; no re-use statement required.

7. *Correctness of the MBSE models themselves.* Since the system design information is captured in models, it is crucial that they be correct, with obvious relevance all the previous six areas and where they relate to the R&M Objectives Hierarchy.

4 MBMA details found in the MBSE literature

This section presents the detailed results of our survey of the MBSE literature as it pertains to space mission engineering concerns, in particular how MBSE approaches are being (or could be) applied to support mission assurance needs. These results are organized into the seven areas introduced in the previous section, namely:

1. Representation and management of systems engineering information
2. Support of the contractual interface between acquirer and potential suppliers
3. Generation of review documentation from the shared MBSE system model
4. Automated assistance for generating reliability artifacts (FMECAs, Fault Trees, etc.).
5. Representation of and reasoning about off-nominal states and behaviors.
6. Support for activities post-design.
7. Correctness of the MBSE models themselves.

4.1 Representation and management of systems engineering information

In general, many papers and presentations argue for the benefit of model-centric rather than document-centric design; the following examples report application to space systems.

Integration of flight software developed for the James Webb Space Telescope's Integrated Science Instrument Module is briefly reported in [Aguilar, 2012]. The C&DH Core Flight Software (FSW) development was done at GSFC and the Science Instrument FSW applications were developed by different teams at several disparate locations. A Rational Rose Structure Diagram was used to unambiguously indicate the core system's communication ports to other subsystem components and to its own internal "capsules".

Use of MBSE to manage development of the ground system for control of the OSIRIS-Rex spacecraft during its encounter with asteroid Bennu is described in [Wibben & Furfaro, 2015]. Three areas are listed as benefiting from MBSE: representation and flow down of the requirements on the ground system, representation of its architecture (leading to development of the formal documentation of that architecture in the form of Interface Control Documents and Operational Interface Agreements), and capture of testing and V&V plans. In addition to diagramming static views of the architecture, FFBDs (Functional Flow Block Diagrams) are used to support discrete-event simulation of system behaviors to validate the system's run-time behavior.

Similar benefits are reported in [Karban et al., 2014] in the related area of systems engineering of astronomical telescopes.

Another important benefit of MBSE's single authoritative source of information is to serve as the intermediary among a federation of special-purpose representations and tools. This is seen, for example, in [Kaslow et al., 2014] where MBSE behavioral modeling of a CubeSat mission is connected to analytic capabilities (MATLAB® and STK®). The use of MBSE to manage the connection of system data with simulation environments is also the subject of [Cencetti, 2014]. Both of these show how the combination of MBSE and simulation can support conducting sensitivity analyses and trade studies of alternative designs. This is useful for the purpose of approaching an optimal design, not merely a good-enough design – an aspect that is called for in the system safety concept of "As Safe As Reasonably Practicable" (ASARP) [Dezfuli et al., 2014], or, for purely robotic missions once they have left Earth, As *Successful* As Reasonably Practicable.

4.2 Support of the contractual interface

A report on "research practices pertaining to methods, tools, and techniques proposed to facilitate the use of MBSE across the contractual interface in a competitive tender environment" is given in [Do et al., 2014]. The authors assert that MBSE has long been successfully applied across contractual boundaries in settings where "mutual trust is well developed and mutual goals are well understood." Their paper addresses the situation of a competitive environment, where a supplier would wish to excise proprietary information from the model they submit as part of the bid, and the acquirer would wish to excise certain sensitive information (e.g., costing, management) from the model they put forth to elicit bids. The paper lists details on these topics resulting from "workshops with key stakeholders." They go on to mention that the acquirer's model served as a good starting point for the supplier to elaborate further into a more detailed model.

4.3 Generation of review documentation

"Document/Expert – Centric Acquisition" is contrasted with "Data-Driven/MBSE Acquisition" in [Montgomery, 2014], which suggests many of the analysis results needed for acquisition decisions can be machine-generated from models, replacing labor intensive human assessments by teams of experts.

Textual forms of the acquirer's Operational Concept Document, Function and Performance Specification and Test Concept Document are described as being generated from a reference model in [Do et al., 2014]. It also goes on to say that some members of the supplier team worked directly from the model, and those that initially preferred to work from the generated textual forms increasingly switched to the model.

A pilot study on a "moderate size flight project" – MISSE-X, a payload for hosting experiments, to be installed on the exterior of the ISS is reported in [Vipavetz et al., 2012]. The report discussed the pros and cons of MBSE in preparation for the project's System Requirements Review. They used:

- SysML to "document the system concept of operations as well as some assembly, integration and test activities" (use-case diagrams for stakeholder interactions, activity diagrams to document system functions, activity diagrams, state-machine diagrams and sequence diagrams to document intended behavior, package diagram of system architecture and external boundaries, IBD for flows and interfaces between systems) and
- Vitech's CORE™ to manage the requirements (traceability through levels of requirements, allocations, owners and verification methods).

They report benefits of consistency, ease of access to complete, current information, and clarity across the team. The review need was to demonstrate existence of a feasible and satisfactory system design (feasible = could be implemented consistent with cost, schedule & risk; satisfactory = design meets project goals). Exports from CORE were used to provide information to team members without requiring them to be CORE users, and to generate complete documents directly from CORE. Review materials were developed from the SysML and CORE models. However, their paper identifies several challenges:

- "no guarantee that the model is correct" – note that they did not pursue extensively execution of models, stating "developing executable models within the model itself was found to be challenging"
- Restarts in creating the meta-model (ontology)
- Default presentation options from SysML tool often needed extensive re-working.

Modeling followed by document generation was used to generate the contents of an assessment report of NASA Ground Systems Development and Operations' (GSDO) plan to verify their command and control software [Aguilar et al., 2014]. The modeling focused on physical and logical interfaces, and its role in the assessment is indicated by Figure 10, below.

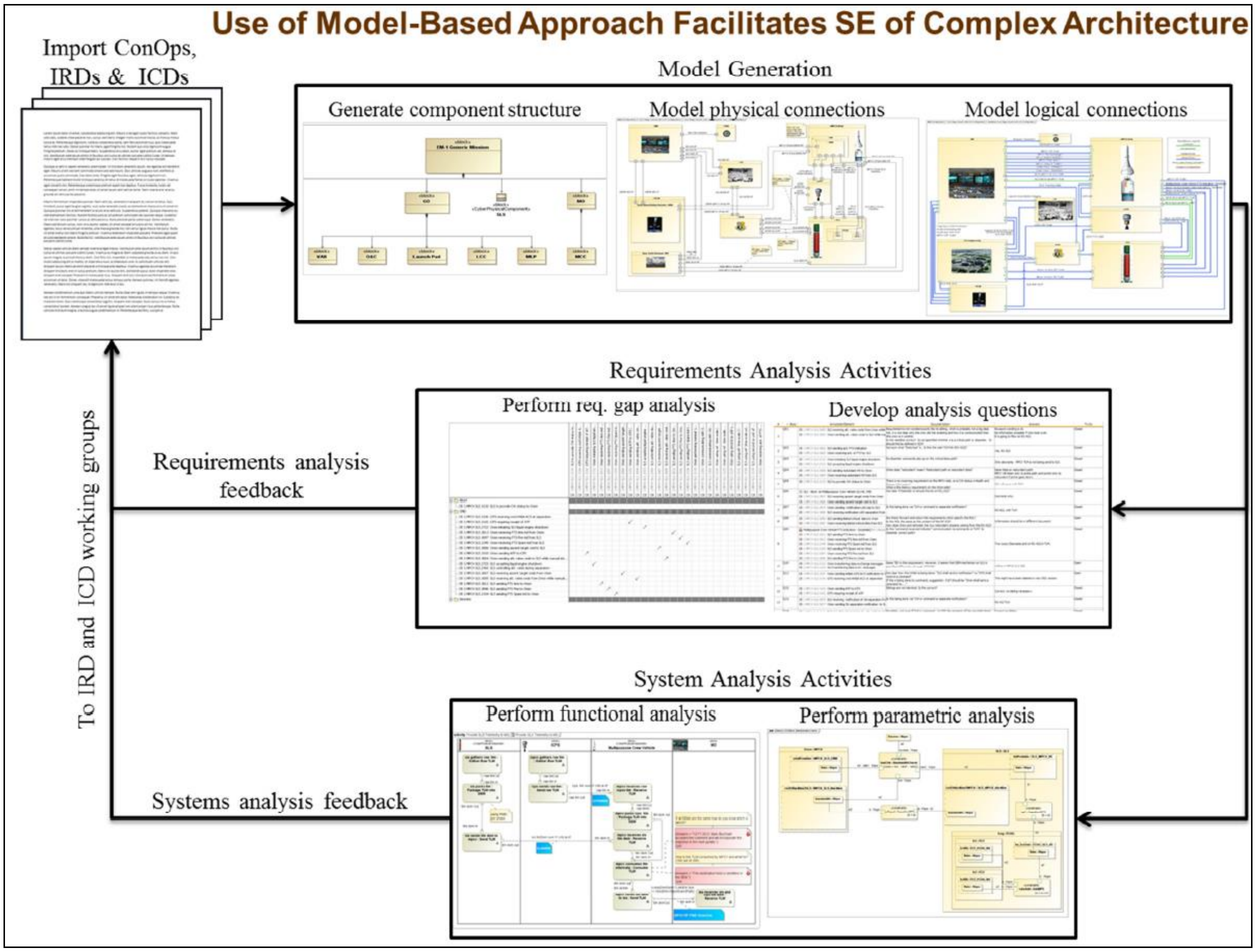


Figure 10 – Model-based IRD/ICD interface review process. Reprinted from M. Aguilar, K. Bonanne, J.A. Favretto, M.M. Jackson, S.L. Jones, R.M. Mackey, M.A. Sarrel & K.A. Simpson, *Review of Ground Systems Development and Operations (GSDO) Tools for Verifying Command and Control Software*, NASA/TM-2014-218278, June 2014, with permission of the authors.

The information available to the review team allowed them to perform requirements gap analysis (looking for missing and inconsistent requirements), and a limited amount of functional analysis. The document further states that *"All text, tables, and illustrations in the GAILA [GSDO Avionics Integration Laboratories Assessment] report were extracted and formatted from the SysML model repository."*

4.4 Generation of reliability artifacts

There are numerous examples of MBSE being used to provide automated assistance to generate reliability artifacts (FMECAs, Fault Trees, etc.).

Generation of FMEAs from SysML information, specifically from Sequence Diagrams (SDs) and Internal Block Diagrams (IBDs), is described in [David et al., 2009] & [Cressent et al., 2011] (see also the next section for further papers by the same set of authors). They assume a database (referred to in the paper as a "Dysfunctional Behavior Database") of components and their failure properties – their failure modes, and (optionally) additional information such as failure rate. They further allow for the following:

- A Parametric Diagram (PD) expressing the computation of functional attributes degradation during the failure mode occurrence.

- A PD indicating the computation of the failure rate of each failure mode. (This constraint depends on the environmental and structural parameters)
- A Statechart Diagram describing the dynamic behavior of the component in the failure mode state.

They stress that in IBDs they utilize two kinds of ports – standard ports and flow ports. Standard ports are suited for representing control and command requests (including exchange of information); flow ports are suited to representation of data, material or energy flowing through the connectors to/from such ports.

Scalable, automated generation of a FMEA, illustrated on a model of a satellite, its ground control system, and ground users is concisely reported in [Hecht et al., 2014]. They assume a SysML model with BDDs, IBDs (in which failure propagation paths are represented), state transition machines (including both normal and failed states) and activity diagrams (that generate the triggers driving state transitions). From these they also automatically generate a model to input into AltaRica ("a tool and language implementing mode automata") to model fault propagation.

Collaborations between Johnson Space Center and Tietronix Software Inc. are reported in [Wang et al., 2015] & [Sargusingh et al., 2015]. Generation of a FMECA and a Fault Tree from a SysML model is illustrated in [Wang et al., 2015]. They too assume that SysML IBD has the details of the system architecture and that the state transition diagrams include nominal and off-nominal (failed) states, using state machine events and guards to encode propagation of failure effects from one component to another. The example they use as illustration is a "Common Cabin Air Assembly" to provide life-critical air circulation in the ISS, and they show how the generated FMECA takes into account the fault-tolerance provided by redundancy in the modeled system. It does not appear that they deal with continuous physical flows in the same manner [David et al., 2009]. Application to design of a water recycling system (the "Cascade Distillation System") intended for use in the context of a human mission to Mars (for which high reliability and low mass are both driving concerns that make the design a challenge) is reported in [Sargusingh et al., 2015]. The paper shows the results of their tooling to (a) "extract the FMECA from the … FSMs (Finite State Machines) defining the possible failed states" and (b) "traverse behavior diagrams to extract the fault event paths for analysis", combining these into a fault tree.

An approach to automatic generation of FMEA and Fault Tree Analysis (FTA) artifacts from system models is outlined in [Mhenni et al., 2014a] & [Mhenni et al., 2014b]. Their FMEA generation process starts from a top-level functional breakdown for the system, and yields a list of generic failure modes for those functions and potential causes and effects. At this stage additional failure modes can be added manually. Having allocated components to functions, the generation of a component FMEA proceeds in a similar manner. Their Fault Tree generation process utilizes the FMEAs, and hinges on graph-traversals of SysML Internal Block Diagrams (IBDs) that express component interactions and the internal structure (connectivity) of the system. They show how they convert patterns inside an IBD representing redundancy or feedback loops into the corresponding fault tree structures using AND and OR gates as appropriate. They use as illustration an electromechanical actuator used to actuate ailerons – this is described as a case study, but not an actual industrial application.

4.5 Off-nominal states and behaviors

Off-nominal behavior, of particular interest to the OSMA practitioners, has begun to be explored in the context of MBSE. Open questions remain regarding the integration of risk into the models and a methodology for managing/reducing these risks.

Verification of fault management behavior by execution of a model of NASA's Ares & Orion communication during abort is briefly reported in [Aguilar, 2013]. This provides an illustration of a missing transition guard, presumably discovered in a simulation that exhibited an unwanted launch delay. Other examples of errors “found through modeling” are also listed.

A small manually conducted feasibility study, of representing failures so as to check for safety and security properties such as “robust to any single failure”, “robust to erroneous data”, “resilient to fake GPS signal” is reported in [Brunel et al., 2014]. They indicate the potential for translation into Alloy, a language and toolset for formal analysis of consistency.

