AEROSPACE REPORT NO.
TOR-2010(8591)-17

Guidance for Space Program Modeling and Simulation

June 30, 2010

Michael J. Baxter

Systems Analysis and Simulation Subdivision
Systems Engineering Division

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space System Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement workshop.

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Acknowledgments

This document has been produced as a collaborative effort of the Mission Assurance Improvement Workshop. The forum was organized to enhance Mission Assurance processes and supporting disciplines through collaboration between industry and government across the U.S. Space Program community utilizing an issues-based approach. The approach is to engage the appropriate subject matter experts to share best practices across the community in order to produce valuable Mission Assurance guidance documentation.

The document was created by multiple authors throughout the government and the aerospace industry. For their content contributions, we thank the following contributing authors for making this collaborative effort possible:

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A special thank you for co-leading this team and efforts to ensure completeness and quality of this document goes to:

Michael Baxter – The Aerospace Corporation
Lawrence Green - NASA Langley Research Center
Michael Trujillo – Boeing

Additional significant contributions were provided by:

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Executive Summary

Although Modeling and Simulation (M&S) plays a significant role in the development of any spacecraft or system, this document is primarily intended for use in unmanned national space system programs. The guidance provided herein is really discipline-independent and should be of value to anyone involved with M&S in any capacity. The document provides guidance based on the experiences and lessons learned from a diverse team of people involved with M&S through various capacities and implementations. The document describes a coherent planned approach to M&S to support key program decisions. This approach when thoughtfully implemented has the capability to positively impact a program through significant risk reduction and potential for cost savings. In contrast, M&S applications not developed using a coherent approach may be neither suitable nor valid for their intended use and these M&S may even waste resources.

The primary purpose of this document is to provide insight and guidance to future space system programs for the implementation of M&S as part of the overall program plan. This document will describe an overall M&S process that can be adapted and used by a program from conception to completion and even into system operation. After the process is described, it is tied to a standard system gate process that is used in the program development life-cycle. A key part of this linking of the process to the gates is the development of a program M&S plan. This document develops an M&S plan that is scalable and can be tailored to fit the needs of multiple programs that vary in size and complexity.

The benefits to a program using a robust M&S plan can be extensive. In many cases it is the only way to establish the requirements that the system must be designed to meet. It is often not possible to perform physical testing of components and systems until on orbit. The use of models and simulations provides input conditions for the system development. M&S also provides a means of establishing requirements and performing development tasks that can be more cost effective than physical testing which may not even be possible in a laboratory setting.

Another area where M&S should play a key role in a complex space program is in risk assessment and management. All space systems have a substantial amount of risk that must be handled or at least understood in order to make sound system decisions. M&S can be used to understand the impact of the risk on the performance and in some cases the survivability of the system. M&S can also be used in place of physical development and testing to assess the risk and to evaluate mitigation strategies. In many instances, it is not possible to perform this effort except through the use of M&S.

Throughout this document, guidance is provided to the user on how to implement M&S in a program and specifically the development of the M&S Plan. Various recommended practices are interspersed throughout this document with explanatory, supporting, background, and descriptive text.

This guidance takes the form of:

- General guidance about the nature of M&S and the entire M&S process.
- A (suggested) common implementation/documentation strategy and structure for M&S:
  - To increase the Mission Assurance level of future space systems
  - To enhance future technology development efforts
  - To facilitate the re-utilization of technology and space systems as may be discussed within other documents emerging from this workshop series

- A (tailorable) template for an M&S Plan.
  - Specific guidance about the content of each section, i.e., what information should be considered, included and/or referenced in that section
  - Consideration of how the people within the target program will develop and interact with the program M&S Plan over the lifecycle of the effort
  - A common lexicon for M&S activities and terms

The intended audience for this document is broad in the sense that it is targeted towards those individuals in a program that need to plan and use M&S to support their activities and tasks as well as those that are responsible for the execution of the tasks. There is utility in the document that will allow a common understanding of the process regardless of the level of expertise of the user. The reference material for this document is listed so that the end user can access the details of the information as needed.

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1. Introduction

1.1 The Purpose and Uses of Modeling and Simulation

Modeling and Simulation (M&S) is the application of engineering/scientific knowledge and judgment to create and exercise simplified representations ("models") of a system in order to understand some aspect of its behavior. In this context, the term "system" is also meant to include any subsystem, component, entity, phenomena, or process for which increased understanding or imitation of behaviors is desired. *The primary purpose for undertaking M&S within a national space system program is to enable risk evaluation*, such as when it is impossible or infeasible to replicate the combined on-orbit conditions (e.g., low gravity, thermal effects, and radiation environment) in a ground-based testing facility, or when critical decisions regarding human safety, performance, mission assurance, or costly expenditures must be made. National space system programs employee M&S when a programmatic need (the "intended use") has been identified as a means to gain significant, reasonable, or sufficient assurance that an approach or design will be able to meet the customers' or users' needs (feasibility and risk reduction), to demonstrate that the proposed or designed system will function as desired and that it will be a preferred approach. When gaining this assurance becomes sufficiently complicated such that engineering judgment and prior experience with similar previous systems are not sufficient to enable the justifiable choice of a likely to succeed and desirable approach (or design), the process of modeling and simulation may be employed. Modeling uses scientific understanding of the pieces of systems, subsystems, and components and the rules that govern their interrelationships, along with the laws of physics, to achieve specific and simplified representation(s) of the actual system appropriate for use in evaluating how the real or imagined, system, subsystem, or component will behave and perform.

The term "models" is specifically intended to include empirical or phenomenological models. Simulation exercises models in an environment where they interact and represent, or allow for assessment of, the resulting system behaviors and performance. This fundamental utility of M&S allows engineers and technical decision makers to more accurately evaluate a system, subsystem or component's feasibility and usefulness without having to actually produce it and place it in an operational environment. This practice of M&S thus enables possible cost reductions for the program through an evaluation of alternatives at a far cheaper cost than actually building multiple candidate systems for evaluation.

Some typical uses of M&S include:

- Exploration of notional system, subsystem, and component models (concept exploration)
- Identifying which system functions and properties are critical to meeting the user's needs (requirements development and assessment)
- Assessment of effective requirement thresholds and objectives (utility, effectiveness, and performance)
- The likelihood and consequences of systems failing to function or perform as desired (risk) and evaluating alternatives to select lower risk (lesser consequences and/or decreased likelihood of failure)
- How well alternative systems, subsystems, and components support meeting the requirements (source selection) or specifications (design)
- Evaluating how well a delivered or operating system is meeting the requirements (test)

- Any of the above, without having to actually build, deploy and access alternative and potentially undesirable systems (cost savings) in difficult, or hard-to-reach environments

In order to successfully execute M&S in a program, it is essential that:

- A programmatic need exists; this usually will take the form of a critical decision [9,26,106] to be made, that will be supported by M&S, for which an M&S intended use statement is developed (see additional information on the intended use statement in Sections 2.1, 4.2 and Appendix I). Note that the intended use consists of the decision or uncertainty to which M&S resources will be applied.

- The process for identifying what will be modeled and simulated is clearly understood and systematically applied (see Section 4 for additional guidance about models and simulation)

- The process for building and evaluating the acceptability of M&S tools is defined and used (see Section 4 and Appendix F for guidance about acceptability criteria, and see Appendix I for guidance about the minimum cost of the required M&S)

- The program documents, reviews, and gates which depend on results from the identified M&S needs and that interface with the M&S effort are identified and the M&S activities are scheduled appropriately (see Section 3 for guidance about the programmatic aspects of M&S)

- A documented plan to conduct the above M&S activities is developed, maintained, adapted, and used to support the program through its lifecycle (see Section 5 for guidance about the M&S Plan)

1.2 Structure of M&S and Use of the Document

The overall conduct of M&S in support of a national space program can be categorized as shown in Figure 1. These categories consist of:

- Determining the program needs for M&S (What to M&S: Section 2)

- The interfaces between the program M&S and the program documents, and the when and where that products will be used to support the program gates and reviews (Programmatics: Section 3)

- The process for conducting M&S to address an identified need (intended use) and organizing the associated tasks and products (Planning: Section 4)

- Capturing and communicating the overall plan, its current status and the sub-plans for addressing individual intended uses (Plan Template: Section 5)

- Actual implementation which consists of using, following, and updating the plan

This document is organized into four main sections corresponding to the M&S categories presented above and as shown in Figure 1. Section 2 describes and illustrates a generic process for identifying the applications or intended uses of M&S in a program. Section 3 addresses the program activities, documentation, reviews, and milestones or gates that an M&S plan and the resulting activities are generally expected to interface with and support. Section 4 describes a generic process for conducting the activities and producing the products to implement M&S for a specific intended used. Section 5 presents a general and tailorable template for documenting and communicating how an M&S effort will be conducted in support of a program or project. The Appendices provide additional detail on a number of topics, including: a summary of this document's recommended practices, an annotated M&S Plan Template[5,7,32,60], an M&S glossary (compiled from several sources[37,62,63,106], a description of M&S process details and key M&S characteristics; please see Table 1 for a complete listing of the Appendix topics).

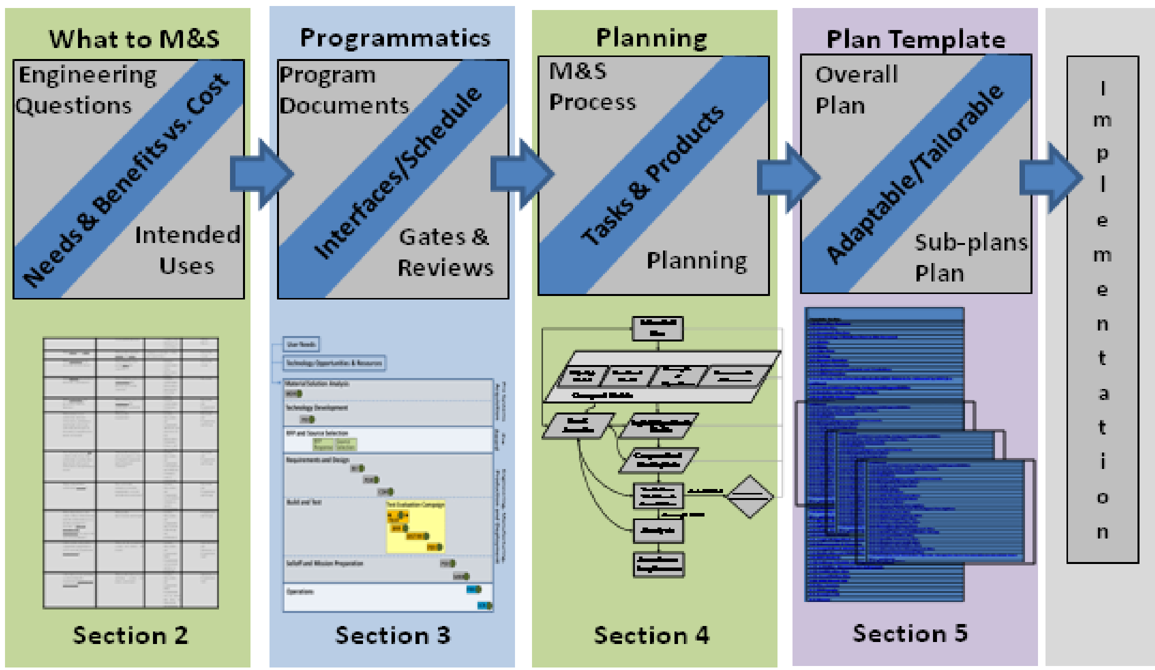


Figure 1. An illustrative structure of M&S and the corresponding organization of this document.

As a potential user of this document may be knowledgeable in one or all of the sections listed above, the four sections described above are designed to be stand-alone in order to support such a user, as well as users less familiar with M&S in general. Appendices are included to provide sufficient background information and references to allow the user to gain insight into any of the main section topics in which they may be unfamiliar. However, successful execution of program M&S requires an understanding and implementation (in some form) of all four section topics.