The need to integrate the representation of, and reasoning about, off-nominal behavior with the standard system engineering process is addressed in [Cressent et al., 2013]. They describe typical reliability activities (e.g., FMEA) and their data sources & sinks. They stress the need to model the dynamics of off-nominal behaviors, presenting a meta-model (ontology extensions) appropriate to this, including treatment of off-nominal behaviors at multiple levels of abstraction (boolean to represent working or not; qualitative to include representation of “degraded” conditions; formulae for quantitative calculations e.g., using failure rate values). Semi-automated mapping from SysML into AADL for purposes of analyzing real-time computational aspects of the system is detailed in [Cressent et al., 2010] (the AADL language and associated tools provide another model-based approach to representation and reasoning for real-time software systems development; see also [Fernández, 2014] for AADL and MBSE).

Figure 11, next page, from [Cressent et al., 2013], shows the role of various forms of analyses and the data they ingest/produce. In that paper it is captioned as “Fig. 1. A project lifecycle process example. Req & Cons, Requirements and Constraints; PHA, Preliminary Hazard Analysis; FMEA, Failure Mode and Effects Analysis; FFMEA, Functional Failure Mode and Effects Analysis (FMEA based on the functions of the system instead of the components of the system).”

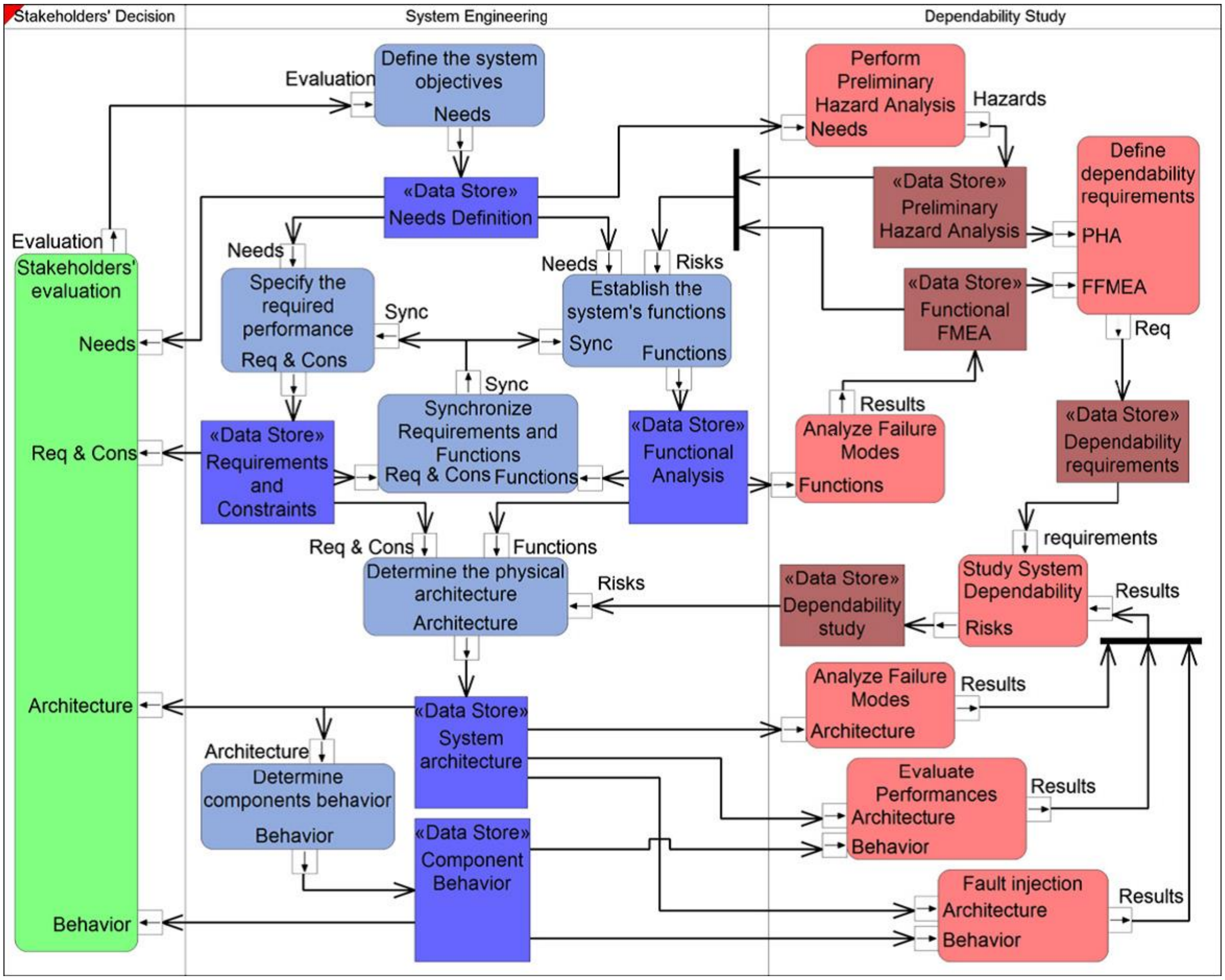


Figure 11 – Various analyses and the data they ingest. Reprinted from *Reliability Engineering and System Safety, 111*, R. Cressent, P. David, V. Idasiak & F. Kratz, "Designing the database for a reliability aware Model-Based System Engineering process," 171-182, copyright 2013, with permission from Elsevier.

A "safety profile" – stereotypes to extend SysML in order to represent information relevant to failures etc. ("safety profile" could equivalently be called meta-model or ontology) is presented in [Mhenni et al., 2014a]. They offer a case study using it to represent failure information for an electromechanical actuator – specifically, an actuator of the ailerons in an aircraft. They also describe semi-automatic generation of FMEAs from this information – see the "Automated assistance for generating reliability artifacts" subsection for further discussion of this.
Some details of their approach to representing off-nominal information are seen in Figure 12 and Figure 13, next page.

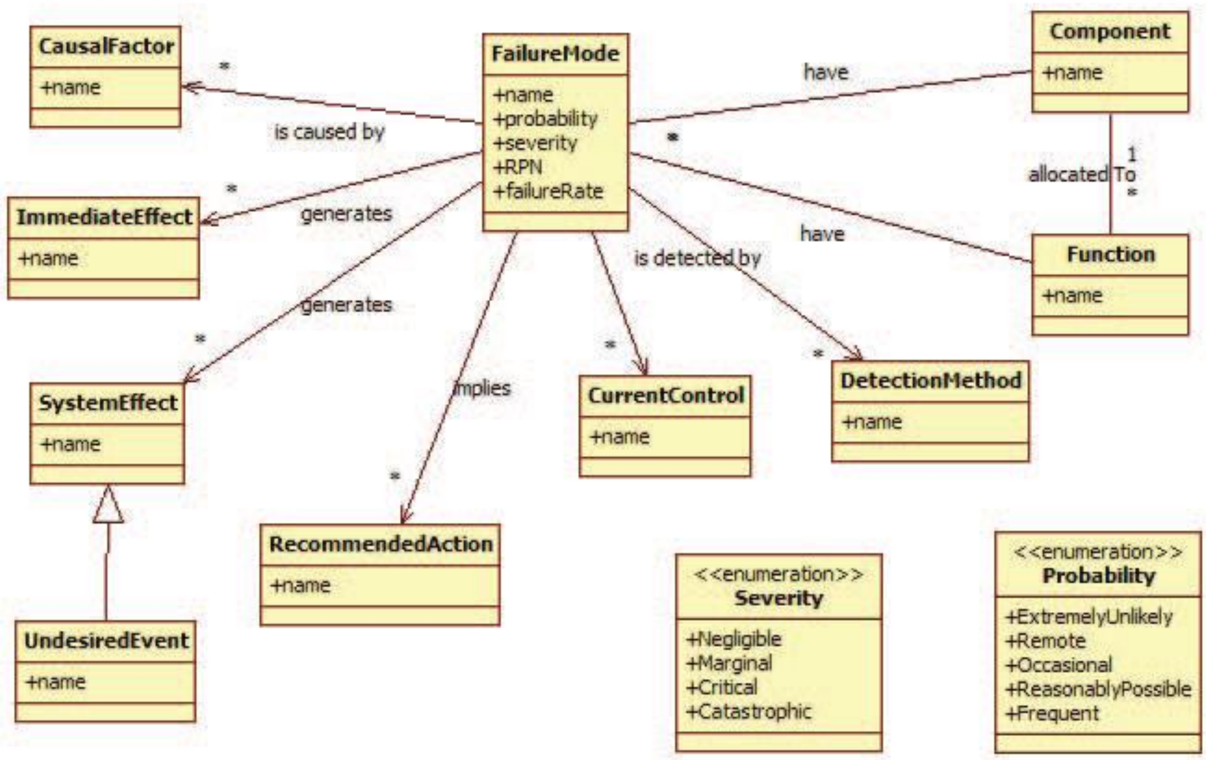


Figure 12 – Class diagram for FMEA artifacts. © IEEE. Reprinted, with permission, from F. Mhenni, J-Y. Choley & N. Nguyen, "SysML Safety Profile for Mechatronics," in *Mecatronics (MECATRONICS), 2014 10th France-Japan / 8th Europe-Asia Congress on*, 2014, pp. 29-34.

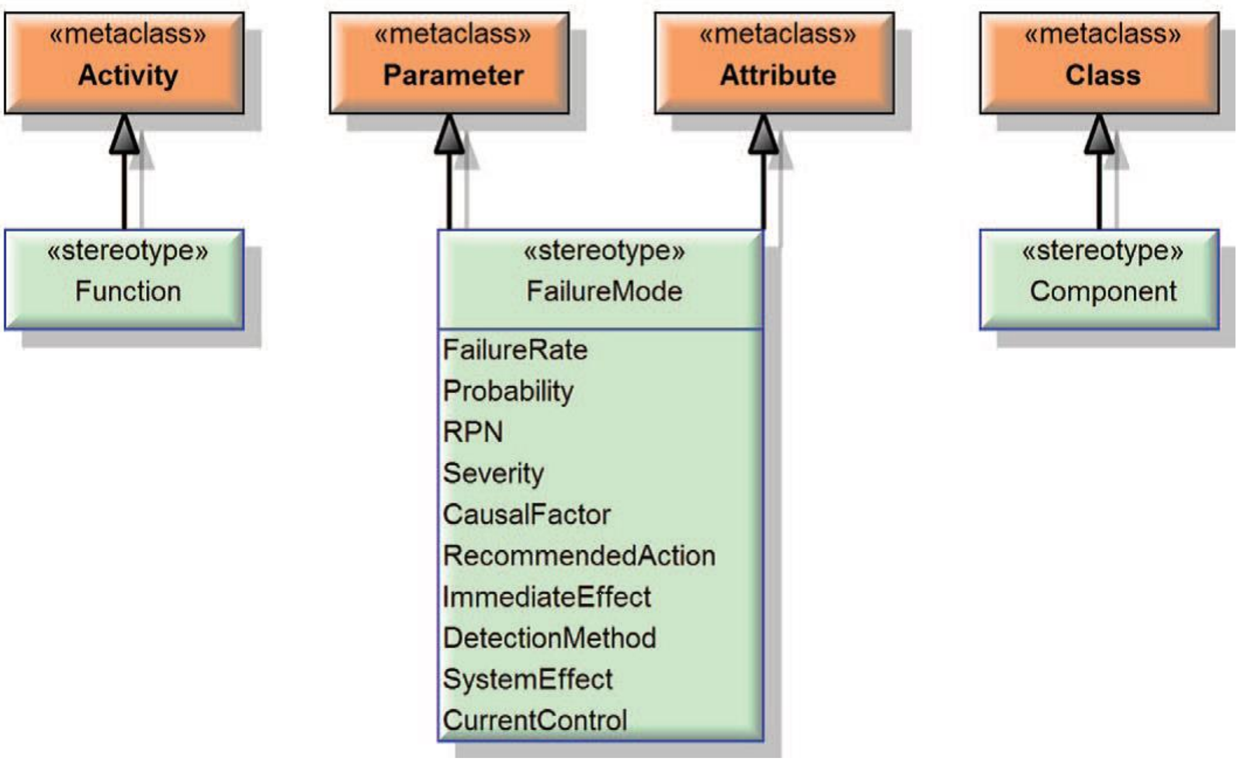


Figure 13 – Safety profile diagram. © IEEE. Reprinted, with permission, from F. Mhenni, J-Y. Choley & N. Nguyen, "SysML Safety Profile for Mechatronics," in *Mecatronics (MECATRONICS), 2014 10th France-Japan / 8th Europe-Asia Congress on*, 2014, pp. 29-34.

A similar approach is followed in [Biggs et al., 2016], presenting a SysML profile (appropriately named "SafeML") specifically for representing safety-related concerns of a system. Profiles are given for representing hazardous events and for defenses to them. The paper also shows the use of alternative model views, generated automatically from the model by a plug-in to the tool being used to support SysML. For example, a matrix view relating harm contexts to the defenses against those harms is used to provide a convenient overview from which it is easy to see which, if any, harm contexts lack defenses. Figure 14, below, shows this paper's SafeML profile to represent hazardous events; see the paper for a similar figure showing the profile for elements related to defenses.

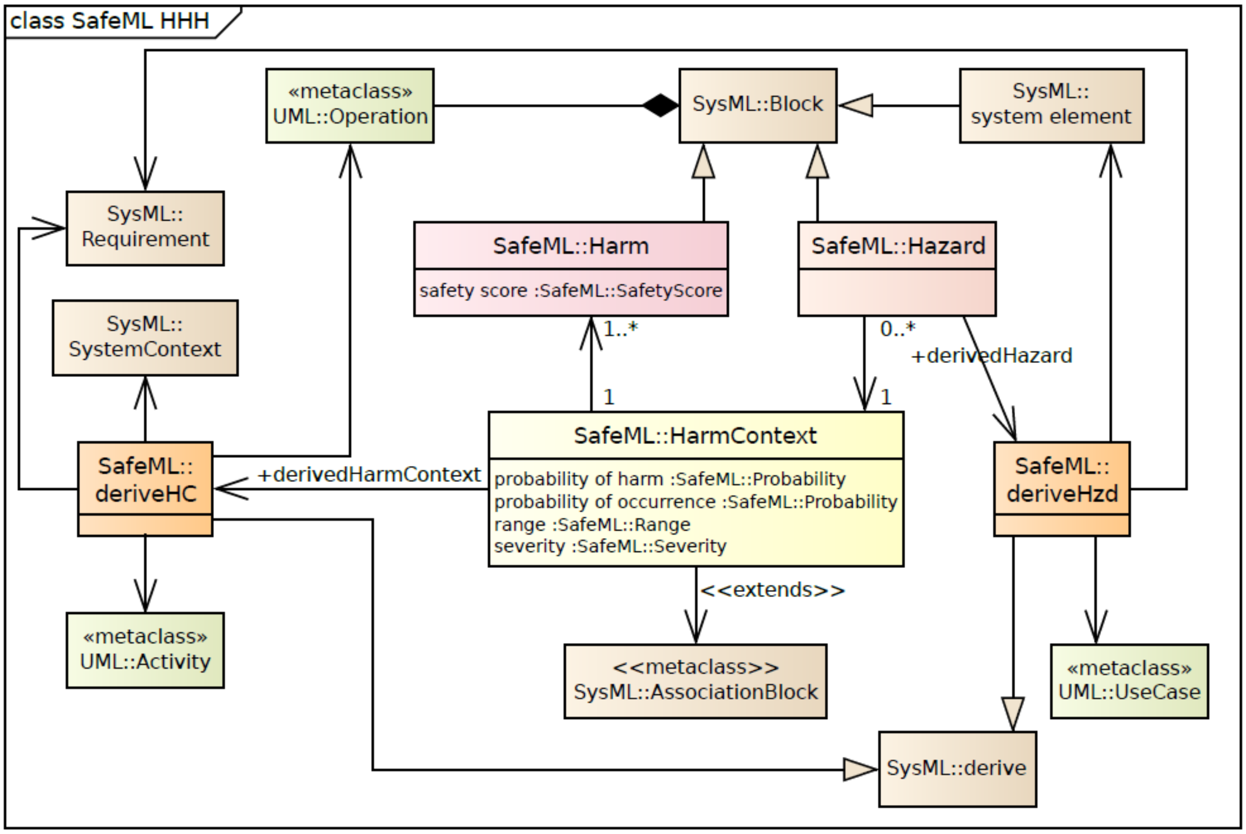


Figure 14 – Profile elements relating to hazardous events. *Springer Journal of Software and Systems Modeling*, "A profile and tool for modelling safety information with design information in SysML," 15(1), 2016, 147-178, G. Biggs, T. Sakamoto & T. Kotoku, © 2016. With permission of Springer.

Note that in terms of what's included, this is similar to the safety profile from [Mhenni et al., 2014a] presented earlier – both approaches to profiles provide attributes of Severity and Probability, for example, but do so in different ways.

4.6 Support for activities post-design

The majority of reports of MBSE applications (and hence the majority of the attention) has so far been focused on systems in their early phases. Nevertheless, several papers take the approach of looking ahead to how MBSE might assist those later lifecycle phases. In particular, using MBSE to model V&V activities is a common theme.

The argument for a model of system information that spans the entire lifecycle, all the way from design choices, through development and V&V, to operation, appeared in [Cornford et al., 2006]. The main elements of this model are requirements, functions, components, risks, work breakdown structure, and implementation – that last encompassing operational scenarios in which the modeled system is analyzed for its operational performance. This end-to-end model allows study of the cost and schedule implications of alternative designs and alternative approaches to their V&V, and the resulting likelihoods of mission success measured in terms of probabilistic attainments of mission objectives. The key addition this paper offered to model based engineering frameworks was its representation of risk (through inclusion of off-nominal behaviors of the system's components).

The Large Synoptic Survey Telescope (LSST) reports having "implemented a Model Based Systems Engineering (MBSE) approach as a means of defining all systems engineering planning and definition activities that have historically been captured in paper documents" [Selvy et al., 2014]. This paper "details the methodology employed to use the tool (Enterprise Architect) to document the verification planning phases, including the extension of the language (SysML) to accommodate the project's needs. They use SysML's extensibility to define a "VerificationPlanning" stereotype, with the attributes appropriate to representation of traditional verification information (e.g., verification method, verification requirement, success criteria). Figure 15, below, from the paper, shows requirements connected to VerificationPlanning elements (indicated by links labelled "<<refine>>") and those VerificationPlanning in turn connected to VerificationActivities (indicated by the links labelled "<<verify>>").

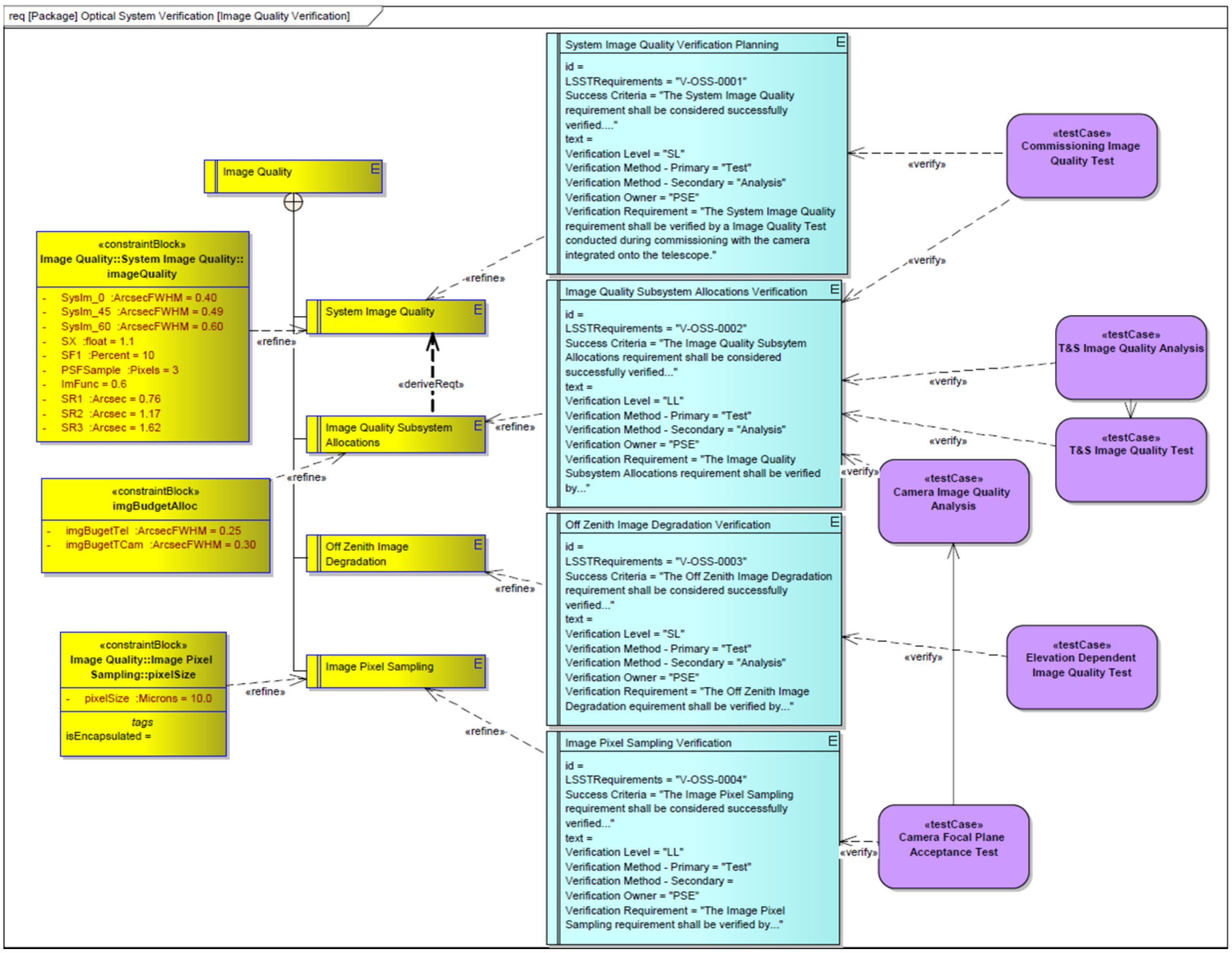


Figure 15 – An information model for Requirements, Verification Planning and Test Cases. Reprinted from B.M. Selvy, C. Claver & G. Angeli, "Using SysML for Verification and Validation Planning on the Large Synoptic Survey Telescope (LSST)," *SPIE Astronomical Telescopes + Instrumentation*, pp. 91500N-91500N. International Society for Optics and Photonics, 2014, copyright SPIE. With permission from SPIE and the authors.

The paper goes on to show use of SysML Activity Diagrams to capture the sequencing of the verification events (test cases), and to show use of SysML behavior diagrams to capture the individual steps (actions) of a verification event.

In a similar fashion, the topic of “Managing the development of system testing using the principles of Model Based System Engineering” is addressed in [Kratzke, 2014]. It makes the observation that requirements, functions and components (which are repeated as the core concepts of many of the systems engineering ontologies) all factor into system testing. Kratzke proposes the ontology shown in Figure 16, below, for representation of information surrounding tests and their role in verification.

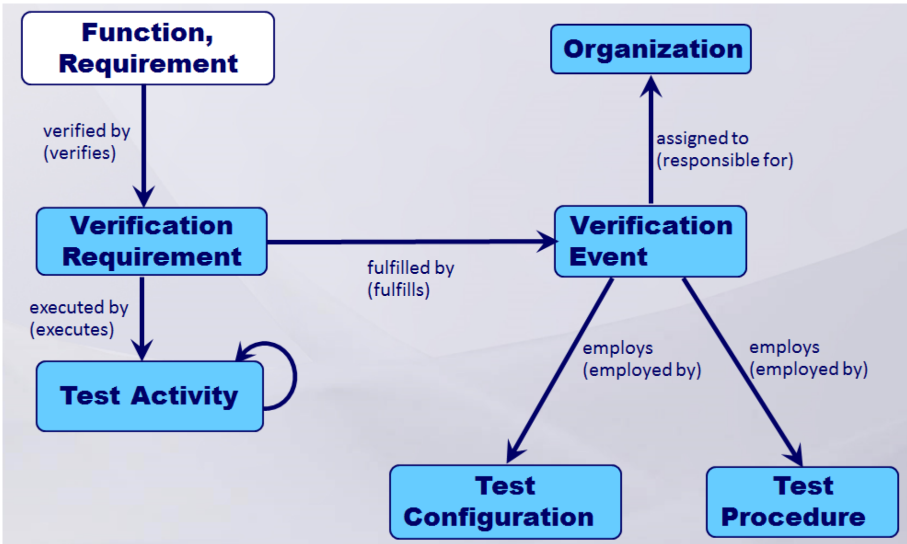


Figure 16 – An information model for test activities and events. Reprinted from R. Kratzke, “MBSE for System Testing,” *Systems Engineering Conference (SEDC2014), 2014*. Reprinted with permission of Vitech Corporation Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-9_Model-based-System-Engineering-MBSE-for.pptx

The question “could system integration and verification planning benefit from the capabilities of MBSE?” is addressed in [Salado, 2013], which also “proposes an information model to use model-based systems engineering to actually plan integration and test activities of a system.” The usual benefits attributed to model-centric representations of design information (single source of information, model-based rather than document based, representation of relationships between artifacts) are described as applicable to systems integration and verification. The paper reports having developed an information model with which to represent integration and test artifacts and activities. This paper offers an information model featuring an Integration and Test (I&T) activity object associated with a Verification requirement, Test Configuration, etc., as seen in Figure 17, next page.

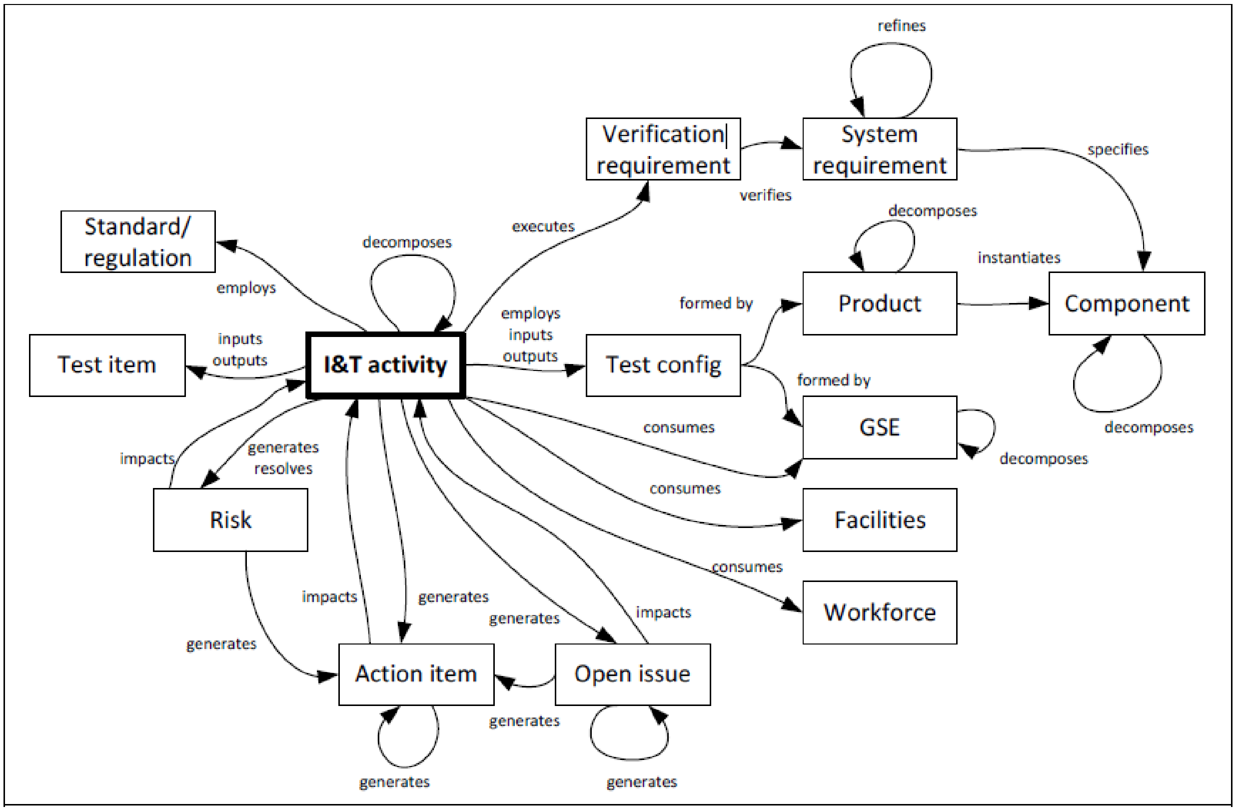


Figure 17 – An information model for system integration and test. Reprinted from *INCOSE International Symposium, Vol. 23, No. 1*, A. Salado, "Efficient and Effective Systems Integration and Verification Planning Using a Model-Centric Environment," 1159-1173, copyright 2013, with permission from John Wiley and Sons.

"V&V may be the biggest benefactor from the MBSE approach" is asserted in [Wibben & Furfaro, 2015], which goes on to say "… by mapping requirements to architecture and defining operational scenarios as they are being developed, …, the basis for defining detailed verification descriptions, success criteria, and other verification artifacts are distributed throughout the lifecycle." Figure 18, below, from the paper, shows high level connections and definitions used for V&V of requirements.