Table 1 is provided as a quick reference tool.

It must be stressed that the M&S process, template, and interactions with the program reviews and gated events is not prescriptive, rather programs and projects should use similar artifacts, particularly the thought process behind their development and definition in planning and executing M&S efforts.

Details on NASA-contracted M&S efforts, from two different organizations (Applied Biomathematics, Setauket, NY; and Vanderbilt University, Nashville, TN), related to industry-standard FireSat satellite design example[114] are available through one of the contributors to this document (Green). These referenced efforts[41,73,117] each solved a simplified version of the FireSat design problem considering the disciplines of orbit, power, and attitude control with two distinct approaches to uncertainty quantification and propagation.

Table 1. M&S Planning Guidance Document Quick Reference

Section	Section Title	Description
2.0	What to Model and Simulate	This section discusses the use of a phased and hierarchical set of engineering problems/questions as a means for identifying appropriate applications (intended uses) of M&S in a program.
3.0	Programmatics	Describes program documentation, gates and reviews that most significantly tie in with the development and use of an M&S plan.
4.0	Planning	Presents a procedure for executing an M&S effort given that the intended uses for M&S have been identified or anticipated. Also discusses the identification of tasks, responsibilities and products, their management and their capture in the plan template.
5.0	Modeling and Simulation Plan, Template and Tailoring	Provides a tailorable template with reference linkages to the document sections and Appendix B that should impact/be addressed in that part of the template.
Appendix A	Collected Recommend Practices	A collection of the recommended practices listed throughout the document.
Appendix B	Annotated M&S Plan Template	Description of the sections of the proposed M&S Plan Template.
Appendix C	Definitions	A list of the definitions used in the document.
Appendix D	Acronyms	A list of the acronyms used in the document.
Appendix E	M&S Process Details	Additional detail and description of the material in Sections 2.0, 4.0 and the types of models discussed in the document.
Appendix F	Description of M&S Characteristics	Discussion of some of the metrics or features characteristic of useful and effective M&S.
Appendix G	Interaction of M&S with Key Lifecycle Work Products	Further detail and discussion of the material in section 3.0.
Appendix H	Guidance for Writing an Intended Use Statement	Detailed discussion about what makes a good intended use statement for an M&S.
Appendix I	Guidance for Determining the Minimum Cost of M&S	Detailed discussion about how management choices influence the minimum cost of M&S within a program.
Appendix J	Annotated Bibliography of M&S to support M&S planning	Detailed bibliography with commentary courtesy of William Tucker, The Boeing Company.

1.3 Intended Audience and Assumptions

The intended audience of this document includes program and M&S managers (including planners), experienced and new practitioners of M&S, and individuals/organizations assessing the state of a program's M&S effort. Program and M&S managers (including planners) need to understand how an M&S effort should be conducted, so they can plan and monitor the use of M&S throughout the program lifecycle. Experienced and new practitioners of M&S need to have a common understanding of their roles and responsibilities in executing M&S. People and organizations assessing a program's M&S planning and execution need to be able to understand whether the program has a sound, systematic M&S plan and a commitment to its use, an effective process for conducting M&S, and if the resulting M&S efforts are sufficient to meet the program goals.

It is assumed that users of this document have some familiarity with spacecraft (customer needs, design, launch and operation)[117]. It is also assumed that users of this document have some familiarity with how M&S is conducted within their organization (computer operations such as programming and execution, data storage, etc.)[5]. It will be helpful for users of this document to have some familiarity with at least one of the engineering or scientific M&S disciplines needed to address an intended use. It is also assumed that the reader has a fundamental understanding of, or access to, sound guidance on the topics of technical risk analysis, systems engineering, requirements development and project management[61,84].

1.4 Scope of Document

This document was developed as part of the U. S. Space Industry Mission Assurance Improvement Workshop (MAIW) 2010 effort. The formal MAIW charter for this effort was to:

- Produce a guidance document for the development of a program's Modeling and Simulation (M&S) Plan focused on understanding how to conduct M&S.
- Provide and emphasis the need to have a process for conducting M&S.
- Provide a flexible and tailorable template for capturing planned M&S processes.
- Illustrate the linkages between the M&S program activities and the program reviews, gated events, and documentation.
- Emphasize the need to conduct M&S as a planned and critical thinking oriented activity within the program context, including the use of a common perspective and lexicon, role in quantifying and assessing risk, and the need to verify and validate its implementation.

Within the Mission Assurance Improvement Workshop for 2010, two related topics were identified for the development of guidance documents: 1) Modeling and Simulation and 2) Testbeds and Simulators. The following view, as illustrated in Figure 2, is provided to help the reader understand the commonality and differences between the two topics.

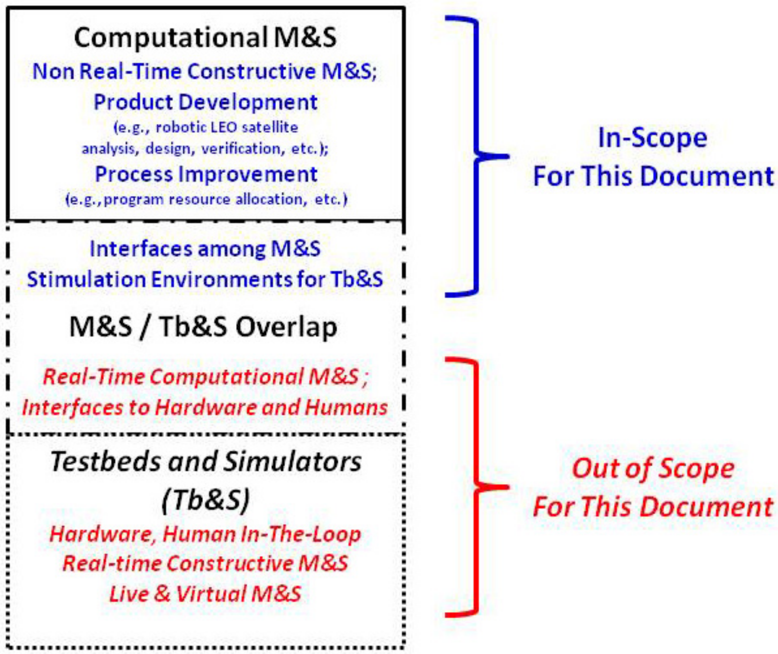


Figure 2. Graphical illustration of the scope of M&S including its relationship with the Testbeds and Simulators (Tb&S) document.

The scope of this guidance document is restricted to the top solid-lined box (labeled "Computational M&S") and the top half of the middle dash-dot-lined box (labeled "M&S/Tb&S Overlap") shown in Figure 2. M&S within this scope is subject to both the general software engineering guidance[83,104] and to more specific M&S guidance[77,97,106]. If and when conflict or confusion arises between the two types of guidance, the M&S guidance should take precedent since it was developed specifically with M&S in mind. The reason for this assumed hierarchy of precedence stems from the results of a detailed examination of both NASA software engineering and M&S guidance existing at the time of the development of NASA-STD-7009, in which it was found that there was a minimal set of conflicting or confusing guidance between the two camps, and that the M&S side was found to be better aligned with the needs and goals of M&S. It should be understood that the defined scope of this document is really intended to include any non-hardware-in-the-loop, non-human-in-the-loop, non-real-time M&S. This scope clearly maps to the conventional group of M&S known as "constructive simulations" and includes:

- The written statement of the system and M&S requirements,
- Conceptual, functional, logical, mathematical, algorithmic and computational models
- Computational simulations with no hardware or human "in the loop"
- Computational simulations in which real-time execution (or variability in execution speed across multiple platforms) is not a factor.

Testbeds and simulators are defined to be the rest of M&S. Thus, Testbeds and simulators would include:

- The union of physical and computational M&S.
- The execution of multiple distinct computational M&S (as defined above, and normally developed independently of each other) which fulfill diverse purposes within the system and which may execute on different computational platforms.
- Those M&S that include hardware and which are program deliverables.
- Those in which any of the following characteristics may be important: real-time execution, hardware or human in the loop, or M&S executing across multiple computational platforms (when the impact of cross-processor communication is material to the result).

As such, the Testbeds and Simulators guidance must address the issue of interfaces between multiple physical or computational M&S, and is subject to both the guidance for M&S, as well as the large amount of available guidance for interfaces and physical testing.

1.5 Notation Used in This Document

Various recommended practices are interspersed throughout this document with explanatory, supporting, background, and descriptive text. However, in order to make the identification of the specific recommended practices in this document more evident, and to allow the reader to easily distinguish any such formal recommendations in the text from any other supporting or descriptive text they are identified using the following notation. The capital letter **R within square brackets, followed by a unique number associated with that recommendation number**, as in: **[R1]** this is the formal recommendation text. These numbered recommendations are then collected in Appendix A without the supporting text.

1.6 Things to Consider When Planning M&S

[R1] It is recommended that before a program M&S Plan is actually written, a phase of M&S planning be undertaken. **[R2]** It is recommended that the M&S planning phase should allow for a significant amount of thought, discussion, and negotiation among the various stakeholders, participants, and customers, and consideration of what is feasible, compared to what is desirable.

[**R3**] It is recommended that the purpose of M&S be considered as a means to gain significant, reasonable or sufficient assurance that an approach or design will be able to meet the customer or user's needs, will function as desired and will be a preferred approach. When gaining this assurance becomes sufficiently complicated such that engineering judgment and prior experience with similar systems are not sufficient to enable the justifiable choice of a likely to succeed and desirable approach (or design), the process of modeling and simulation may be employed.

The decision to execute a program M&S effort necessarily involves a tradeoff. [**R4**] It is recommended that the potential benefits of spending the time and money to produce, maintain, sustain, and use M&S should always be evaluated against the costs of potentially designing, building and testing a system, subsystem or component that fails to function or perform as needed or desired. In the case of space systems, M&S is generally very cost effective at the system, subsystem and critical component level. Most of these systems are expensive, often are mission critical and often cannot be retrieved for repair or modification. In conditions such as these, it is often possible, through the use of a well planned and focused M&S program, to significantly reduce the uncertainty in how a system will behave or perform (i.e., assessing risks and evaluating alternatives and designs to reduce the likelihood and consequences of failure).

Use of constructive M&S can reduce the risk and cost of development activities throughout the development lifecycle of a space system. It is typically much easier to build and conduct experiments with a software model than a hardware model. Design decisions are often made early in a development program, and validation of these decisions can provide significant avoidance of costs further in the program.

In general, [**R5**] it is recommended that models and simulations should only be as complicated as necessary to address the concern at hand with the desired fidelity[50]. Of course, the availability of a higher-fidelity model than is needed may be more desirable than developing a new, proper fidelity model from scratch. Before embarking on the development of an ambitious M&S program, the systems engineer should decide if it is really necessary and, if so, to what extent. Although valuable in reducing program risk and cost, M&S activities can also be expensive and time consuming in and of themselves, especially those requiring high-fidelity fluid dynamics, structures, and kinematics analyses, for example. Simulation may not be necessary at all. Analytical approaches in which a mathematical model is used to determine static performance may be sufficient. Acquisition of simulation tools, configuration management and maintenance of the tools and data, and the required expertise, education, and training to operate these tools should also be considered.

[**R6**] It is recommended that at the initial stages of planning, the benefits vs. cost of Modeling and Simulation Efforts should be considered and integrated into the program risk reduction and planning discussions. Estimates of cost and time to pursue a particular M&S plan, along with the associated risks, should be considered in determining a course of action that is best suited for the program's goals, budget and schedule.

[**R7**] It is recommended that in both the planning and execution phases of M&S activities, it is crucial to ensure that the benefits gained in refining and testing a design, identifying an effective approach, reducing the risk or in establishing requirements are sufficient to justify the cost. The objective of M&S may not be to fully understand the system performance or to very accurately predict its behavior. Rather, the objective of M&S may be to enable the program to spend its resources as wisely and efficiently as possible while gaining sufficient understanding to have a reasonable assurance that the selected approach will be able to meet the user's needs. [**R8**] It is recommended that assessment of the benefits versus costs of conducting modeling and simulation should be tied to specific questions to be answered and the activities needed to obtain answers. Such assessments should be required at the start and periodically throughout the execution of a program.

A major issue related to the development and use of M&S, and unique among software engineering[*] efforts, is that of ***credibility***. The purpose of M&S is to represent a system, entity, phenomena, or process. If the chosen representation of the target system, entity, phenomena, or process lacks credibility to a decision maker[9,26], the M&S will be of little use and may be misleading or wrong. The importance of the issue of M&S credibility was addressed by the Aerospace Safety Advisory Panel (ASAP) during its recent meeting in Washington DC on April 30, 2010[8]; this influential committee strongly endorsed a multi-factor M&S Credibility Assessment approach[106].

[**R9**] It is recommended that successful implementation of M&S in a complex space system program is characterized by use of the four basic elements identified in Table 1 and their implementation.

[*]See references 1, 13, 16, 20, 27, 28, 39, 46, 49, 53, 54, 55, 59, 72, 74, 75, 76, 81, 88, 92, 95, 99, 103, 105, 106, 109, and 112 in Section 6.

2. What to Model and Simulate

2.1 Intended Uses of M&S

When there is uncertainty in what the alternatives are, or how well the alternatives will support the user's needs or vision (metrics, thresholds and objectives) and to what degree of assurance (risk), such decisions become problems to be resolved, or in other words, they become engineering problems (this term can also be broadly expanded to include managerial problems for which an engineering approach may be helpful in identifying a solution). The process of finding a solution to the problem generally consists of identifying known alternatives (or searching for potential alternatives and making them known), assessing the ability of the alternatives to achieve the desired new state, determining the feasibility of these alternatives (including risk, cost, and functionality) and selecting the alternative most likely to achieve the desired end state within acceptable costs. It should be noted that such alternatives may consist of actual objects or metrics.

Engineering uses the mapping of scientific knowledge into a design as a process to ensure that the product has some level of assurance in achieving a given purpose (in the case of systems development, the user's needs or sponsor's vision). As human beings have limited abilities to internalize, coordinate, and access knowledge; this mapping is necessarily broken down into a sequence of problems or uncertainties that are resolved hierarchically and often iteratively at the next underlying level of greater detail. Such engineering problems[79,91,102] readily decompose to specific levels of detail as shown in Table 2. The first column presents a general hierarchy of the engineering problems encountered in the lifecycle of a space system. The second column displays the related types of criteria used in selecting alternatives (i.e., for selecting solutions), the third column provides general examples of the metrics and alternatives that are likely to be involved and the fourth column indicates the lifecycle phase in which the corresponding engineering problems occur.

The resolutions or solutions to these engineering problems deemed critical with respect to achieving overall mission success are generally designated as the system requirements. Such requirements may specify such things as architecture and components, metric thresholds and objectives (utility, effectiveness and performance), functionality and acceptable risk. While M&S is used to address these critical requirements (sometimes classified as the Key Performance Parameters), it is also used to identify solutions to less critical but still necessary design focused engineering problems or specifications. Thus, M&S is applicable to defining the system requirements to the level of detail determined to provide reasonable assurance and to the development of the system design to the level of buildable specifications. The decision to apply M&S resources to resolving these types of engineering problems should be made on the basis of whether there is significant uncertainty in the answer and the potential benefits versus costs of reducing the uncertainty. Engineering problems identified as an application of program M&S resources are referred to as "intended uses."

The steps involved in identifying the M&S intended uses consist of:

1. Identifying which or what type of engineering problems need to be addressed using M&S and ensuring that the problems are clearly defined and adequately structured and informed by past (higher in the hierarchy or level of detail) solution decisions.

2. Determining the phase or phases the M&S effort will cover.

3. Identifying the potential alternatives and the means of assessing alternatives (i.e., alternative effects or functions or architecture), and what metrics will be used to evaluate utility, effectiveness or performance. These metrics are the actual values identified in response to the type of questions shown in the second column of Table 2.

Table 2. Generalized Engineering Decision Questions Addressed by M&S During Program Execution

Engineering Problems	Assessment Questions	Potential M&S Intended Uses (Alternatives/Metrics)	Primary Phases
What *effects* have *value?*	What are the expected *benefits* and *costs?*	Alternative Concepts/ Utility and Value Metrics	Prior to Pre-Award
What *capability(ie*s) can deliver the desired effects?	What determines how useful (*utility*) the capability is?	Notional Architectures/ Utility, Effectiveness Metrics	Prior to Pre-Award
What *functions* are needed to deliver the capability(ies)?	What determines how well (*effectiveness*) the functions provide the capability?	Notional Architectures/ Effectiveness, Functionality, Feasibility Metrics	Pre-Award
What *architectures* can provide the identified functions?	What determines how well (*performance*) the architectures perform the functions?	Notional Architectures/ Performance Metrics	Pre-Award and Requirements and Design
What minimal set of architecture, functions, effectiveness, performance and design is necessary, sufficient and desirable to reasonably assure the user's needs will be met?	What are the requirements?	Systems, Subsystems and Components/ Thresholds and Objectives for Key Effectiveness, Performance Metrics, and Specifications	Pre-Award and Requirements and Design
How much uncertainty (*risk*) is there in the ability of the architectures to perform their functionality and to given effectiveness and performance levels?	What are the likelihoods and consequences of not meeting the requirements under operational conditions?	Systems, Subsystems and Components/ Consequences and Likelihoods of failure to achieve requirements	Pre-Award and Requirements and Design
What is the preferred architecture (*selection*)?	How well do the alternatives meet the requirements, cost, risk and other decision factors?	Systems, Subsystems and Components/ Assessment of Alternatives against Requirements	Pre-Award and Requirements and Design
What characteristics and values of those characteristics must the architecture possess (technical performance measures – *TPMs are measures of the characteristics*) to achieve the specified performance?	What are the Specifications and design?	Systems, Subsystems and Components/ Specifications (both design and performance)	Requirements and Design

Is the system, subsystem or component being produced able to meet the requirements *(production test)*?	What are the production system test metrics and results?	Systems, Subsystems and Components/ What Requirements will be tested and how in production	Build and Test and Operations, or Requirements V&V
Is the deployed and operating system meeting the requirements (*operational test and monitoring*)?	What are the deployed and operating system test metrics and results?	Systems, Subsystems and Components/ What Requirements will be tested and how in deployment and operation	Operations, or Requirements V&V

2.2 M&S Requirements

In general, the term requirements refers to the set of limits, constraints, thresholds and objectives leveled on the design and production of a system. However, similar limits are also leveled against the performance of any general task and the conduct of M&S is no exception. For M&S, the associated requirements generally consist of the following:

- The coordinated set of intended uses identified through a process like the one described in 2.1 and accepted as M&S needs by the program management; guidance for constructing a good intended use statement is given in Appendix I.

- Identification of the amount of resources (cost) to be allocated to conducting the associated M&S activities for each intended use; guidance for determining a lower bound on the resources needed for M&S is given in Appendix J.

- Description of the objective benefits to be obtained through the use of M&S for each intended use (level of understanding, detail and/or accuracy, access level of risk consequences or likelihood of failure, etc.). This should also include definition of what constitutes a sufficient benefit of M&S (and when to stop).

3. Programmatics

3.1 Programmatic Roles and Responsibilities

The M&S literature[106,111] identifies numerous roles that need to be filled to successfully execute an M&S process including: Analyst, Customer, Decision Maker, Developer, Manager, M&S Management, Operator, Program/Project Management, Proponent, Sponsor, Subject Matter Expert (SME), Technical Authority, Tester, User, and Verification/Validation Agent. Typically, each of these roles (or a select, grouped subset of these roles) is assigned to one or more unique individuals; within small M&S efforts, it is not uncommon for a single person to fulfill more than one role. Each of these roles is then assigned a variety of responsibilities. Likewise, the responsibilities may be delegated among the people available, rather than by strict association with specific roles. *The important point is that someone must fulfill all the responsibilities in order to achieve a useful and successful M&S implementation.*

The term "***M&S management***" is used broadly in this document to encompass the specific, balanced roles and responsibilities of the programmatic, technical authority, and safety/mission assurance management groups. It is assumed that members of this team will ultimately act in concert to achieve the best overall M&S effort, despite potentially conflicting desires and requirements throughout the program lifecycle. None of these groups should be allowed to have more control over the M&S process than the others. The ***M&S management team*** is responsible for the overall planning and managing of resources, directing the overall simulation effort, and overseeing configuration management and maintenance of the simulation. NASA-STD-7009[106] enumerates specific responsibilities for the M&S management team; however, because of certain NASA-specific restrictions, the responsibilities of the M&S management team are described in NASA-STD-7009 in a fairly obtuse manner. In order to more clearly illuminate these specific and critical roles and responsibilities, that guidance is paraphrased in the following two paragraphs. The roles and responsibilities of the other stakeholder groups are more clearly enumerated in NASA and DMSO documents[107,112] and are not described in detail in this document.

[**R10**] It is recommended that *the M&S management team* be considered to have two initial responsibilities: 1) to identify and document those sections of the reference documents (this guidance document included) that are applicable for the M&S effort, and 2) to identify and document the parties responsible for complying with the applicable guidance in this and other reference documents. It is important to note that the actual personnel identified by the M&S management team to fulfill the specific roles and responsibilities described in the guidance documents will likely vary depending upon the context of the guidance; for example, the responsible party might be the lead, or another supporting person associated with the model development, operation, analysis, and/or reporting of results to decision makers.

[**R11**] It is recommended that *the M&S management team* should also identify and document the critical decisions to be addressed with M&S and perform, or request, risk assessments to determine which M&S are within the scope of the applicable guidance. [**R12**] It is recommended that *the M&S management team* also have the responsibility to identify and document the training requirements for personnel within the program, to identify and document the extent and level of formality of documentation needed to meet the documentation guidance in this and the other reference documents, and to assure that: a) risk assessments for any M&S used in critical decisions are documented, and b) M&S that are within scope of the applicable guidance are identified and documented. [**R13**] It is recommended that the M&S management team should likewise identify and document:

- The acceptance criteria for M&S products, including any accreditation requirements for the M&S effort (these are obtusely called endorsements within NASA STD-7009[106])

- The intended use of the M&S
- The safety, performance, cost and schedule metrics (all programmatic and technical metrics) relevant to the M&S effort
- The requirements for verification, validation, and uncertainty quantification
- The requirements for reporting of M&S information for critical decisions
- The requirements for Configuration Management (CM), i.e., the specific artifacts, timeframe, and processes)
- The requirements for the program deviation/waiver process
- The specific person or groups responsible for complying with the specific applicable guidance related to:
  - Performing risk assessment
  - Performing scope assessment
  - Developing technical objectives
  - Developing requirements
  - Developing technical plans
  - Planning, conducting, and documenting technical reviews
  - Tracking waivers, deviations, risks, mitigations, hazards, and issues
  - Capturing any process maturity metrics, e.g., those related to Capability Maturity Model Integration (CMMI[84,105]) characteristics such as the work product management, process definition, process measurement, process control, process change, and continuous improvement process
  - Performing modeling
  - Performing simulation and analysis
  - Performing verification
  - Performing validation
  - Performing uncertainty quantification
  - Performing uncertainty management
  - Performing accreditation (including certification)
  - Identifying, using and/or developing relevant, discipline-specific best practice guides
  - Performing credibility assessment of M&S[†], if this is to be performed, and
  - Reporting M&S results

[†]See references 14, 17, 21, 29, 50, 54, 56, 55, 73, 75, 77, 82, 89, 100, 104, 106, and 107 in Section 6.