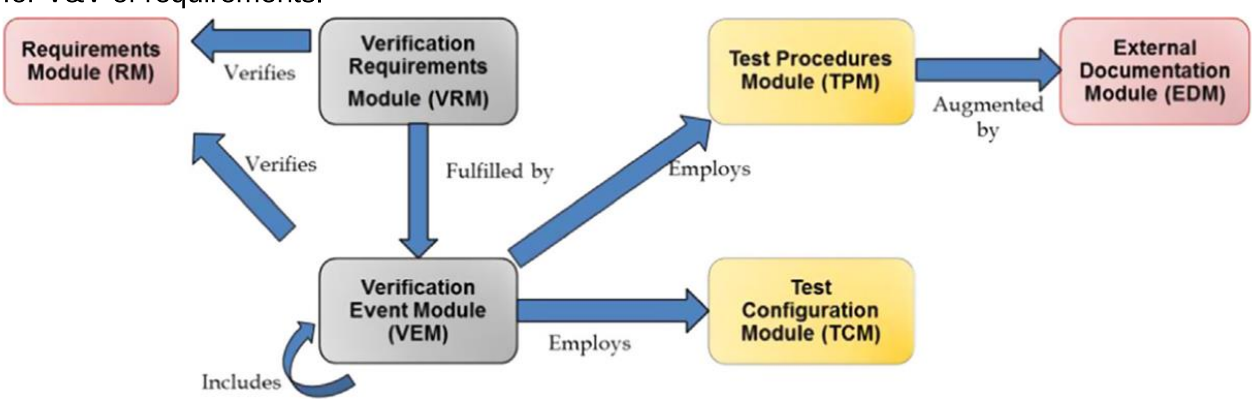


Figure 18 – An information model for verification. Reprinted from *Acta Astronautica, 115*, D.R. Wibben & F. Furfaro, "Model-Based Systems Engineering approach for the development of the science processing and operations center of the NASA OSIRIS-REx asteroid sample return mission," 147-159, copyright 2015, with permission from Elsevier.

Verification of safety requirements in software-intensive systems is considered in [Pétin et al., 2010]. They point out that formal (mathematical) methods are required to rigorously prove safety properties, and discuss translation from typical SysML representations to the models and properties needed by the formal methods, for example the model checker UPPAAL (from www.uppaal.org "UPPAAL is an integrated tool environment for modeling, validation and verification of real-time systems modeled as networks of timed automata, extended with data types (bounded integers, arrays, etc."). They present an example of a mechanical press controlled by software in a programmable logic controller, considering the verification of requirements allocations from system to its components, a mix of software, mechanical and electro-mechanical.

The use of Model Based Software development to develop much of the on-board software of the LADEE spacecraft, and also to develop ground code to simulate the spacecraft, is reported in [Gundy-Burlet, 2013] and [Benz et al., 2015]. The latter was used in extensive testing of the on-board software, in operator training during mission simulations and readiness testing, and for verification of command sequences prior to their uploading to the spacecraft during the operational portion of the mission.

4.7 Correctness of the MBSE models themselves

Ways to address the question of correctness of MBSE models are advocated in [Montgomery, 2014]. It describes useful (manual) inspections of several of the kinds of models found in typical MBSE developments, using as illustration reference systems from grad school projects (in the naval domain). The inspections are listed below. Briefly, they cover: requirements; mission and operations and interoperability; functionality, interfaces and continuity; system content flow; system behavior; system realization; allocation, and integrity; integrate-ability; qualify-ability.

List of inspections extracted from [Montgomery, 2014], with permission of the author:

- Requirements:
    - "Hierarchy depth indicates strength of requirements derivation"
    - "Requirements allocated to system functions/components sets foundation for qualification (V&V)"
- Mission and operations and interoperability
    - "External system diagramming [using ICOM diagrams - inputs, control, outputs, and mechanisms] identifies critical interoperability interfaces" – check the sources/destinations of the ICOM inputs and outputs
    - Check that a "CONOP must manifest into mission activities and data flow"
- Functionality
    - "Hierarchy depth indicates functional design understanding and fidelity"
    - Inspect for appropriate depth, allocations, orphans
- Interfaces and continuity: "Ensure connection completeness"
    - "N2 diagramming is good tally of interfaces (both functional and physical) and is a "Better "eye-ready" assessment", during which look for: "missing squares", Vacant quadrant, Sparse matrix, Missing externals, High density I/O – Figure 19, next page.

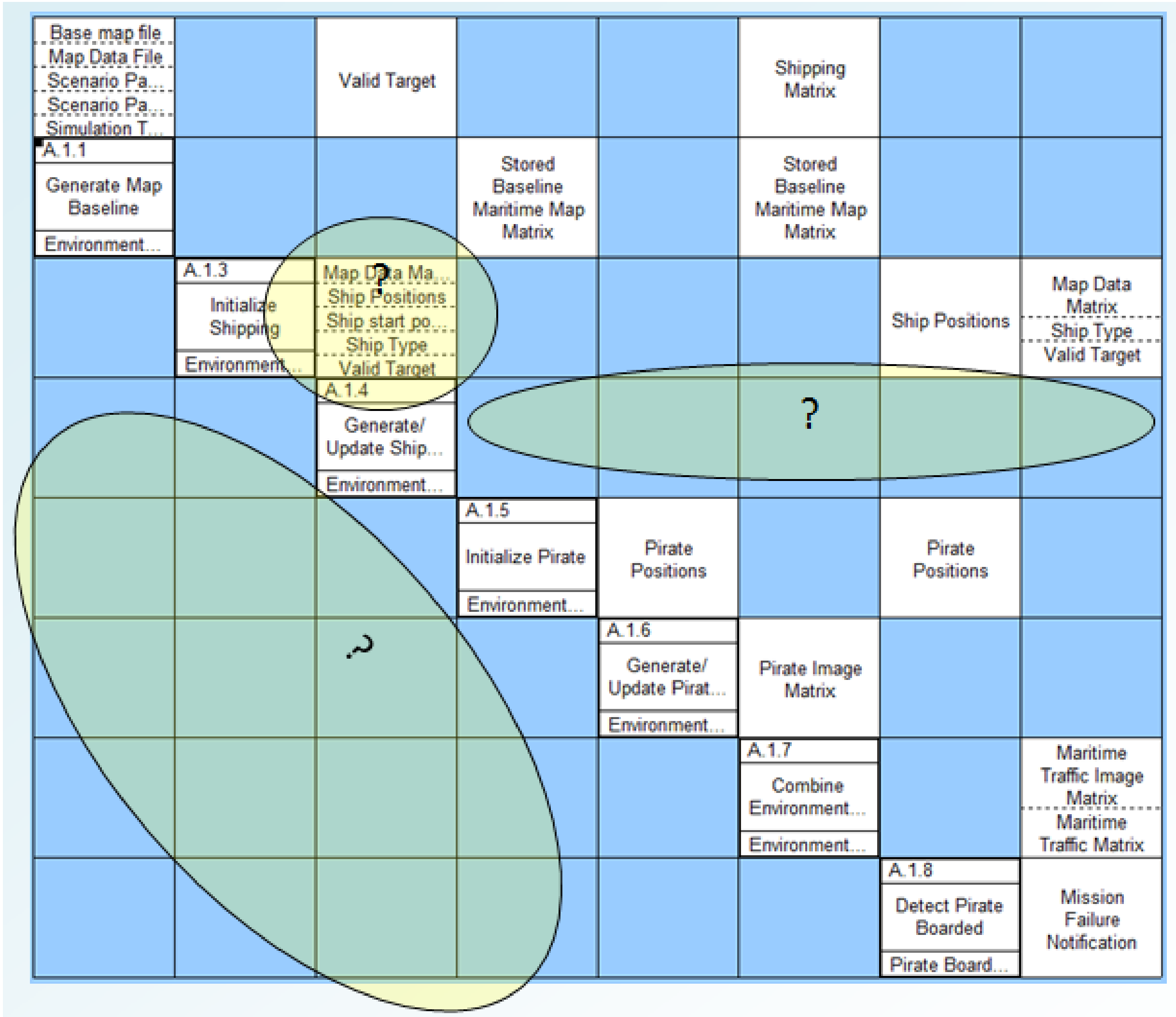


Figure 19 – An N2 diagram of system interfaces. Reprinted from "'Top-10' MBSE Tool Inspections to Analyze System Design Quality," P. Montgomery, *Systems Engineering Conference, 2014 (SEDC2014),* copyright 2014 Paul R. Montgomery, with the permission of the author**.** Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-1_Top-10-MBSE-Tool-Inspections.ppt

- System Content Flow (presented in an IDEF0 diagram); inspect for:
  - Disconnects, Missing ICOM inputs/outputs
  - System Logical control; inspect the control flow (linear sequences, branching, loops, iterations, etc.)
- System Behavior – inspect sequence diagrams for:
  - Un-triggered functions, No follow-on trigger, Unallocated functions
- System Realization, Allocation, and Integrity; inspect for:
  - Allocations, Traceability, Continuity, Uneven Depth
- Integrate-ability; inspect for:
  - Complex functional interactions; Poor external interface definition; Conops-design breakage; Loss of taxonomy control
- Qualify-ability; inspect for:
  - Poor external interface definition (validation risk); Conops-design breakage; Loss of taxonomy control; Quantifiable requirements; Lack of V&V traceability

Some of the inspections listed above could be implemented as automated checks (e.g., to look for “Unallocated functions” in sequence diagrams) while some require human judgement to assess (e.g., “complex functional interactions”) – the latter bear a resemblance to the typical metrics suggested for Object Oriented designs (e.g., coupling, cohesion).

Accreditation of models used in embedded systems, specifically diagnostic models, is the subject of [Kodali & Robinson, 2014]. As pointed out in this paper, accreditation of such models is *not* sufficiently covered by NASA-STD-7009A [NASA, 2016] (whose focus is on the physics in models and simulations), the software engineering requirements of NPR 7150.2A, [NASA, 2014] or the combination of the two. The diagnostic models they consider, while not MBSE models per se, have similar characteristics to MBSE system models.

5 Observations derived from stakeholder interviews

As technologies and new approaches emerge, there is a predictable phenomenon of local pockets of early adoption which grow and eventually become the new norm. NASA has such an innovative culture that inevitably some of its local pockets of early adopters of MBSE are unaware of each other. The stakeholder interviews performed were an important part of this MBMA roadmapping effort, and aimed to accomplish two things:

1. Discover ideas, concerns and opportunities from those interviewed (stakeholders)
2. Share ongoing ideas and efforts identified by the literature search.

The intention was to both learn and teach. Often, fear of new ideas is a result of misunderstandings about the new idea.

The interviews were informal and most were in person. See appendix A Stakeholder Interviews for the names and roles of those interviewed. Interviews covered five main topic areas:

- Awareness of, and familiarity with, MBSE
- Current challenges facing OSMA, and how MBSE might (or might not) help address them
- Emerging challenges facing OSMA, and how MBSE might (or might not) help address them
- Priorities
- MBSE features of interest

5.1 Stakeholders

Most of those interviewed were generally aware of MBSE, although most were not familiar with its details. Most were not clear about the impacts MBSE might have on OSMA disciplines and operations. All were generally open to the opportunities presented to avoid the "stupid" errors that computers/logic would readily avoid or catch. Most expressed concerns about things *"slipping through the cracks"* if OSMA practices change significantly. Much of this is because the current OSMA "tapestry of coverage" has been stitched together over years, and there is great confidence in how it is currently working, but concern that something will be overlooked if it is "re-stitched."

Responses to the topic of current challenges varied widely, but many of the same themes were repeated:

- The challenges of providing timely information and of finding and accessing current data
  - The "n-1" problem[1]
  - Chasing down documents
  - Never sure about latest version
- The ability to have OSMA folks trained and learning curves
- What happens during the transition period?
- The widening gap between HW and SW assurance
- The ability to tap into data being generated

[1] In traditional (non-MBSE) engineering some of the artifacts generated by Mission Assurance take significant manual effort to produce; hence by the time they have been created and analyzed, the project may have already moved on to version "n", rendering results for the project's version "n-1" potentially obsolete.

In addition, a number of challenges were identified that were somewhat more discipline specific:

- Utilization of COTS parts
- Integration between system-level behavior and low-level attributes (parts, solder joints, etc.)
- Ability to identify/develop/utilize surrogate models
- Ability to integrate both lessons learned and Lessons Learned.
- Ability to integrate checklists

In most cases, the emerging challenges were very similar to the current challenges with the acceptance of MBSE. The emerging challenges were all about making sure the current capabilities and successes are not lost.

Most of those surveyed were optimistic about the opportunities for improvement afforded by the transition to MBSE. The Safety Case approach which integrates all available information (both quantitative and qualitative) is consistent with the MBSE approach to providing Views linked to relevant information. The ability to directly include risk in both implementation and operation models will provide an unprecedented opportunity to directly trade-off margins and risk with performance and cost.

5.2 Practitioners

The practitioners surveyed included a variety of people ranging from Lead System Engineers, to System Engineering researchers, to modelers. They all were extremely capable in some or all aspects of MBSE. They are currently overwhelmed with work, as the transition to MBSE has been rapid. Many were not aware of some aspects of ongoing research. All welcomed support and contribution by OSMA personnel but did not have the time or inclination to teach them the language of SysML. They encouraged us to provide them with some well-trained support that would act as the interface between the modelers and the OSMA stakeholders.

6 Primary findings / observations

6.1 Assurance is a latecomer to MBSE

The initial focus of the MBSE community has been on addressing the core competencies and activities of systems engineering – developing the means by which a system's requirements, structure, behavior, development, testing and operation can be addressed in a model-centric manner. Our examination of some of the published literature on revealed that so far assurance has been given little, if any, attention. For example, [Kaslow et al., 2015] reports on the INCOSE Space Systems MBSE Challenge team's investigation of the applicability of MBSE for designing CubeSats; the reference model presented there shows the diagram of CubeSat stakeholders, Figure 20, below, from which assurance is noticeably absent.