3.2 Primary Documentation

Documentation is a vital part of the modeling and simulation process. Documents are some of the most important products of the M&S process. Documentation is used to establish the intended use, the M&S requirements, the M&S process itself, and then to demonstrate the quality of the models through V&V, and preserve that quality and credibility for future use. Documents produced specifically for, or by, the M&S process may contribute to documents that are part of the overall program lifecycle (as outlined in Section 3.4).

3.2.1 Overall Plan

The overall modeling and simulation plan should be documented. This document should establish the overall purpose of the models and simulations, how they will be developed, the schedule, and the resources to be used[‡]. The plan should provide an overview of the high level steps in the process (requirements, V&V, etc.). The plan should also discuss the other documents that will be created during the process, e.g., the Documentation Plan may be encompassed in the overall M&S plan.

The overall plan is developed using results from applying the M&S process to the problem in question (intended uses), as described in Section 4. High level decisions are made as to what is to be examined, to what fidelity and which metrics to use. This information is used to develop the details in the plan and the other documents.

3.2.2 M&S Requirements

The planning documentation should list the detailed requirements that have been created to satisfy the overall purpose of each model or simulation at the correct fidelity and accuracy as outlined in the overall plan. The requirements documentation should supply traceability from the specific development requirements to the overall purpose of the simulation or model and the desired output metrics[26,59,95]. The development of the requirements should be undertaken with all of the relevant stakeholders. The detailed requirements rely heavily on subject matter experts to determine exactly what details need to be modeled. The requirements can then be scoped to feed into the resources and schedule portions of the overall plan.

3.2.3 VV&A Plan/Results

The VV&A plan should document the process that will be used to verify and validate the models or simulations[§]. The plan should follow the overall purpose and intended use of the simulation as documented in the M&S plan as it relates to the amount of VV&A and the acceptability criteria used. The actual tests run, along with their methodology, acceptance criteria, required inputs, etc. should be documented in the plan and the VV&A results document. The document should outline any risks or impacts associated with the implementation of the VV&A as planned. The plan should be within the scope of the resources available. Note: In some cases the VV&A requirements can be provided by an external party (e.g., accreditation agency). The plan should then discuss how the external VV&A requirements will be implemented. See also: VV&A Guidance in Appendix E.

3.2.4 Development Plan

The development plan outlines the development process. The plan can document the specifics of the implementation of the requirements as well as outline a unique methodology to be used during development (for example: Rational Unified, Scrum, Extreme Programming [XP], etc.). The plan

[‡]See references 5, 8, 33, and 61 in Section 6.
[§]See references 5, 8, 12, 15, 16, 18, 33, 48, 52, 53, 61, 78, 79, 98, 112, and 117 in Section 6.

should cover the specific tasks necessary to meet the above requirements and should relate the development to the VV&A plan and schedule. It should also include any development required by the VV&A process (test harnesses, etc.). At the completion of the development plan you should have a complete model and/or simulation that is ready for the final stages of testing, i.e., Validation or Accreditation.

3.2.5 Interface Control

Interfaces from one model or simulation to another external model, simulation, or user must be documented. Interface control documents (ICDs) describe the form, content, and structure of data that is input to or output from a model or simulation. An ICD allows external components to be built to communicate to the model.

3.2.6 Configuration Management Plan

The configuration management plan should discuss the methods and processes used to control the products produced and used in the M&S process. Items under configuration management should include:

- Documentation:
  - Requirements – requirements documentation that includes the requirement descriptions, rationale for change and the change history.
  - Intended use statement – this documents the programmatic need or existing capability.
  - Interface description documents (ICDs) – changes to these documents and their rationale should be under configuration management.
  - Plans and other documents – the plans and documents mentioned in the documents section as well as those outlined in the plan template should be considered for configuration management.
- Models and software:
  - Conceptual models – the conceptual models and their descriptions.
  - Functional models – the functional models and descriptions.
  - Logical models – logical models and their descriptions.
  - Mathematical models – unless these are easily found in the open literature, such as the "Navier-Stokes Equations."
  - Algorithmic models.
- Descriptions of environments and scenarios used for analysis, VV&A, etc.
- Descriptions of processes (including VV&A) and execution scripts.

The control process should also include a change management process where changes to any baseline model or data product are carefully managed. Details of the configuration or change management process are out of scope of this document but further information can be found in the references section.

3.3 Additional Plans

The following additional plans are specified within IEEE Std 1058-1998[61]. These may be part of other program documentation or may be contained within the set of M&S Plan documents. They are listed here simply so that someone in the program is tasked with developing and documenting the information required of each additional plan.

Risk Management Plan – outlines any risks associated with the M&S Plan[4,70]. This plan will describe the risks (likelihood and consequences), their risk level, and any necessary mitigation steps. The plan should document the process of managing the risks throughout the M&S project. These risks should flow up to the overall program Risk Plan.

Infrastructure Plan – details any infrastructure required for the M&S project. This could include any necessary hardware, software, or facilities that are necessary to implement the overall M&S plan.

Product Acceptance Plan – is an alternative location to put the overall acceptance criteria related to the M&S products. The information is likely to be encompassed by the VV&A Plan described elsewhere.

M&S Integration Planning – outlines how the different component simulations or models will be integrated during development and when. This information could be contained in the Development Planning part of the document as described above. Furthermore, any integration related testing may be outlined in the VV&A Planning part of the document.

System Integration Plan – covers integration of the M&S capability into an external entity. This could be the use of a model developed for integration into a testbed or perhaps into a larger simulation capability. The plan would cover any particulars associated with this activity.

Quality Assurance Plan – should cover any additional activities undertaken to ensure the quality of the simulation or data products produced. This would be anything in addition to the V&V already described. It could address specific process or review activities in addition to those already discussed.

3.4 Modeling and Simulation and Program Milestones

Modeling and Simulation (M&S) is an inherent part of the Systems Engineering, development, and Test and Evaluation processes utilized throughout a program's lifecycle. M&S may take on different roles during the program lifecycle starting with the identification of user needs and technological opportunities through end of life, including:

- Decision making
- Allocation and sub-allocation of requirements
- Risk reduction prior to test
- Risk reduction and performance verification prior to launch
- Correlation of predicted performance vs. on-orbit capability

The M&S activities should be time phased to correspond with program milestones to support the decision and verification processes at each key milestone as shown in Figure 3. M&S efforts commence prior to the start of the pre-systems acquisition phase-award timeframe and continue throughout the design and build phase with final verification on-orbit.

Figure 3 displays a program's lifecycle along the vertical axis on the left side, starting with pre-systems acquisition and proceeding through a number of phases and then ending with operations.

Numerous versions of this chart are available in the existing space program acquisition literature[**]. The program life cycle used in this document is a hybrid of versions found in DoD 5000.2[35] and Aerospace Corporation Report Number TOR-2009(8583)-8545[2]. The horizontal axis represents the level of detail. Reviews are shown occurring sequentially in time (phase) and in increasing level of detail as the variables of both axes progress. Such reviews provide the users, procuring agents, and system builders the opportunities to guide, oversee, and confirm that the engineering and production of a system will have a reasonable assurance of being able to meet the user's needs within a set of constraints (such as time and cost).

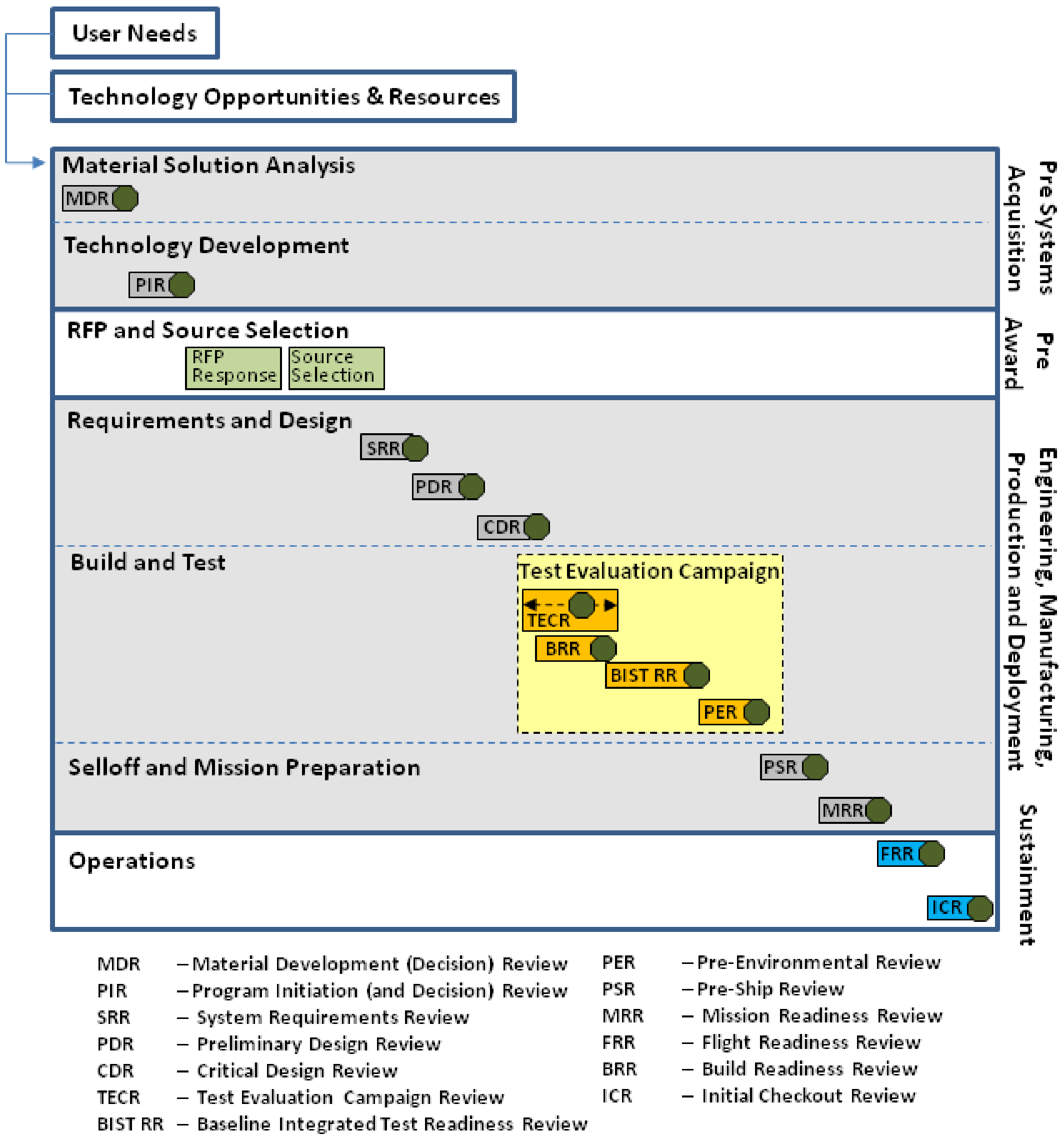


Figure 3. Critical gated events for a generalized space system lifecycle.

[**]See references 4, 5, 25, 34, 35, 36, 37, 86, and 111 in Section 6.

While M&S may be an informal process during the pre-systems acquisition time frame, it is crucial in performing the trade studies used to develop the system design during concept development/evaluation. Various M&S tools may also be implemented to demonstrate that the conceptual design satisfies mission requirements (i.e., payload performance, etc.) during the proposal process.

M&S planning and resource needs are developed as part of the proposal process with M&S plans for systems engineering, development, and evaluation activities detailed in the program's M&S plan.

Systems engineering should develop the M&S plan to guide the use of M&S throughout the program life cycle. The M&S plan should be used to integrate the use of M&S within program planning activities and across functional disciplines. The major M&S activities to accomplish this are:

- Plan for the integrated use of M&S throughout the program's life cycle including definition of M&S requirements derived from the program technical requirements and identification and allocation of available M&S resources and support infrastructure.
- Use of existing M&S during the program prior to initiating development/modification of M&S products and support reuse of M&S to the maximum extent possible.
- Deliver M&S products as required by the program.

M&S is integral to the systems engineering process from pre-systems acquisition through requirements development to verification, as illustrated in Figure 4. Prior to System Requirements Review and through Preliminary Design Review, M&S is used to derive and allocate requirements from system to segment to subsystem levels.

As illustrated in the systems engineering "V" of Figure 4, the requirements flow down from the higher levels to the lower levels during the program life cycle in sync with the schedule flow from Figure 3. As M&S is used to facilitate the sub-allocation of requirements, it is also used to verify requirements at the different stages scaling up the "V."

The system requirement verification process is composed of multiple elements. Typically, three parts of the verification process are key: M&S, system-level test, and on-orbit testing.

The verification process includes the development of system-level test and verification plans, establishing verification methodology for each requirement, systems engineering support during system, element, and subsystem testing, and the review of system, element, and subsystem analysis, test, and design documentation to verify that both the system's design and performance meet requirements. The verification plans developed as part of this process specifically address the following:

The Requirements Verification Matrix (RVM) identifies the verification methods, levels, and events associated with the final verification of each system requirement. All verifications associated with each requirement are identified in the requirements tracking database. Requirements are verified when the program concurs that the activities identified in the RVM are complete and the pass/fail criteria has been satisfied. The content of the RVM should include:

- Requirement
- Verification method (verification methods include analysis, inspection, test, demonstration)
- Verification success criteria

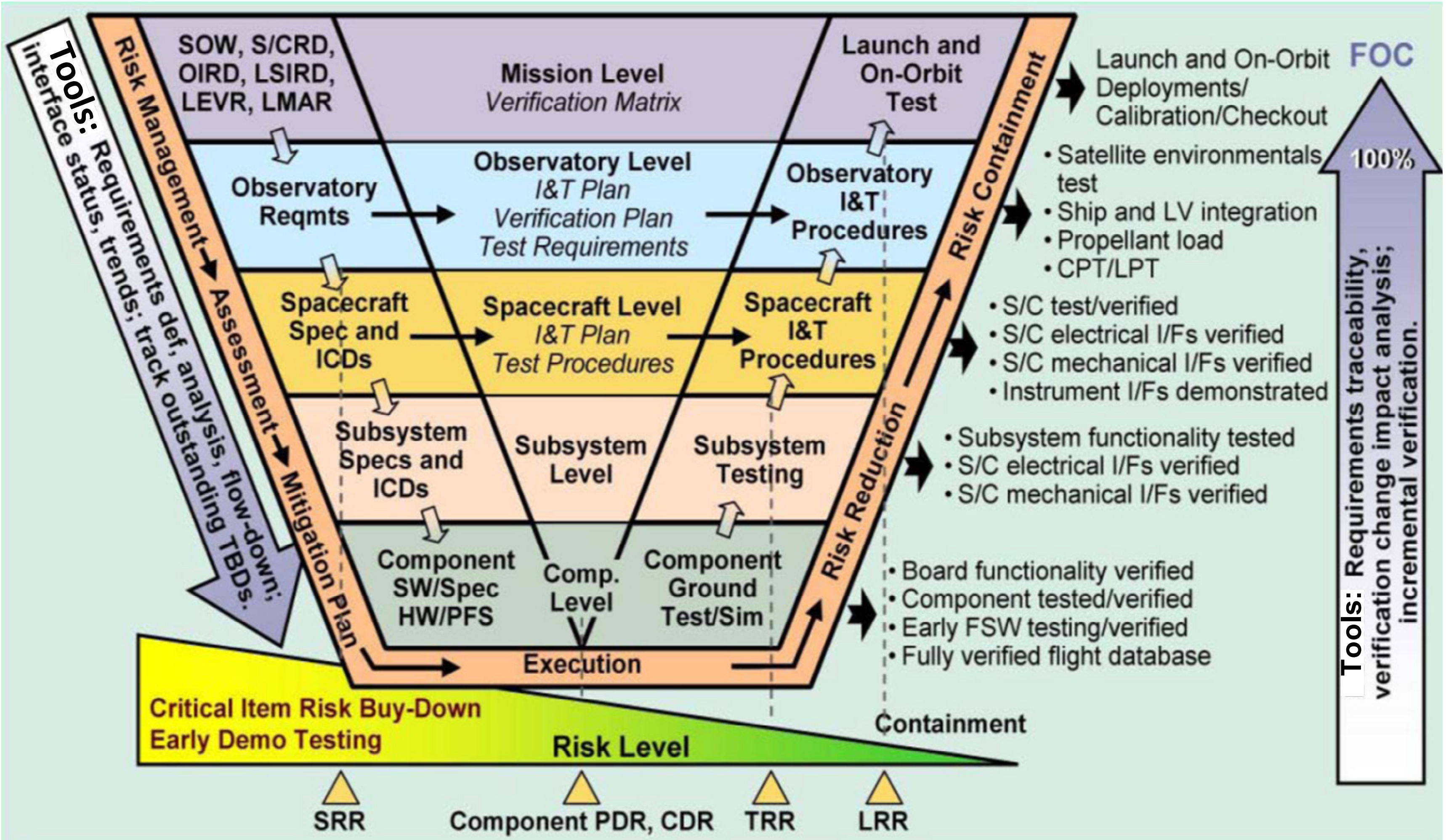


Figure 4. Systems engineering process as related to the program milestones[119]

- Required inputs and resources
- Verification process description
- Assumptions
- Description of lower level input verifications
- Description of outputs including pass/fail criteria
- Verification results

3.4.1 Interaction between M&S and Mission Assurance

The System Verification Plan (SVP), generated by Systems Engineering and Mission Assurance, should specify which system requirements can be met by Analysis, Inspection, Test, or Demonstration. The M&S Plan's identified intended uses should fully correlate with the SVP, specifying which requirements are to be met by Analysis, to assure that on-orbit performance requirements can be met prior to launch. These requirements can include mission performance (e.g., coverage, revisit, collection capacity), payload performance (e.g., RF link closure for communication missions or NIIRS for electro-optical missions), and spacecraft performance (e.g., attitude modes and accuracies, thermal control, electrical power generation and distribution and communications link budgets for command and control as well as data downlinks).

For those requirements that cannot be verified by Inspection, Test, or Demonstration prior to launch due to physical, schedule or cost constraints, analysis is necessary to assure mission success by verifying statistically that adequate margins exist in the design. In addition, certain requirements will require a modeling and simulation effort prior to final verification by test (i.e., dynamics) to assure that the satellite will satisfy test environments prior to testing.

3.4.2 Program Development Timelines and Decision Points

The M&S activities and Plan should provide the necessary detail to support design decisions during the design phase of the program (i.e., through CDR[††]). At the design reviews (primarily System Requirements Review) the M&S activities are applied to allocated requirements and their designated segment, element, and/or component. At the Preliminary Design and Critical Design Reviews, the M&S activities should validate the design decisions or allow for a reallocation of requirements to other segments, elements, and/or components to compensate for a variation in the current allocation.

These key decision points align with the major program reviews as shown in Figure 3.

3.4.3 M&S Guidance Through Gated Events

3.4.3.1 Gated Events and Work Products

As described in the Aerospace Corporation Report Number TOR-2009(8583)-8545[2], "Guidelines for Space Systems Critical Gated Events," the developmental and operational lifecycle of a space system is associated with a number of managerial and technical reviews intended to evaluate the program technical maturity, the program risks and opportunities, the challenges associated with the next phase of the program, stakeholder expectations, and program readiness for the next phase. In TOR-2009(8583)-8545, these reviews are called "Gated Events." The NASA Procedural Requirements (NPR) 7123.1A[85], "NASA Systems Engineering Processes and Requirements," refer to

[††]See references 2, 4, 5, 25, 34, 36, 37, 41, 62, 67, 68, 85, 86, and 111 in Section 6.

these reviews as Key Decision Points (KDP). DoD 5000.2[35] refers to these events as milestones and reviews.

Managerial reviews are intended to:

- Evaluate actual progress versus planned progress
- Evaluate the degree to which global control is maintained through an adequate allocation of resources
- Evaluate the potential for changing program direction or determining the need for alternative planning
- Evaluate and manage risk issues that may jeopardize the success of the project

Technical reviews are intended to:

- Evaluate that components, subsystems, and systems are complete, as appropriate for the stage of the lifecycle at which the review occurs
- Evaluate that components, subsystems, and systems comply with applicable standards and their specifications
- Evaluate that changes to components, subsystems, and systems have been properly implemented, documented, and are subject to appropriate configuration management
- Evaluate that the development of components, subsystems, and systems are adhering to their cost, schedule, and performance allocations

To this end, TOR-2009(8583)-8584 defines 11 Gated Events. Various documents called Work Products (WPs) are described and about 100 such documents are noted in the report. The WPs are created, updated, baselined, revised, and finalized at various points during the program lifecycle and the development process. These WPs are clearly tied to the Gated Events. In order to focus the discussion, this document will address 7 of the 11 Gated Events that are generally common among the report and NASA, and which represent several of the most important points within a program lifecycle. Likewise, 8 of the 100 WPs described in TOR-2009(8583)-8584 that are generally common among various sources are briefly discussed.

The 5 Gated Events to be addressed in this section are:

1. System Requirements Review (SRR)
2. Preliminary Design Review (PDR)
3. Critical Design Review (CDR)
4. Integration Readiness Review (IRR)
5. Pre-Environmental Test Readiness Review (TRR)
6. Pre-Ship Readiness Review (PSRR)
7. System Verification Review (SVR)

The 8 WP items to be addressed in this section are:

1. Analysis and Simulation Plan (or M&S plan)
2. Requirements Verification Plan
3. Reliability Analysis
4. Worst Case Analysis
5. Algorithm Development Plan
6. Error Budget and Allocation Analysis

7. Concept of Operations
8. Technical Performance Metrics Plan

3.4.3.1.1 Gated Events

While modeling and simulation can be used for demonstrating performance during pre-award, the M&S Plan may be developed during this phase as a deliverable with the proposal, if required, or developed after Authority to Proceed (ATP) as part of the documentation required for the System Requirements Review.

Initial modeling and simulation analysis results should be used within the proposal to demonstrate mission, payload, and/or spacecraft performances and compliance to technical requirements.

3.4.3.1.1.1 System Requirements Review

SRR is the technical review to ensure that the program can proceed into initial systems development, and that all system requirements and performance requirements derived from the program technical requirements are defined and testable, and are consistent with cost, schedule, risk, and technology readiness constraints. This review assesses the program requirements as captured in the system specification, and ensures that the system requirements are consistent with the mission requirements as well as available technologies. The intent is to evaluate the understanding of segment requirements and allocation of requirements to elements.

Modeling and Simulations implementation takes on two forms for SRR:

1. Used in the trades and analysis process to allocate requirements from the system level to segment, element and component levels, and

2. To specify the methodology for those system, segment, element, and component requirements to be verified by analysis.

3.4.3.1.1.2 Requirements Verification Plan/Matrix

The System Verification Plan (SVP) specifies the methodology for verifying each system requirement and at what phase of the program each needs to be completed. The methods for requirements verification are Inspection, Test, Analysis and Demonstration. Certain requirements may specify multiple methods for verification but time-phased with the program development.

The M&S plan encompasses the requirements that are verified by Analysis.