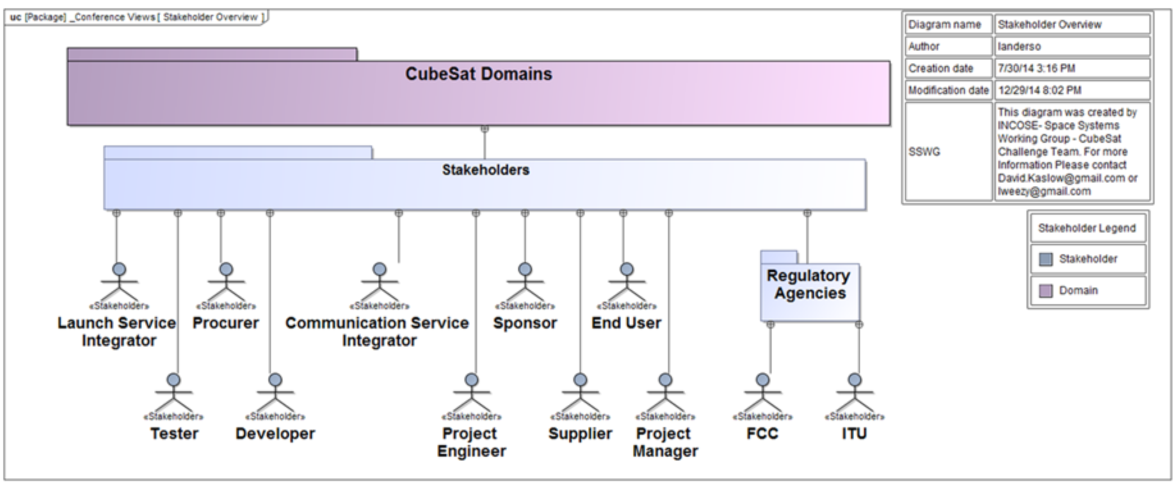


Figure 20 – CubeSat stakeholders. © 2015 IEEE. Reprinted, with permission, from D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani & R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status," *2015 IEEE Aerospace Conference*, pp. 1-16, 2015.

At least there is a mention of assurance in the paper, in the form of the statement *"System engineering artifacts can be extracted from the model, which can be used to demonstrate mission assurance to the stakeholders."* Many other papers lack *any* explicit mention of assurance.

The initial lack of focus on assurance is reasonable – MBSE first has to demonstrate its viability for engineering purposes in order to become accepted, and this process remains still very much a work in progress. There is a danger, however, that by being a latecomer to treatment by MBSE community, assurance will be overlooked for too long.

An indication that the time is ripe to making assurance more involved in the MBSE-based engineering processes is seen in the interplay between MBSE and NASA's traditional review processes, where at Key Decision Points (KDPs) a project must demonstrate the adequacy of its status relative to its stage in the development lifecycle. MBSE practitioners have stated that for the time being they prepare for these reviews by generating (from the MBSE models) the forms of textual documentation traditionally expected by review boards (for example the quotation above). This is appropriate as a way to interface an MBSE-savvy project with a non-MBSE-savvy review board. The latter need not be concerned with the way the review material was created, and continue to perform their scrutiny and assessment of the review materials as they would for any kind of project. However, such an approach isolates the review board from taking advantage of MBSE to achieve improvements to the review process itself. Some of the possibilities in this direction are discussed next.

6.2 A potential change of emphasis for assurance

A key tenet of MBSE is its shift towards a “single-source-of-truth,” in which every engineering data element is stored exactly once, thus ensuring that all artifacts generated from this information are all consistent with one another. To make this possible, MBSE strives to represent as much as possible of the systems engineering information in computerized models, rather than as paper or electronic documents. For example, the abstract of [Chung et al., 2012] reads in part as follows:

> *When designing a flight system from concept through implementation, one of the fundamental systems engineering tasks is managing the mass margin and a mass equipment list (MEL) of the flight system. While generating a MEL and computing a mass margin is conceptually a trivial task, maintaining consistent and correct MELs and mass margins can be challenging due to the current practices of maintaining duplicate information in various forms, such as diagrams and tables, and in various media, such as files and emails. We have overcome this challenge through a model-based systems engineering (MBSE) approach within which we allow only a single-source-of-truth.*

One of the implications for reviews is that there is far less need to check for this kind of consistency. Instead, the review board members’ time would be better spent on applying their engineering judgement to assess the less readily quantifiable aspects of a project. For example, [Wibben & Furfaro, 2015] report on MBSE used in development of the science processing and operations center for an upcoming NASA mission, and state:

> *“…this [MBSE] approach has been lauded in key mission reviews as a significant strength of the project, especially for its ability to provide a consistent approach for the entire ground systems team”*

However, in order to relax their usual scrutiny of consistency a review board would have to have the confidence that the MBSE process has indeed ensured consistency. To do so they would want to ensure themselves that the MBSE computing infrastructure can be relied upon (e.g., document generation processes faithfully reproduce the information in the models) and that configuration control has been appropriately conducted on the models and the generated artifacts. This means the board would have to have an awareness and understanding of the MBSE processes.

More significantly, could the review board take advantage of access to the MBSE models themselves, instead of to just the documentation artifacts of a traditional review? For example, might the review board wish to explore the models directly? Might they wish to formulate their own queries of the model to derive answers to questions as they arise in the review?

Within an engineering team it is natural to incrementally transition towards use of MBSE by first providing non-MBSE-savvy engineers access to the traditional forms of documentation they are accustomed to. As they become exposed to their MBSE-savvy colleagues’ direct use of models they may then transition. This phenomenon is reported in [Do et al., 2014] where they state:

> *“It is interesting to note that some project members found the documents easier to digest, particularly if they were familiar with CDD [Capability Definition Document] documents whereas others, whereas those with substantial MBSE experience were happier familiarizing themselves with the project definition material directly from the model.* ***As the project progressed, the model was used increasingly by all participants****.”* [emphasis added]

While this kind of transition might be expected to occur within an engineering team, it will likely take a more directed effort to achieve the same transition in review boards given that they are deliberately chosen to be independent of the project they are reviewing.

6.3 Reliability: where assurance advantages of MBSE are beginning to be realized

Our survey of the MBSE literature, and our observation of MBSE activities within NASA, both point to *reliability* as an area where the assurance advantages of MBSE are thought to be available, and in some instance beginning to be realized in project applications.

In traditional (non-MBSE) systems engineering it is common for Fault Trees and FMECAs to be generated for purposes of reliability engineering and assurance. Traditionally, these kinds of artifacts are prone to what might be termed the “n-1” problem: their creation takes significant manual effort; hence by the time they have been created and analyzed, the project may have already moved on, rendering their results potentially obsolete. Furthermore, these artifacts draw upon system-wide information (e.g., for Fault Tree construction, to assess the different causes of a mission failure within a system design; for FMECA construction, to assess the system and mission effects of a component failure). This makes it appealing to consider generating them automatically (or at least semi-automatically, reducing if not entirely eliminating the manual effort) from the information contained in MBSE models.

Reports of reliability artifact creation from MBSE information having been developed and applied are seen in the following:

- the FMEA of an experimental ramjet powered vehicle [Cressent et al., 2001];
- the FMEA of a satellite’s ground control system [Hecht et al., 2014];
- the FMEA and Fault Tree of an electro-mechanical actuator that controls ailerons [Mhenni et al., 2014b];
- the FMECA and Fault Tree of the “Cascade Distillation System,” the flight-forward prototype of a system to recover water from wastewater ultimately indented to become a payload experiment on the ISS [Sargusingh et al., 2015].

The last one is particularly noteworthy because the success of the initial activity, performed by Tietronix under an SBIR in conjunction with systems engineers at JSC, led to a continuation of the approach at JPL for application (it is anticipated) to JPL projects. In addition, the JPL ontology experts collaborated with JPL reliability experts to develop the portions of an ontology suited to representation of off-nominal conditions (faults and failures, the scenarios in which they may occur, their causes, their consequences, their mitigation, etc.). In phase 1 Tietronix developed prototype plug-ins to a SysML tool that would automatically construct a FMECA and a Fault Tree from the SysML-represented system information. In Phase 2 of Tietronix’s SBIR they plan to adapt their plug-ins to work with the elaborated ontology that has resulted from the JPL work. This is an exemplary demonstration of the cross-center transfer of advancements in MBSE’s support for assurance. It also illustrates how ontology development is intertwined with development of tool support: the initial activity employed just enough of an ontology of faults to be able to demonstrate the viability of automatic FMECA and Fault Tree generation. The subsequent JPL work has extended this ontology to make it suitable for a wider range of reliability purposes, including representation and generation of risk scenarios (the foundation of Probabilistic Risk Assessment) and representation and generation of Fault Containment Regions and the list of interfaces that cross their boundaries.

6.4 Assurance of MBSE’s models, processes and tools

Assurance to establish confidence in MBSE’s models, processes and tools is an aspect noticeably *lacking* in the literature examined, and the stakeholder discussions held. If key engineering decisions are being made with a reliance on information stored in and derived from MBSE models, this surely is an important consideration.

7 Recommendations

Based on what the information gathered in this effort there are a number of recommendations that can be made.

Continue with OSMA Objective Hierarchy efforts

These will help codify the objectives at the Agency level, allowing Center/Mission tailoring as appropriate. This will also encourage foundational-level ontology elements, and possibly discipline-level, to be consistent across the agency. This will greatly facilitate cross Agency communication, sharing and reviews. Currently, a handful of the Objective Hierarchies (out of an anticipated total of more than 20) have been completely generated. These should be integrated into a single over-arching hierarchy, paving the way for the remainder, as they are developed, to also be fit within this over-arching OSMA hierarchy.

Encourage/motivate Center-wide and NASA-wide efforts

Many of the Centers have a number of efforts with varying maturity ongoing. Few of these efforts are aware of efforts at other Centers. Even within a Center, efforts may be only vaguely aware of other efforts at their Center. JPL has instituted Integrated Model-Centric Engineering (IMCE) whose function is to develop foundation-level ontologies, assist in the development of discipline-level ontologies and support mission level applications. IMCE greatly enables progress at JPL by integrating previously disparate efforts, engaging stakeholders, and producing results as they went along. GSFC has also begun the process of piloting MBSE following an initial education/familiarization process.

Support collaborations

Many of the current efforts are pilots, and as such may not have the necessary resources to include elements beyond their immediate focus. It is especially hard for pilots to span the entire lifecycle of a mission, and thus hard for them to reveal the benefits of early lifecycle activities reflected later in the lifecycle. OSMA should encourage collaborations between its own researchers and practitioners and those of programs and projects. As our literature search clearly identified, there are a large number of efforts upon which OSMA can “piggyback”. Even without an over-arching program, there should be motivation for cooperation between OSMA disciplines. For example, the consolidation of the Objective Hierarchies discussed above.

For fostering of inter-center collaboration and coordination, organizational structures that span the Centers (OSMA of course; also NESC) could play a key role. This could be in the form of workshops and other TIGs to allow sharing of results and promising directions.

Establish a Program

The creation of a specific MBMA Program will accomplish a number of objectives. It will provide an indication to practitioners and other stakeholders that OSMA is serious about reaping the benefits. It will provide a central place where proposals can be evaluated, collaborations can be fostered and results can be shared across a broader community.

Have a portfolio

There should be a portfolio of efforts spanning near- mid- and long-term payoffs.

It is important that some efforts focus on immediate products since “buy in” comes more quickly when users realize that the output products (artifacts) they get in an MBSE setting can look the same and contain the same information (or more) as before. However, there is the need to be cautious about too much “low hanging fruit” as quick hits may become overly wedded to existing capabilities (e.g., the current form of ontology), and their dependence on these may be impediment to future changes.

To compensate, there should also be efforts focused on medium- and long-term problems. For example, the integration of MBSE with problem reporting and inspection reporting systems could be a desirable medium-term pursuit, while the incorporation of risk into the space systems engineering ontology would be a long-term pursuit of obvious interest to Mission Assurance.

There should also be a portfolio of mission types and development phases to which MBSE is applied. To some extent this is already taking place. At JPL the primary application of MBSE is to the Europa Clipper pre-project, which is a large-scale project in its early stages of formulation. Meanwhile, the MBSE activities reported in [Selvy et al., 2014] were focused on the verification planning phases for the Large Synoptic Survey Telescope. At the other end of the spectrum in terms of scale, INCOSE efforts have focused on CubeSats as an exemplary target for MBSE. CubeSats are appealing because their development proceeds at a relatively fast pace, hence they may become the first applications of MBSE to span the entire lifecycle from conception to operation. However, their very limited budgets offer very little scope for prototyping of MBSE – augmenting their funding would be needed to permit such studies.

Another avenue of pursuit is to retrospectively demonstrate MBSE on elements of a previously completed mission. This allows comparisons of the quality of the artifacts that MBSE is able to produce to those that were produced by traditional development means. An instance of this is taking place at JPL, where the FMECA generated in the course of developing a previous mission is being retrospectively generated using MBSE-based technology. Of course this kind of study is of no help to the previously completed mission, so can only be justified as an activity to further understanding and evaluation of MBSE.

Address what's key but missing

The MBSE literature examined had almost nothing to say about risk. Yet risk permeates the practice of mission assurance It plays a key role in and around the Risk Informed Safety Case featured in NASA's System Safety framework [NASA, 2011].

Also note that Section 2.3 "Developing an ontology for space systems engineering" cited risk into as an especially cross-cutting concept yet to be incorporated into a space systems engineering ontology.

In summary

MBSE holds great promise as a means to improve upon many, perhaps all, aspects of NASA missions' systems engineering practices. MBSE shows every indication of being here to stay – it is not a "passing fad." It is also progressing rapidly, and the time is ripe for S&MA to become intimately involved.

Appendixes

A. Stakeholder Interviews

As technologies and new approaches emerge, there is a predictable pattern of local pockets of early adoption which grow and eventually become the new norm. NASA has such an innovative culture that inevitably some of its local pockets of early adopters of MBSE are unaware of each other. The stakeholder surveys we performed were an important part of this MBMA roadmapping effort. We wanted to accomplish two things:

- Discover ideas, concerns and opportunities from those interviewed (stakeholders)
- Share ongoing ideas and efforts identified by the literature search.

Thus, our intention was to both learn and teach. Often, fear of new ideas is a result of misunderstandings about the new idea.

Survey Question areas:

- Questions about familiarity with MBSE
- Questions about *current* challenges facing OSMA
    - General
    - Mission-specific
    - Center-specific
- Questions about *emerging* challenges facing OSMA
    - General
    - Mission-specific
    - Center-specific
- Questions about priorities for solving problems
- Questions about MSBE features of interest

We interviewed people from NASA OSMA, various MA disciplines, and in particular those doing applications of MBSE with awareness of MA. The surveys were kept informal, and comments were made in anonymity as the goal was to extract real concerns and opportunities.