3.4.3.1.1.3 Modeling and Simulation Plan

The M&S plan (referred to as the Analysis and Simulation Plan within TOR-2009(8583)-8584) should specify the methods, tools, and techniques mapped to the verification of each requirement. Each model and/or simulation should specify the environments that are modeled and the assumptions.

The M&S plan should specify the simulation scenarios that are needed to encompass both nominal and worst case extremes of established missions and align with the Concept of Operations (CONOPS).

- Methods, algorithms, tools and techniques
- Environments modeled, assumptions
- Simulation scenarios including target and/or threat modeling

3.4.3.1.1.4 Performance Metrics

The key Technical Performance Metrics (TPMs) should be established and updated during each phase of the program. Predictions for each TPM will be updated as the M&S efforts mature and when test data is integrated into performance predictions.

3.4.3.1.2 Preliminary Design Review (PDR)

System PDR is the culmination of a series of subsystem and component PDRs that are conducted to ensure that the program can proceed into detailed design and meet the stated technical performance requirements within cost and schedule constraints.

M&S should be used at design reviews to demonstrate that the system (segment, element, or component) performance satisfies the designated performance requirements. The detail in M&S will vary as the program progresses with further detail later in the program allowing for the reduction of margin.

At PDR, M&S should provide preliminary results of each model and simulation demonstrating larger performance margins to account for the lack of model details.

Examples of M&S products at PDR are:

- Initial simulation results for mission performance including mission level requirements analysis and CONOPS verification
- Initial simulation results for payload performance including collection capacity and sensitivity
- Initial simulation results for each attitude control mode
- Initial simulation results for power generation and distribution
- Initial simulation and modeling results for structural dynamics
- Initial simulation results of satellite thermal control
- Initial analysis results of communications link budgets

3.4.3.1.3 Critical Design Review

System CDR is the culmination of a series of subsystem and component CDRs that are conducted when detailed design is complete. The objective is to ensure that the detailed design can proceed into integration and meet the stated technical performance specifications within cost and schedule constraints.

M&S should be used at CDR to demonstrate how the final as-designed system (segment, element, or component) performance satisfies the designated performance requirements. The detail in M&S should account for how the system will perform on-orbit and demonstrate margin against each requirement. Examples of M&S products at CDR are:

- Detailed simulation results for mission performance (i.e., coverage and revisit)
- Detailed simulation results for payload mission (i.e., collection capacity)
- Detailed simulation results for each attitude control mode

- Detailed power energy balance
- Detailed simulation and modeling results for structural dynamics (i.e., NASTRAN)
- Detailed simulation results of satellite thermal control (i.e., TRASYS, SINDA)
- Detailed analysis results of communications link budgets

3.4.3.1.4 Integration Readiness Review (IRR)

IRR is conducted to ensure readiness to build the system before commencing manufacture of a unit. The IRR reviews results of qualification testing and plans for testing remaining requirements to determine readiness to proceed with integration and test activities.

M&S should be used at IRR to demonstrate how the system (segment or element) performance satisfies the designated performance requirements. The detail in M&S should account for component level test results and performance capability.

3.4.3.1.5 Pre-Environmental Test Readiness Review (TRR)

TRRs are technical reviews designed to ensure that the system is ready to proceed into formal test. The TRR assesses test objectives, test methods and procedures, scope of tests, and confirms that required test resources have been properly identified and coordinated to support the tests. It is conducted for each environmental test to determine whether the test procedures are complete and to ensure that the program is prepared for testing. Test procedures are evaluated for compliance with respective test plans and descriptions, and for adequacy in accomplishing test requirements. Typically, there are a series of TRRs prior to each environment, i.e., EMI/EMC, dynamics, thermal vacuum, etc.

M&S should be used at TRR to demonstrate how the as-built System performance satisfies the designated performance requirements. The detail in M&S should account for space vehicle functional test results. Examples of M&S products at TRR are:

- Hardware-in-the-loop simulation results for each mission mode
- Final simulation results for mission performance scenarios
- Final simulation results of satellite thermal control
- Final simulation and modeling results for structural dynamics
- Final analysis results of communications link budgets

3.4.3.1.6 Pre-Ship Readiness Review (PSRR)

The purpose of PSRR is to receive authorization to ship the satellite to the launch site for final launch processing. The PSRR evaluates the status of the launch vehicle, launch operations procedures, and launch facility readiness. Any deficiencies should be corrected and disposed of before the Flight Readiness Review.

M&S should be used at PSRR to demonstrate how the as-tested system satisfies the designated performance requirements. The detail in M&S should correlate with environmental test results for on-orbit performance prediction. Examples of M&S products at PSRR are:

- Hardware-in-the-loop simulation results for each mission mode
- Final simulation results for mission performance scenarios
- Correlation of satellite thermal control model with thermal vacuum test
  - On-orbit prediction simulation results

- Correlation of structural dynamics model with structural dynamics tests (i.e., acoustics, random vibration)
- Correlation of communications link budgets with compatibility test(s)

3.4.3.1.7 On-orbit Verification

The program shall conduct a System Verification Review to demonstrate successful verification of all program requirements via on-orbit testing. M&S may be used during on-orbit check-out to demonstrate how the on-orbit System performance satisfies the designated performance requirements. The detail in M&S should be correlated with on-orbit data to account for variations in System performance.

3.4.3.2 The Association of M&S with Gated Events and Work Products (WPs)

At this point, the eight selected WPs, noted above are discussed. TOR-2009(8583)-8584 defines the development schedule of about 100 specific WP items that go through the phases of Created (C), Updated (U), Baselined (B), Revised (R), and Finalized (F) during the program life cycle. This subset of all the WP items was determined through a sort to group all the WP items with similar development schedules, as shown in Table 3. From this list, the eight selected WPs were extracted which are thought to be significantly impacted by the M&S characteristics described above, and which were representative of perhaps several WP items from the same groupings.

Table 3. TOR Work Products Grouped By Their Development Schedules

Work Product	SRR	PDR	CDR	IRR	PSRR
Analysis and Simulation Plan (ASP)	C	U	B	F	F
Requirements Verification Plan	C	U	B	R	F
Reliability Analysis	C	U	B	R	F
Worst Case Analysis	C	U	B	R	F
Algorithm Development Plan	C	U	U	B	F
Error Budget and Allocation Plan	C	U	U	B	F
Concept of Operations	C	U	B	R	F
Technical Performance Metrics Plan	C	U	U	B	F

4. Planning

4.1 Generalized Process for Implementing Modeling and Simulation

Figure 5 displays one approach to executing a modeling and simulation development effort or process to address an M&S intended use. This, or a similar[‡‡] process, should be executed to address each identified M&S intended use using the approach illustrated in Table 2. The Figure 5 process consists of six basic activities:

1. Defining the intended use
2. Conceptual modeling
3. Logical/algorithmic modeling, including environments and scenarios
4. Development of computational models/tools
5. Execution of verification, validation and accreditation procedure
6. Use of the resulting models and simulations in analysis

The end products are:

- Models and/or simulations for use in establishing requirements and specifications

- Checking the ability of design alternatives to meet requirements and specifications and in establishing the behavior and characteristics of systems, subsystems and components

This process is discussed in greater detail in Appendix E.1.

4.2 Defining the Intended Use

As in any engineering process, the actual execution of the process steps is highly iterative and interactive. This process is started by identifying the intended use to be worked including what decisions will be addressed, the purpose to be served in developing a solution, the identifiable alternatives and the evaluation metrics that will be used. This activity is listed as the Intended Use Definition part of the general process depicted in Figure 5. For further details see Table 2 and Appendix E.1.1; the characteristics of a good intended use statement are also described in Appendix H. The importance of this step cannot be overstated and yet many times the formal execution of this step is skipped completely, or the process is short-cut in favor of moving on towards a solution. However, the proposed solutions will always reflect the problem definition with which they are associated. Proposed solutions for an incorrect or incomplete intended use definition, no matter how good, will never fully satisfy the customer's intended requirements. For example, in the effort to develop a new satellite, this step first entails defining a viable mission against which a variety of feasible solutions can be proposed. Many possible missions can be screened out at this phase through a rich knowledge of past similar endeavors and the use of some simple parametric studies (essentially, "back of the envelope" analyses)[31,43,99]. Therefore, [**R14**] it is recommended that a substantial effort be placed in the intended use definition activity.

[‡‡]See references 22, 23, 71, 83, 90, 94, 101, 109, and 116 in Section 6.

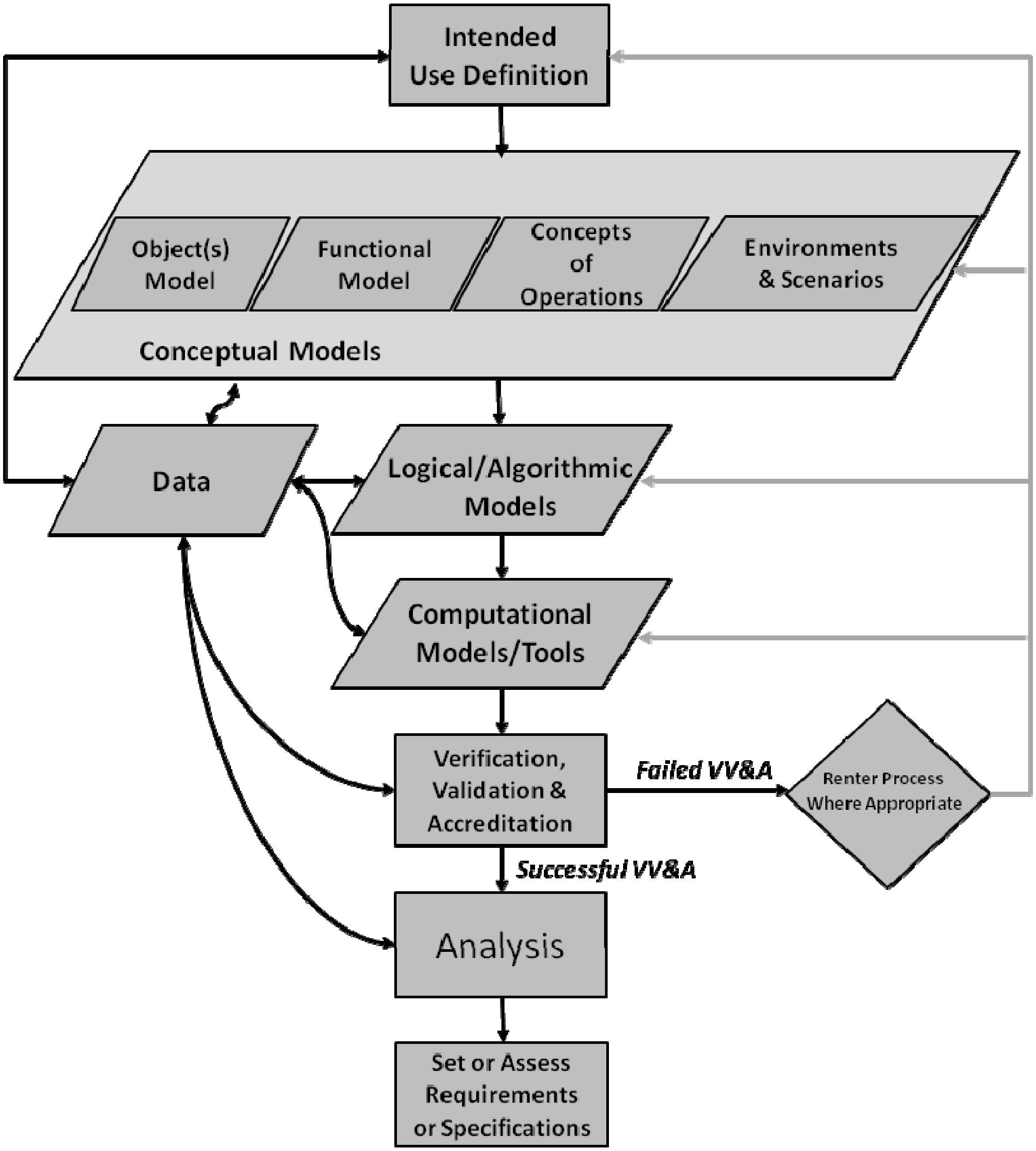


Figure 5. A generalized example of a modeling and simulation process.[19,20]

4.3 Conceptual/Functional Models

As this activity matures, the next step involves looking at how one or a set of possible solutions (i.e., alternative system, subsystems, and components combinations) can be used to deliver a desired effect, capability, or function. It also involves examining what functions or tasks can deliver the desired effect or capability as well as allocating notional objects and interfaces to the identified alternative sets of functions or tasks. This step is displayed in Figure 5 as the Conceptual Models activity. It also involves the organization of objects and functions into a Concept(s) of Operations to define how the modeled systems and interfacing external systems will be used and operated. Similarly, the conditions under which the operation of the notional system or systems is envisioned are captured as models of the applicable environments and scenarios. As the Conceptual Modeling activity progresses, the decision metrics identified in the Intended Use Definition step are used to determine which properties of the conceptual models can be used to mathematically calculate the values of the decision metrics (utility, effectiveness, performance, etc.). For further details see Appendix E.1.2.

4.4 Logical/Algorithmic Models

In the instances where alternative tasks or functions can be executed by the conceptual model(s), logical modeling is also done (i.e., "if variable x > 1, then transmit, otherwise do not transmit). Mathematical models are also generated to determine the value of the identified utility, effectiveness and performance metrics as a function of the properties, and interactions between the conceptual models objects and functions. This work is captured as the Logical/Algorithmic Models activity in Figure 5. It should also be noted that the focus here is only on modeling those characteristics which significantly affect the calculation of the higher level decision metrics. It should also be pointed out that the models developed in this phase represent the system or part of the system that needs to be understood and accessed in finding a satisfactory resolution to the designated intended use. For further details see Appendix E.1.3 – E.1.5.

4.5 Data and Computational Models/Tools

Concurrent with the modeling activities is the selection and development of the Data (including the information which defines the initial system states, the environments and the applicable scenarios) that the models will be evaluated against. This activity should address:

- How the potential solution system, subsystem, or component will be affected by external entities
- How it is intended to be used
- The range of values of the external input variables identified in the modeling activities

The Computational Models/Tools activity centers on assessing the means for capturing and manipulating the models developed in the modeling activities (i.e., back of the envelope calculations, spreadsheets, software based calculations, simulations, and testbeds).

4.6 Environments and Scenarios

The conditions, states, and inputs external to the model (or simulation) which affect the states or behavior of the model of interest constitute the environment (or environments). Scenarios go a step further, and beyond, and consist of the changes in states and the actions of entities and systems within the environment that have occurred in time and lead up to the point in time when the model or simulation is initialized. Both the environments and scenarios used in M&S must be developed as additional models. For further details see Appendix E.1.5.

4.7 Notional Model Lifecycle

Models have a lifecycle much like all the other products within an M&S or programmatic effort[65,66]. The following figure (Figure 6) is intended to notionally introduce the idea of a model lifecycle. A typical model lifecycle begins with an intended use; this might be an identified programmatic need or an identified capability that can solve a problem of interest. The intended use is basically a statement of what the M&S is expected to do (or not do). More details about how the intended use should be documented are given in Appendix H.

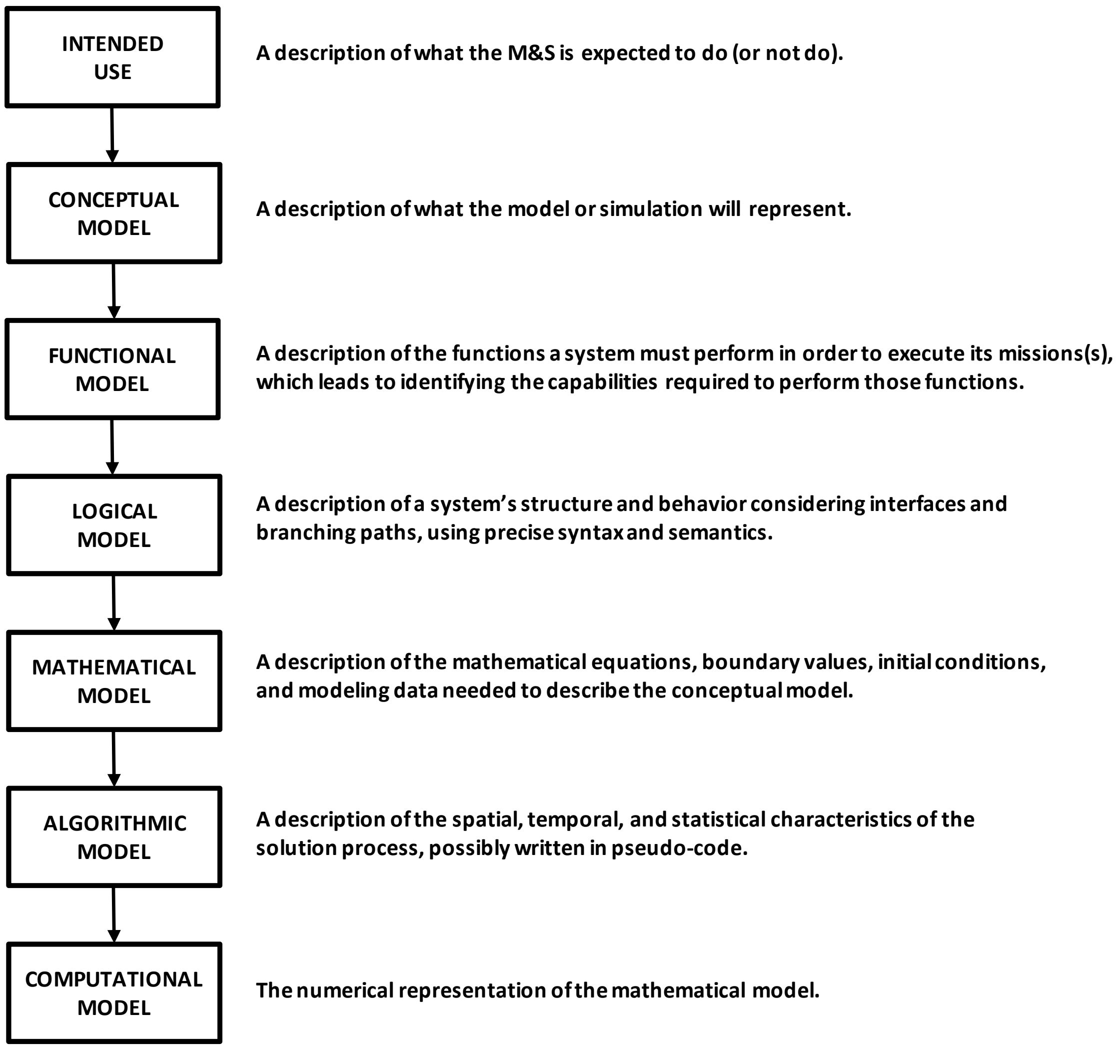


Figure 6. A notional model lifecycle.

From the intended use, a conceptual model might arise that presents a very high level vision of what the M&S should represent. From the conceptual model, a functional model might follow. The functional model builds upon the conceptual model to identify specific functions that are required to meet the intended use and identifies specific capabilities that might achieve those functional needs; there will usually be more than one capability that could satisfy a given function need, so some choices need to be made beginning at this point and the rationale for any choices made should be documented. The logical model begins to detail specific actions, and the decision paths through M&S interfaces leading to those actions, that will accomplish the functional needs; the logical model employs accepted logical constructs (looping and branching expressions) and syntax (possibly, pseudo-code, or non-specific computer language syntax).

The mathematical model specifies the mathematical constructs, usually a set of equations that will be employed to implement the solution; there may again be several choices (different levels of mathematical fidelity) that can be used to solve the problem and the rationale for choices made should be documented. The algorithmic model describes the developer's plan to implement the mathematical model for the intended use to satisfy the functional needs; this begins to fill in the details within the logical model branches, modules and interfaces; the logical model is likely written in some form of pseudo-code or as a flow chart illustration. Again, there may be several choices for the algorithm that may be used, each of which may result in different spatial, temporal, or statistical approximations. Finally, the algorithmic model is implemented in a specific computer programming language (e.g., C, C++, Matlab, Fortran, etc.) for execution on one or more chosen computer systems.

4.8 Verification, Validation and Accreditation (VV&A)

Success, completion, and usefulness are determined for the products of the proceeding activities in the VV&A processes. Verification is the process of checking to ensure that the models accurately represent the underlying mathematical model and its solution from the perspective of its intended use. Validation is the process of checking to ensure that the resulting models and simulations accurately reflect how the actual systems, subsystems, and/or components will behave and perform in the defined environments and scenarios. Validation measures the degree to which outcomes of the M&S agree with outcomes of physical experiments or observations. Validation is accomplished only at a finite number of experimental measurement points. More rigorous validation is achieved through improved characterization of both experimental and simulation uncertainties, and through improved coverage of the domain of interest. Although more detail on this topic is provided in Appendix E.1.6, [**R15**] it is recommended that, as a minimum, the following points about validation should be considered:

- Are experimental flight results available for validation or only computational results (note that many people do not accept as validation the comparison of different computational results)?
- More generally, the type and quality of the referent.
- The sources for uncertainty information about the referent and the M&S.
- What quantities will actually be validated?

Accreditation is gaining official subject matter knowledge body acceptance of the modeling and simulation products. In many cases within the aerospace industry, some form of certification and/or accreditation must be accomplished *before the M&S can be used to generate results for an analysis or design process*. However, if the analysis or design process is not being used to support mission-critical or budget-critical decisions, and especially within NASA, certification and accreditation may not be performed at all. If certification and/or accreditation are to be accomplished in NASA, these activities will normally follow a set of externally-imposed requirements to demonstrate the thoroughness of the documentation, verification, validation, and process control aspects of the program. [**R16**] It is recommended that a risk/benefit analysis be performed to quantify the value of undertaking a formal accreditation program for a given M&S, weighed against the associated cost. Some of the potential benefits include increased credibility of the M&S and demonstrated compliance with industry-accepted best practices; some of the cons to this undertaking include perhaps a substantial increase in the program cost and a significant increase in the length of time that may be needed to generate results. [**R17**] It is recommended that accreditation of M&S be considered, at a minimum, when the M&S meets one or more of the following conditions:

- The M&S is developed by one person and used by another
- The results of M&S are used in mission- or budget-critical decisions
- The M&S itself is a deliverable to the customer
- The M&S is expected to be reused over multiple programs

4.9 M&S Analysis (Implementation of M&S)

The actual use of the resulting models and simulations to assess feasibility, functionality, utility, effectiveness, performance, and cost of notional system, subsystem, and/or component architectures is the Analysis activity. The qualitative and quantitative results of the analysis step provide the basis for defining requirements, specifications, and for estimating or checking the ability of designs and products to meet requirements and specifications. For further details see Appendixes E.1.7.