Table 1 – Interviewees

	NASA HQ OSMA	NASA Center MA	Reliability	JPL IMCE	Safety	Project Applications
Sue Aleman (NASA OSMA)	1				1	
Genji Arakaki (JPL MA: Europa MAM)		1				1
Todd Bayer (JPL: Principal System Engineer)						1
Brian Cox (JPL: SE)						1
Chrishma Derewa (JPL: Europa SE)					1	1
Homayoon Dezfuli (NASA OSMA)	1				1	
Dan Dvorak (JPL: IMCE)				1		
George Greanias (JPL MA: MAM, Environmental Requirements)		1	1		1	
Chester Everline (JPL MA: PRA, Reliability)		1	1			
Frank Groen (NASA OSMA)	1					
Jairus Hihn (JPL: Early phase Cost and Risk modeling)						1
Steve Jenkins (JPL: IMCE Technical Lead)				1		1
Kin Man (JPL MA: Environmental Requirements)		1				
Anthony Mittskus (JPL MA: RM)		1				
Tracy Neilson (JPL: Fault Protection Engineer)						1
Jeffrey Nunes (JPL MA: Reliability)		1	1			
Bob Rasmussen (JPL: Engineering Fellow)						1
Kris Romig (GSFC)						1
Jessica Samuels (JPL MBSE: V&V Application)				1		1
Harald Schone (JPL MA: Technologist)		1				
Doug Sheldon (JPL MA: Technology Program Manager)		1				
Marc Sarrel (JPL: SE)						1
Martha Wetherholt (NASA OSMA)	1				1	
	4	**8**	**3**	**3**	**5**	**11**

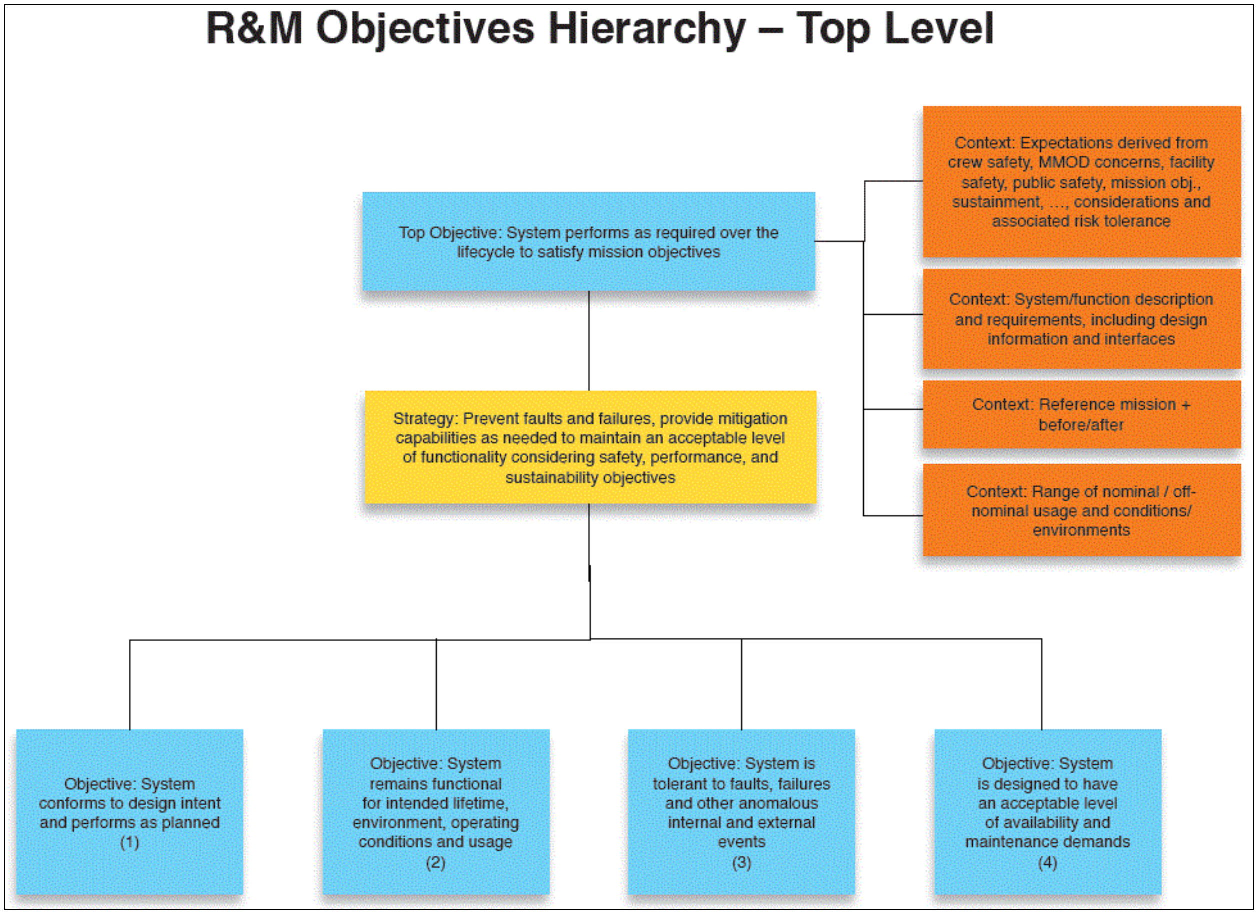
B. The Reliability and Maintainability Objectives Hierarchy

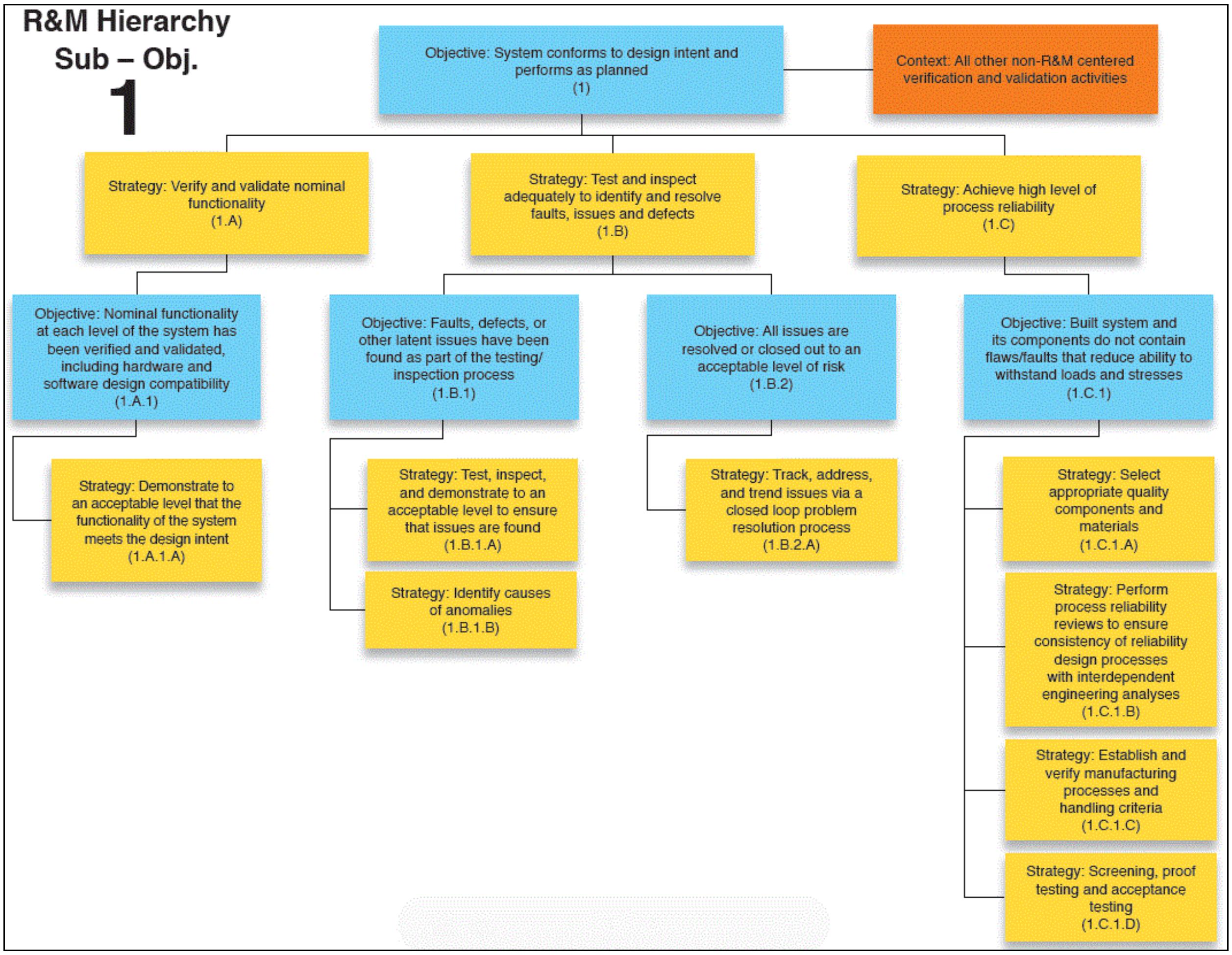
The five images of this subsection are taken from: https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4

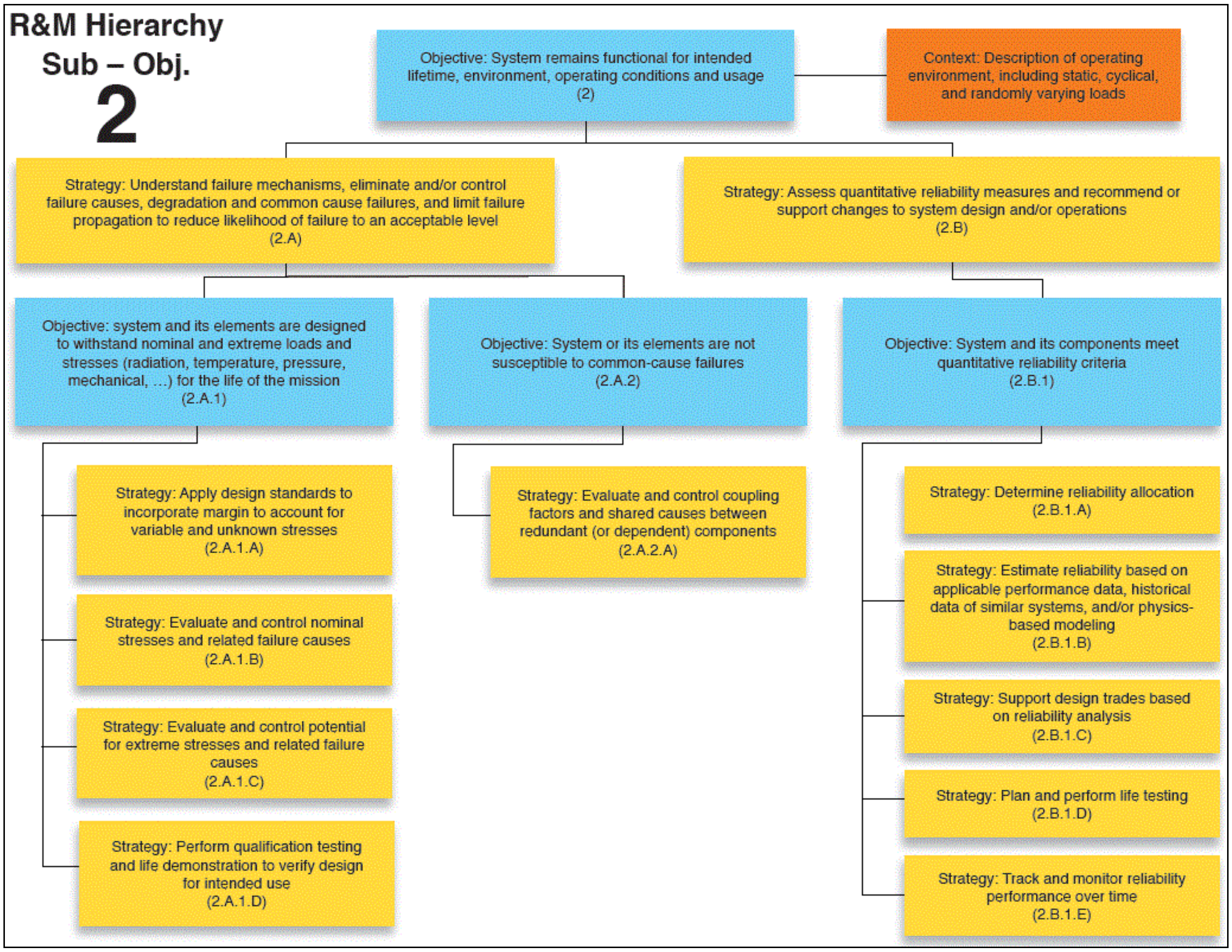
The page that introduces this and other of OSMA's objectives-based strategies is: https://sma.nasa.gov/news/articles/newsitem/2014/12/04/osma-introduces-new-objectives-based-strategies Unlimited distribution of Government document; no re-use statement required.

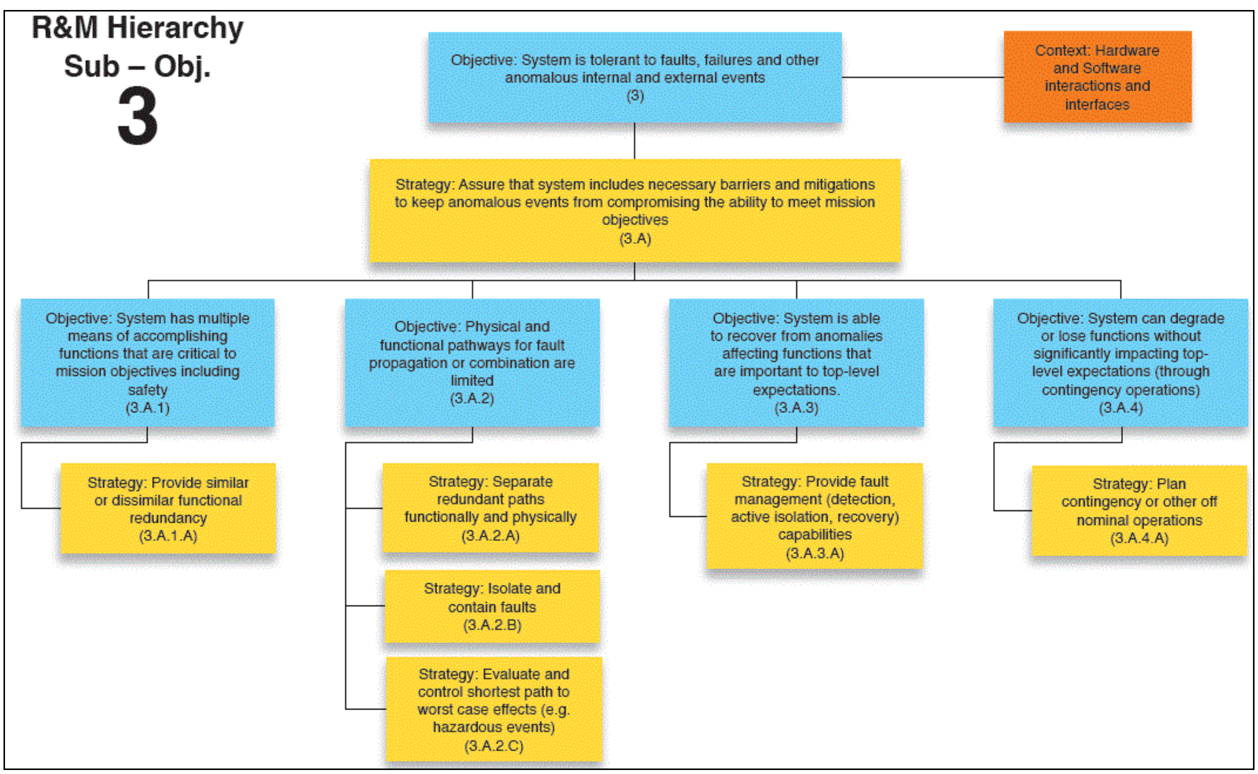
The five images that follow are:

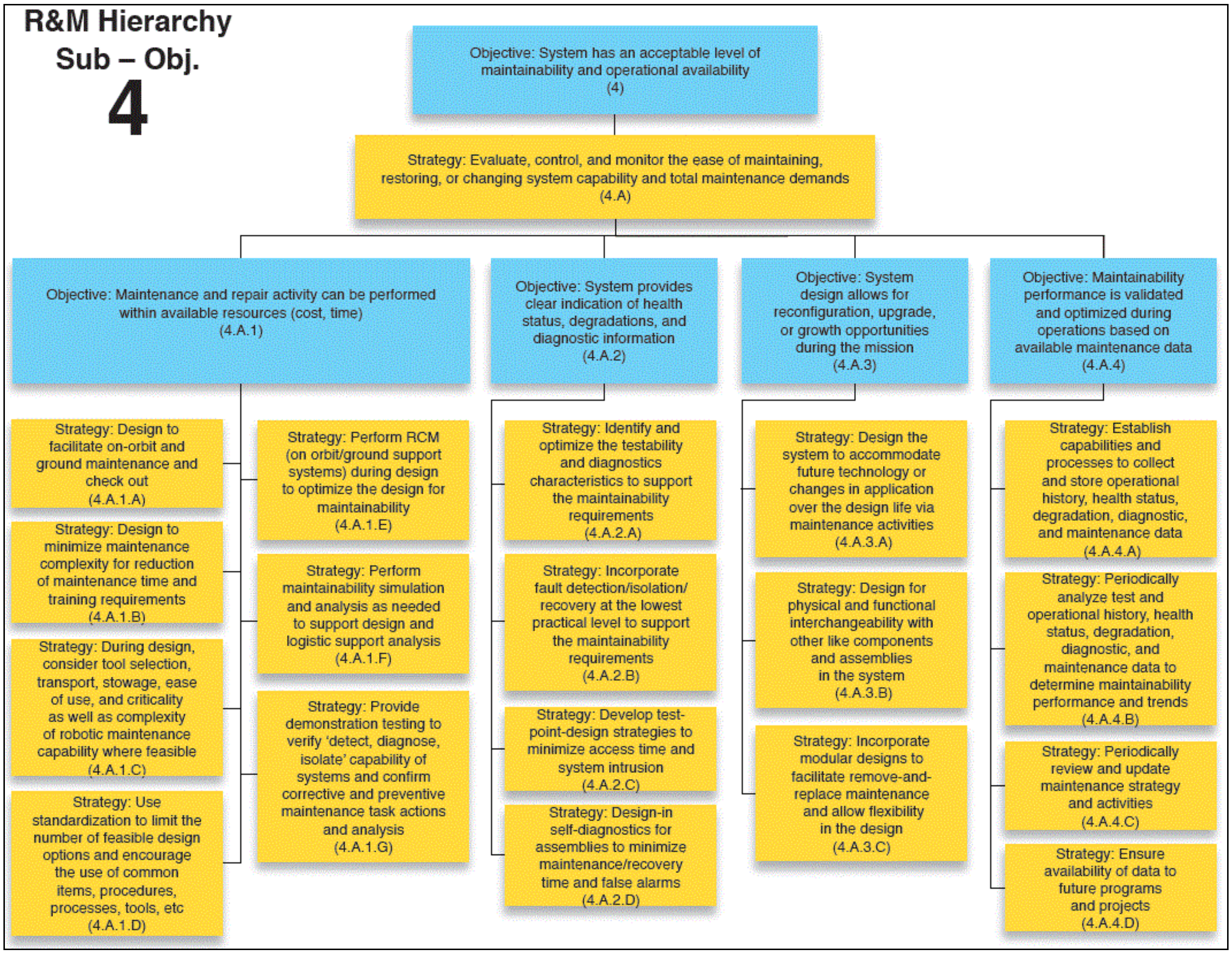
- R&M Objectives Hierarchy – Top Level
- R&M Hierarchy Sub – Obj. 1
- R&M Hierarchy Sub – Obj. 2
- R&M Hierarchy Sub – Obj. 3
- R&M Hierarchy Sub – Obj. 4




R&M Hierarchy
Sub – Obj.
1
Objective: System conforms to design intent and performs as planned (1)
Context: All other non-R&M centered verification and validation activities
Strategy: Verify and validate nominal functionality (1.A)
Strategy: Test and inspect adequately to identify and resolve faults, issues and defects (1.B)
Strategy: Achieve high level of process reliability (1.C)
Objective: Nominal functionality at each level of the system has been verified and validated, including hardware and software design compatibility (1.A.1)
Objective: Faults, defects, or other latent issues have been found as part of the testing/ inspection process (1.B.1)
Objective: All issues are resolved or closed out to an acceptable level of risk (1.B.2)
Objective: Built system and its components do not contain flaws/faults that reduce ability to withstand loads and stresses (1.C.1)
Strategy: Demonstrate to an acceptable level that the functionality of the system meets the design intent (1.A.1.A)
Strategy: Test, inspect, and demonstrate to an acceptable level to ensure that issues are found (1.B.1.A)
Strategy: Identify causes of anomalies (1.B.1.B)
Strategy: Track, address, and trend issues via a closed loop problem resolution process (1.B.2.A)
Strategy: Select appropriate quality components and materials (1.C.1.A)
Strategy: Perform process reliability reviews to ensure consistency of reliability design processes with interdependent engineering analyses (1.C.1.B)
Strategy: Establish and verify manufacturing processes and handling criteria (1.C.1.C)
Strategy: Screening, proof testing and acceptance testing (1.C.1.D)


R&M Hierarchy
Sub – Obj.
2
Objective: System remains functional for intended lifetime, environment, operating conditions and usage (2)
Context: Description of operating environment, including static, cyclical, and randomly varying loads
Strategy: Understand failure mechanisms, eliminate and/or control failure causes, degradation and common cause failures, and limit failure propagation to reduce likelihood of failure to an acceptable level (2.A)
Strategy: Assess quantitative reliability measures and recommend or support changes to system design and/or operations (2.B)
Objective: system and its elements are designed to withstand nominal and extreme loads and stresses (radiation, temperature, pressure, mechanical, …) for the life of the mission (2.A.1)
Objective: System or its elements are not susceptible to common-cause failures (2.A.2)
Objective: System and its components meet quantitative reliability criteria (2.B.1)
Strategy: Apply design standards to incorporate margin to account for variable and unknown stresses (2.A.1.A)
Strategy: Evaluate and control nominal stresses and related failure causes (2.A.1.B)
Strategy: Evaluate and control potential for extreme stresses and related failure causes (2.A.1.C)
Strategy: Perform qualification testing and life demonstration to verify design for intended use (2.A.1.D)
Strategy: Evaluate and control coupling factors and shared causes between redundant (or dependent) components (2.A.2.A)
Strategy: Determine reliability allocation (2.B.1.A)
Strategy: Estimate reliability based on applicable performance data, historical data of similar systems, and/or physics-based modeling (2.B.1.B)
Strategy: Support design trades based on reliability analysis (2.B.1.C)
Strategy: Plan and perform life testing (2.B.1.D)
Strategy: Track and monitor reliability performance over time (2.B.1.E)


R&M Hierarchy
Sub – Obj.
3
Objective: System is tolerant to faults, failures and other anomalous internal and external events (3)
Context: Hardware and Software interactions and interfaces
Strategy: Assure that system includes necessary barriers and mitigations to keep anomalous events from compromising the ability to meet mission objectives (3.A)
Objective: System has multiple means of accomplishing functions that are critical to mission objectives including safety (3.A.1)
Objective: Physical and functional pathways for fault propagation or combination are limited (3.A.2)
Objective: System is able to recover from anomalies affecting functions that are important to top-level expectations. (3.A.3)
Objective: System can degrade or lose functions without significantly impacting top-level expectations (through contingency operations) (3.A.4)
Strategy: Provide similar or dissimilar functional redundancy (3.A.1.A)
Strategy: Separate redundant paths functionally and physically (3.A.2.A)
Strategy: Isolate and contain faults (3.A.2.B)
Strategy: Evaluate and control shortest path to worst case effects (e.g. hazardous events) (3.A.2.C)
Strategy: Provide fault management (detection, active isolation, recovery) capabilities (3.A.3.A)
Strategy: Plan contingency or other off nominal operations (3.A.4.A)


R&M Hierarchy
Sub – Obj.
4
Objective: System has an acceptable level of maintainability and operational availability (4)
Strategy: Evaluate, control, and monitor the ease of maintaining, restoring, or changing system capability and total maintenance demands (4.A)
Objective: Maintenance and repair activity can be performed within available resources (cost, time) (4.A.1)
Objective: System provides clear indication of health status, degradations, and diagnostic information (4.A.2)
Objective: System design allows for reconfiguration, upgrade, or growth opportunities during the mission (4.A.3)
Objective: Maintainability performance is validated and optimized during operations based on available maintenance data (4.A.4)
Strategy: Design to facilitate on-orbit and ground maintenance and check out (4.A.1.A)
Strategy: Design to minimize maintenance complexity for reduction of maintenance time and training requirements (4.A.1.B)
Strategy: During design, consider tool selection, transport, stowage, ease of use, and criticality as well as complexity of robotic maintenance capability where feasible (4.A.1.C)
Strategy: Use standardization to limit the number of feasible design options and encourage the use of common items, procedures, processes, tools, etc (4.A.1.D)
Strategy: Perform RCM (on orbit/ground support systems) during design to optimize the design for maintainability (4.A.1.E)
Strategy: Perform maintainability simulation and analysis as needed to support design and logistic support analysis (4.A.1.F)
Strategy: Provide demonstration testing to verify 'detect, diagnose, isolate' capability of systems and confirm corrective and preventive maintenance task actions and analysis (4.A.1.G)
Strategy: Identify and optimize the testability and diagnostics characteristics to support the maintainability requirements (4.A.2.A)
Strategy: Incorporate fault detection/isolation/recovery at the lowest practical level to support the maintainability requirements (4.A.2.B)
Strategy: Develop test-point-design strategies to minimize access time and system intrusion (4.A.2.C)
Strategy: Design-in self-diagnostics for assemblies to minimize maintenance/recovery time and false alarms (4.A.2.D)
Strategy: Design the system to accommodate future technology or changes in application over the design life via maintenance activities (4.A.3.A)
Strategy: Design for physical and functional interchangeability with other like components and assemblies in the system (4.A.3.B)
Strategy: Incorporate modular designs to facilitate remove-and-replace maintenance and allow flexibility in the design (4.A.3.C)
Strategy: Establish capabilities and processes to collect and store operational history, health status, degradation, diagnostic, and maintenance data (4.A.4.A)
Strategy: Periodically analyze test and operational history, health status, degradation, diagnostic, and maintenance data to determine maintainability performance and trends (4.A.4.B)
Strategy: Periodically review and update maintenance strategy and activities (4.A.4.C)
Strategy: Ensure availability of data to future programs and projects (4.A.4.D)

C. Acronyms

AADL	Architecture Analysis and Design Language
ASARP	As Safe As Reasonably Practicable
BDD	Block Definition Diagram [of SysML]
C&DH	Command and Data Handling
CDD	Capability Definition Document
CM	Configuration Management
CONOP	Concept of Operations
EHM	Europa Habitability Mission
ELV	Expendable Launch Vehicle
FFBD	Functional Flow Block Diagram
FFMEA	Functional Failure Mode and Effects Analysis
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FSM	Finite State Machine
FSW	Flight Software
GPS	Global Positioning System
GSDO	Ground Systems Development and Operations
GSFC	Goddard Space Flight Center
GSN	Goal Structuring Notation
GRC	Glenn Research Center
HQA	Hardware Quality Assurance
HW	Hardware
KDP	Key Decision Point
I&T	Integration and Test
I/O	Input/Output
IBD	Internal Block Diagram [of SysML]
ICAM	Integrated Computer Aided Manufacturing
ICD	Interface Control Document
ICOM	Inputs, Control, Outputs and Mechanisms
IDEF0	ICAM Definition for Function Modeling
IMCE	Integrated Model-Centric Engineering
INCOSE	International Council on Systems Engineering
ISS	International Space Station
IT	Information Technology
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KDP	Key Decision Point
LADEE	Lunar Atmosphere and Dust Environment Explorer
LSST	Large Synoptic Survey Telescope
MA	Mission Assurance
MAM	Mission Assurance Manager
MBMA	Model-Based Mission Assurance
MBSE	Model-Based Systems Engineering
MEL	Mass Equipment List
MISSE-X	Materials on ISS Experiment-X
NESC	NASA Engineering and Safety Center
NPR	NASA Procedural Requirements
OMG	Object Management Group
OSMA	Office of Safety and Mission Assurance
OWL	Web Ontology Language
PD	Parametric Diagram [of SysML]
PDMS	Product Data Management Systems
PHA	Preliminary Hazard Analysis
PRA	Probabilistic Risk Assessment
QA	Quality Assurance
R&M	Reliability and Maintainability
RISC	Risk Informed Safety Case
RM	Risk Management
SBIR	Small Business Innovation Research
SE	Systems Engineering / Systems Engineer
SD	Sequence Diagram [of SysML]
S&MA	Safety and Mission Assurance
SME	Subject Matter Expert
SSWG	Space Systems Working Group [of INCOSE]
SW	Software
SysML™	Systems Modeling Language
TIG	Technical Interest Group
UML	Unified Modeling Language
V&V	Verification and Validation

D. References

[Aguilar 2013] M. Aguilar, *Assess/Mitigate Risk through the Use of Computer-Aided Software Engineering (CASE) Tools*, NASA/TM-2013-218031, NASA Engineering and Safety Center (NESC), Hampton, VA, August 2013.

[Aguilar et al., 2014] M. Aguilar, K. Bonanne, J.A. Favretto, M.M. Jackson, S.L. Jones, R.M. Mackey, M.A. Sarrel & K.A. Simpson, *Review of Ground Systems Development and Operations (GSDO) Tools for Verifying Command and Control Software*, NASA/TM-2014-218278, June 2014.

[Benz et al., 2015] N. Benz, D. Viazzo & K. Gundy-Burlet, "Multi-Purpose Spacecraft Simulator for LADEE." In *2015 IEEE Aerospace Conference*, IEEE, 2015, pp. 1-14.

[Biggs et al., 2016] G. Biggs, T. Sakamoto & T. Kotoku, "A profile and tool for modelling safety information with design information in SysML." *Software & Systems Modeling* 15(1), 2016, pp. 147-178.

[Brunel et al., 2014] J. Brunel, D. Chemouil, L. Rioux, M. Bakkali & F. Vallée, "A Viewpoint-Based Approach for Formal Safety & Security Assessment of System Architectures." In *11th Workshop on Model-Driven Engineering, Verification and Validation*, Spain, Vol. 1235, September 2014, pp. 39-48.

[Cencetti, 2013] M. Cencetti, *Evolution of Model Based System Engineering Methodologies for the Design of Space Systems in the Advanced Stages of the Project (Phases B C)*. PhD thesis, Politecnico di Torino, Torino, Italy. Available from http://porto.polito.it/2572760/ (Accessed December 15, 2016)

[Cooke, 2015] B. Cooke, "Model-based Systems Engineering Mission Formulation on the Europa Clipper Pre-Project." In *NASA/JPL Symposium & Workshop on Model-Based Systems Engineering*, Pasadena, CA, January 2015. Workshop presentations are available from https://drive.google.com/drive/folders/0B3hsmXWocH2JZVpTSzdzaUxYQzA (Accessed December 15, 2016)

[Cornford et al., 2006] S.L. Cornford, M.S. Feather & J.S. Jenkins, "Intertwining Risk Insights and Design Decisions (PSAM-0193)." In *Proceedings of the Eighth International Conference on Probabilistic Safety Assessment & Management (PSAM)*, ASME Press, 2006.

[Chung et al., 2012] S.H. Chung, T.J. Bayer, B. Cole, B. Cooke, F. Dekens, C. Delp & D. Lam, "Model-Based Systems Engineering Approach to Managing Mass Margin." In *5th International Workshop on Systems & Concurrent Engineering for Space Applications*, Lisbon, Portugal, October 2012.

[Cressent et al., 2010] R. Cressent, P. David, V. Idasiak & F. Kratz, "Increasing Reliability of Embedded Systems in a SysML Centered MBSE Process: Application to LEA Project." In *M-BED 2010*, Dresden, Germany, 2010.

[Cressent et al., 2011] R. Cressent, P. David, V. Idasiak & F. Kratz, "Dependability analysis activities merged with system engineering, a real case study feedback." *Advances in safety, reliability and risk management: ESREL,* 2011, pp. 2003-2010.

[Cressent et al., 2013] R. Cressent, P. David, V. Idasiak & F. Kratz, "Designing the database for a reliability aware Model-Based System Engineering process." *Reliability Engineering and System Safety* 111, 2013, pp. 171-182.

[David et al., 2009] P. David, V. Idasiak & F. Kratz, "Improving reliability studies with SysML" In *2009 Annual Reliability and Maintainability Symposium (RAMS)*, IEEE, 2009, pp. 527-532.

[Dezfuli et al., 2014] H. Dezfuli, C. Everett & F. Groen, "The Evolution of System Safety at NASA." *International System Safety Training Symposium 2014*. Available from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140010745.pdf (Accessed December 15, 2016)

[Do et al., 2014] Q. Do, S. Cook & M. Lay, "An investigation of MBSE practices across the contractual boundary." *Procedia Computer Science* 28, 2014, pp. 692-701.

[Evans et al., 2016] J. Evans, S. Cornford & M.S. Feather, "Model Based Mission Assurance (MBMA): NASA's Assurance Future." In *2016 Annual Reliability and Maintainability Symposium (RAMS)*, IEEE, 2016, pp. 1-7.

[Fernández, 2014] M.M. Fernández, "Using AADL to Enable MBSE for NASA Space Mission Operations." In *SpaceOps Conference, Pasadena, CA*, 2014.

[Friedenthal et al., 2015] S. Friedenthal, A. Moore & R. Steiner, *A Practical Guide to SysML: The Systems Modeling Language*, 3rd edition," Morgan Kaufmann, 2015.

[Groen et al., 2015] F.J. Groen, J.W. Evans & A.J. Hall, "A Vision for Spaceflight Reliability: NASA's Objectives Based Strategy." *In 2015 Annual Reliability and Maintainability Symposium (RAMS)*, IEEE, 2015, pp. 1-6.

[Gundy-Burlet, 2013] K. Gundy-Burlet, "Validation and Verification of LADEE Models and Software." *In 51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2013.

[Hecht et al., 2014] M. Hecht, E. Dimpfl & J. Pinchak, "Automated Generation of Failure Modes and Effects Analysis from SysML Models," In *ISSRE Workshops*, 2014, pp. 62-65.

[Karban et al., 2014] R. Karban, L. Andolfato, P. Bristow, G. Chizz, M. Esselborn, M. Schilling, C. Schmid, H. Sommer & M. Zamparelli, "Model Based Systems Engineering for Astronomical Projects," In *SPIE Astronomical Telescopes+Instrumentation*, Vol 9150, International Society for Optics and Photonics, 2014, pp. 91500L-1 – 91500L-15.

[Kaslow et al., 2014] D. Kaslow, G. Soremekun, H. Kim & S. Spangelo, "Integrated Model-Based Systems Engineering (MBSE) Applied to the Simulation of a CubeSat Mission." In *2014 IEEE Aerospace Conference*, IEEE, 2014, pp. 1-14.

[Kaslow et al., 2015] D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, B. Shiotani & R. Thompson, "Developing a CubeSat Model-Based System Engineering (MBSE) Reference Model – Interim Status." In *2015 IEEE Aerospace Conference*, IEEE, 2015, pp. 1-16.

[Kelly & Weaver, 2004] T. Kelly & R. Weaver, "The Goal Structuring Notation – A Safety Argument Notation." In *Proceedings of the dependable systems and networks 2004 workshop on assurance cases,* 2004.

[Kodali & Robinson, 2014] A. Kodali & P. Robinson, "Towards Accreditation of Diagnostic Models for Improved Performance." In *Annual Conference of the Prognostics and Health Management Society 2014*. Available from https://www.phmsociety.org/sites/phmsociety.org/files/phm_submission/2014/phmc_14_024.pdf (Accessed December 15, 2016)

[Kratzke, 2014] R. Kratzke, "MBSE for System Testing," *Systems Engineering Conference, 2014 (SEDC2014)*, Washington D.C. Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-9_Model-based-System-Engineering-MBSE-for.pptx (Accessed December 15, 2016)

[Lin et al., 2015] C. Lin, R. Fradet & D. Dvorak, "NASA/JPL Symposium & Workshop on Model-Based Systems Engineering," Pasadena, CA, January 2015. Workshop presentations are available from https://drive.google.com/drive/folders/0B3hsmXWocH2JZVpTSzdzaUxYQzA (Accessed December 15, 2016)

[Mhenni et al., 2014a] F. Mhenni, J-Y. Choley & N. Nguyen, "SysML Safety Profile for Mechatronics." In *Mecatronics, (MECATRONICS), 2014 10th France-Japan / 8th Europe-Asia Congress on*, IEEE, 2014, pp. 29-34.

[Mhenni et al., 2014b] F. Mhenni, N. Nguyen & J-Y. Choley, "Automatic Fault Tree Generation From SysML System Models." *In 2014 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics*, IEEE, 2014, pp. 715-720.

[Montgomery, 2014] P. Montgomery, "'Top-10' MBSE Tool Inspections to Analyze System Design Quality," *Systems Engineering Conference, 2014 (SEDC2014)*, Washington D.C. Available from http://www.sedcconference.org/wp-content/uploads/2014/04/M-1_Top-10-MBSE-Tool-Inspections.ppt (Accessed December 15, 2016)

[NASA, 2011] NASA/SP-2010-580, *NASA System Safety Handbook Vol. 1*, NASA, Washington, D.C., November 2011.

[NASA, 2014] NPR 7150.2B, *NASA Software Engineering Requirements*, NASA, available from http://nodis3.gsfc.nasa.gov/main_lib.html (Accessed December 15, 2016)

[NASA, 2016] NASA-STD-7009A, *Standard for Models and Simulations*, NASA, Kennedy Space Center, July 2016.

[NASA OSMA, 2014] "OSMA Introduces New Objectives-Based Strategies", https://sma.nasa.gov/news/articles/newsitem/2014/12/04/osma-introduces-new-objectives-based-strategies (Accessed December 15, 2016)

[NASA OSMA R&M] "Reliability and Maintainability Objectives Hierarchy" https://sma.nasa.gov/docs/default-source/News-Documents/r-amp-m-hierarchy.pdf?sfvrsn=4 (Accessed December 15, 2016)

[Pétin et al., 2010] J-F. Pétin, D. Evrot, G. Morel & P. Lamy, "Combining SysML and formal models for safety requirements verification." In *22nd International Conference on Software & Systems Engineering and their Applications*, Paris, France, 2010.

[Salado, 2013] A. Salado, "Efficient and Effective Systems Integration and Verification Planning Using a Model-Centric Environment." In *INCOSE International Symposium*, Vol. 23, No. 1, 2013, pp. 1159-1173.

[Sargusingh et al., 2015] M.J. Sargusingh, M.R. Callahan, S. Okon, "Cascade Distillation System Design for Safety and Mission Assurance." *45th Int. Conf. on Environmental Systems*, Bellevue, Washington, 2015. ICES-2015-151.

[Selvy et al., 2014] B.M. Selvy, C. Claver & G. Angeli, "Using SysML for Verification and Validation Planning on the Large Synoptic Survey Telescope (LSST)." In *SPIE Astronomical Telescopes + Instrumentation*, International Society for Optics and Photonics, 2014, pp. 91500N-91500N.

[SysML] "OMG Systems Modeling Language" http://www.omgsysml.org/ (Accessed December 15, 2016)

[Vipavetz et al., 2012] K. Vipavetz, D. Murphy & S. Infeld, "Model-Based Systems Engineering Pilot Program at NASA Langley." *AIAA SPACE 2012 Conference and Exposition*, 2012. DOI: 10.2514/6.2012-5165

[Wang et al., 2015] L. Wang, M. Izygon, S. Okon, M. Bareh, J-F. Castet, J. Nunes & L. Fesq, "Model Based System Engineering Methodology for Fault Management System Design." *NASA/JPL Symposium and Workshop on Model-Based System Engineering*, Pasadena, CA, January 2015. Workshop presentations are available from https://drive.google.com/drive/folders/0B3hsmXWocH2JZVpTSzdzaUxYQzA (Accessed December 15, 2016)

[Weilkiens et al., 2015] T. Weilkiens, J.G. Lamm, S. Roth & M. Walker, *Model-Based System Architecture*. John Wiley & Sons, 2015.

[Wibben & Furfaro, 2015] D.R. Wibben & F. Furfaro, "Model-Based Systems Engineering approach for the development of the science processing and operations center of the NASA OSIRIS-REx asteroid sample return mission," *Acta Astronautica* 115 (2015), pp. 147-159.

[Wikipedia: Ontology] https://en.wikipedia.org/wiki/Ontology (Accessed December 15, 2016)

[Wikipedia: Ontology (Information Science)]: https://en.wikipedia.org/wiki/Ontology_(information_science) (Accessed December 15, 2016)

[Witulski et al., 2016] A. Witulski, R. Austin, J. Evans, N. Mahadevan, G. Karsai, B. Sierawski, K. LeBel & R. Reed "Goal Structuring Notation in a Radiation Hardening Safety Case for COTS-based Spacecraft." *GOMAC Tech 2016 Government Microcircuits Applications & Critical Technologies Conference*, Orlando, FL, March 16, 2016. Available from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160005315.pdf (Accessed December 15, 2016)

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
08-29-2016	Contractor Report	

4. TITLE AND SUBTITLE Model Based Mission Assurance in a Model Based Systems Engineering (MBSE) Framework State-of-the-Art Assessment	**5a. CONTRACT NUMBER** NNN12AA01C
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Cornford, Steven L. and Feather, Martin S.	**5d. PROJECT NUMBER** 105140
	5e. TASK NUMBER 30.31.13
	5f. WORK UNIT NUMBER 724297.30.31.11
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Jet Propulsion Laboratory California Institute of Technology 4800 Oak Grove Drive Pasadena, CA 91009	**8. PERFORMING ORGANIZATION REPORT NUMBER** D-97731
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/CR-2016-219272

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 38 (Quality Assurance and Reliability)
Availability: NASA CASI (757) 864-9658 Distribution: Nonstandard

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report explores the current state of the art of Safety and Mission Assurance (S&MA) in projects that have shifted towards Model Based Systems Engineering (MBSE). Its goal is to provide insight into how NASA's Office of Safety and Mission Assurance (OSMA) should respond to this shift. In MBSE, systems engineering information is organized and represented in models: rigorous computer-based representations, which collectively make many activities easier to perform, less error prone, and scalable. S&MA practices must shift accordingly. The "Objective Structure Hierarchies" recently developed by OSMA provide the framework for understanding this shift. Although the objectives themselves will remain constant, S&MA practices (activities, processes, tools) to achieve them are subject to change. This report presents insights derived from literature studies and interviews. The literature studies gleaned assurance implications from reports of space-related applications of MBSE. The interviews with knowledgeable S&MA and MBSE personnel discovered concerns and ideas for how assurance may adapt. Preliminary findings and observations are presented on the state of practice of S&MA with respect to MBSE, how it is already changing, and how it is likely to change further. Finally, recommendations are provided on how to foster the evolution of S&MA to best fit with MBSE.

15. SUBJECT TERMS
Aerospace engineering, assurance, models, quality, reliability, safety, systems engineering

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UU	57	HQ-STI-INFODESK at hq-sti-infodesk@mail.nasa.gov

U	U	U			**19b. TELEPHONE NUMBER (Include area code)** 757-864-9658