M&S analysis actually consists of three sub-activities:

1. M&S execution
2. Extracting knowledge from the M&S results
3. Communicating this derived knowledge to decision makers

The first sub-activity involves the execution of an existing, and possibly certified and/or accredited, M&S under the proper conditions and scenarios, and within the prescribed environments, to generate results that will contribute to decisions. Analysts should be meticulous in tracking down and documenting the sources of all warning and error messages that may result from the M&S execution, as well as considering the impacts of such planned contingencies upon the program. The second sub-activity is where a senior analyst draws upon all of their skills and subject matter expertise to ensure that the results produced by the case execution are correct numerically, logically, and physically, and to ensure that relevant physical findings within the results are identified, documented, and suitably justified by whatever means may be needed. In this sub-activity, the analyst should seek to identify and explain any wildly anomalous results that defy logic or known physics, and also attempt to identify situations that could lead to nearly correct, but not actually correct, results and other unplanned and formerly unidentified contingencies. The third sub-activity involves the correct and complete communication of all relevant findings from the second sub-activity to those needing to make decisions on behalf of the program. It is recommended that [**R16**] it be considered the primary functions of the analyst is to identify all relevant physical findings within the M&S results and to convey to the decision makers a complete and unbiased technical assessment of these M&S results, including any known limitations, caveats, questions, or idiosyncrasies about the results. The reader is referred to the guidelines from NASA-STD-7009 for M&S for more on this topic of reporting results to decision makers.

4.10 M&S Tasks, Responsibilities, and Products

In order to adequately plan for program M&S, [**R18**] it is recommended that the following steps be considered as critical:

1. Identify the intended uses for M&S (to the extent currently known and updated as the program progresses). See Section 2.
2. Assign responsibility for each identified intended use to a M&S team lead

3. Have the team lead identify the appropriate team members
4. Define a general M&S process (like the one provided in Figure 5) and assign the resulting tasks (for example “validation”) and work with the team members to define the actual work activities, products, required inputs and needed resources. See Sections 5.1 – 5.5 below.
5. Determine when, to whom, and in what format and medium the results of the M&S activities are required by the program and integrate the M&S plan with the program plan and schedule. See Section 3.
6. Capture, document, communicate, and update each of the intended use sub-plans within the overall program M&S plan. See Section 5 below.

5. Modeling and Simulation Plan, Template and Tailoring

5.1 Planning and Reviews

The M&S activities that should be part of a space system development program need to be documented in an M&S plan. The M&S plan document should include all of the information relating the development and application of M&S throughout the program lifecycle. During development of this document, it is important to distinguish between Modeling (conceptual/mathematical/algorithm development) and Simulation (experimentation using models and data inputs) as they are distinctly different activities requiring different resources.

M&S planning should occur concurrently with the planning of System Engineering activities. For example, M&S planning for verification activities should occur at the same time as planning for the verification activities themselves. Similarly, M&S planning for validation activities should occur during the requirements allocation phase of the program. System engineering planning should integrate M&S into all of its life-cycle activities.

At a minimum, a current version of the M&S Plan should be generated at the beginning of a program and updated for the System Requirements Review. At this time, it should be clear as to how M&S will be used to allocate requirements. At subsequent milestones, the M&S Plan will mature to define how M&S will support definition, verification, and validation efforts. Updates to the M&S Plan should be made as required at each major program review cycle.

M&S planning should involve all stakeholders. This includes developers, analysts, systems engineering, information technology (IT), customers, and program management; the reason for including these groups is fairly obvious except for IT which may need involvement from a computer security stand point.

5.2 Elements of a Generic Plan

IEEE 12207.1[65] describes a plan as a document to define when, how, and by whom specific activities are to be performed, including options and alternatives, as required. The document further states that the elements a plan should include are:

- Date of issue and status
- Scope
- Issuing organization
- References
- Approval authority
- Planned activities and tasks
- Macro references (policies or laws that give rise to the need for this plan)
- Micro references (other plans or task descriptions that elaborate details of this plan)
- Schedules
- Estimates
- Resources and their allocation
- Responsibilities and authority
- Risks
- Quality control measures
- Cost
- Interfaces among parties involved
- Environment/infrastructure, including safety needs
- Training

- Glossary
- Change procedures and history

5.3 M&S Plan Template

A central goal of this document is to provide guidance for the development of a U. S. Space Program Modeling and Simulation Plan. The reader is referred to Appendix B for more detail on the M&S Plan Template. A central goal of this document is to provide guidance for the development of a U. S. Space Program Modeling and Simulation Plan. Software Project Management Plan (IEEE STD 1058-199861, was combined with sample M&S Plans derived from other sources, to yield the recommended template for a program M&S Plan as shown below (Figure 7). More detail is provided in Appendix B; Appendix B includes notes about the expected content of the sections within the proposed M&S Plan template. It is not necessary that all the information identified in the templates from Appendix B actually be contained in the program M&S Plan, but [R19] it is recommended that decisions should be made as to whether the identified information needs to be addressed in the M&S Plan. Also, the extent to which the information needs to be addressed and whether it is placed in the M&S Plan document or simply referenced should be assessed.

The template (Figure 7, with more detail in Appendix B) is provided as a starting point in the development of the program M&S Plan. While the template lists many of the sections commonly found in M&S plans, it is not all inclusive and the user should keep in mind that any M&S plan is only as useful as the thinking, preparation, and organization of information put into its development and employment in guiding M&S activities.

5.4 Tailoring

The core elements of any plan consist of identifying what needs to be done, when, by whom, and to whom the products will be delivered. With this in mind, the reader is urged to either use the provided template in Figure 7 (or any of the number of other relevant templates that are available) as a checklist for assessing what information may be useful in a M&S plan, but also to modify and tailor any template used as extensively as necessary to maximize its utility. Note that this template is a superset of several proposed M&S Plan templates, and is primarily intended to stimulate thinking about the kinds of information that should be documented; the specific form of how this information gets documented (and the decision as to whether it all appears in one document, or is distributed among numerous documents) need to be discussed among the interested parties. The use of tailoring, while useful for one program, should be balanced with the advantages of having a standardized approach within an organization or between cooperative organizations.

As the M&S activities are generally intended to reduce risk within the program, and since developing the M&S Plan is essentially a risk reduction technique within the scope of possible and relevant M&S activities, it makes sense that tailoring of the M&S Plan elements should be done with an eye towards risk evaluation.

It should also be noted that sections 1 through 6 and section 8 of the template encompass the broad overall plan for a program, while section 7 is the plan for an intended use. For instances when more than one or a set of related intended uses will be addressed, a plan may include multiple section 7's (one for each of the identified intended uses).

Template Section	Relevant Process Sections	Annotation in Appendix B
1.0 Executive Summary		pg. 51 (1.0)
2.0 Introduction		pg. 51 (2.0)
2.1 Document Structure		pg. 51 (2.1)
2.2 Terminology/Notations Used in this Document		pg. 52 (2.2)
2.3 Mission	From Program Documents	pg. 52 (2.3)
2.4 Vision	From Program Documents	pg. 52 (2.4)
2.5 Objectives	From Program Documents	pg. 52 (2.5)
2.6 Strategy	Sections 2 and 4	pg. 52 (2.6)
2.7 Program Overview	From Program Documents	pg. 52 (2.7)
2.7.1 System Overview	From Program Documents	pg. 52 (2.7.1)
2.7.2 System-Level Constraints and Limitations	From Program Documents	pg. 52 (2.7.2)
2.7.3 M&S Overview	Section 2	pg. 53 (2.7.3)
2.7.4To-Date List of Decision/Evaluation/Risk Points to be Addressed by M&S (i.e. intended uses)	Section 2.1	pg. 53 (2.7.4)
2.7.5 List of M&S Leadership Assignments/ Responsibilities	Section 3.1	pg. 53 (2.7.5)
3.0 Evolution of the program M&S Plan	Section 5	pg. 53 (3.0)
4.0 Applicable Documents	From Program Documents	pg. 53 (4.0)
5.0. Definitions	Appendix C	pg. 53 (5.0)
6.0 Related Program and M&S Documents	From Program Documents and Section3	pg. 53 (6.0)
6.1 M&S Managerial Process Plans	Section 4	pg. 54 (6.1)
6.1.1 M&S Project Start-Up Plans	Section 4	pg. 54 (6.1.1)
6.1.2 M&S Work Plans	Section 4	pg. 54 (6.1.2)
6.1.3 M&S Controls Plans	Section 4	pg. 54 (6.1.3)
6.1.4 M&S Risk Management Plans	Section 4	pg. 54 (6.1.4)
6.1.5 M&S Project Closeout Plans	Section 4	pg. 54 (6.1.5)
6.2 M&S Technical Plans	Sections 2 and 4	pg. 54 (6.2)
6.2.1 Process Model Description	Sections 2 and 4	pg. 54 (6.2.1)
6.2.2 Methods, Tools and Techniques Descriptions	Sections 2 and 4	pg. 54 (6.2.2)
6.2.3 Infrastructure Plan	Sections 2 and 4	pg. 55 (6.2.3)
6.2.4 Product Acceptance Plan	Sections 2 and 4	pg. 55 (6.2.4)
6.2.5 M&S Integration Plan	Section 3	pg. 55 (6.2.5)
6.2.6 System Integration Plan	Section 3	pg. 55 (6.2.6)
6.3 M&S Supporting Process Plans	Section 4	pg. 55 (6.3)
6.3.1 Configuration Management Plan	Section 4	pg. 55 (6.3.1)
6.3.2 Verification and Validation Plan(s)	Section 4	pg. 55 (6.3.2)

Template Section	Relevant Process Sections	Annotation in Appendix B
6.3.3 Documentation Plan	Section 4	pg. 55 (6.3.3)
6.3.4 Quality Assurance Plan	Section 4	pg. 55 (6.3.4)
6.3.5 Reviews and Audit Plan	Section 4	pg. 55 (6.3.5)
6.3.6 Problem Resolution Plan	Section 4	pg. 56 (6.3.6)
6.3.7 Subcontractor Management Plan	Section 4	pg. 56 (6.3.7)
6.3.8 Process Improvement Plan	Section 4	pg. 56 (6.3.8)
7.0 Modeling and Simulation Specific Plan(s) for Each Identified Decision/Evaluation/Risk Point (i.e., intended use)	Section 2.1	pg. 56 (7.0)
7.1 Specific Problem to be addressed by M&S	Sections 2.1 and 4.2	pg. 56 (7.1)
7.2 Options/Alternaties/Tradespace	Sections 2.2 and 4.1	pg. 56 (7.2)
7.3 M&S Limits, Constraints and Requirements (Objectives and Thresholds)	Sections 2.1 and 2.2	pg. 57 (7.3)
7.4 Expected Return on Investment and Risk Reduction	Sections 2, 5, and 4.10	pg. 57 (7.4)
7.5 Conceptual Logical/Algorithmic Models	Sections 4.3 and 4.4	pg. 57 (7.5)
7.6 Environments and Scenarios	Section 4.6	pg. 57 (7.6)
7.7 Computational Models and Tools	Section 4.5	pg. 57 (7.7)
7.8 Verification and Validation Approaches	Section 4.8	pg. 57 (7.8)
7.9 M&S Products	Section 4.9	pg. 57 (7.9)
7.10 Delivery Schedule and Dependent Activities	Section 3 and 4	pg. 57 (7.10)
7.11 Activities, Resources and Assignments	Section 4	pg. 58 (7.11)
7.12 Certification and Accreditation Plan	Section 4.8	pg. 58 (7.12)
7. 13 M&S Report List	Section 3.4.3	pg. 58 (7.13)
8.0 Plan Annexes		pg. 58 (8.0)
8.1 Bibliography		pg. 58 (8.1)
8.2 Acronym List		pg. 58 (8.2)
8.3 Glossary		pg. 58 (8.3)

Figure 7. Generic M&S plan template.

6. References

1 A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report. B2005-100968, January 30, 2004 [URL: http://www.nasa.gov/pdf/55691main_Diaz_020204.pdf].

2 Aerospace Corporation Report Number TOR-2009(8583)-8545, The Aerospace Corporation, May 9, 2008.

3 Aerospace Corporation Report Number TOR-2009(TBD)-TBD Testbeds and Simulators, The Aerospace Corporation, (TBD).

4 Air Force Instruction 16-1002, "Modeling and Simulation (M&S) Support to Acquisition," June 1, 2000.

5 Air Force Policy Directive 16-10, "Modeling and Simulation (M&S) Management," January 30, 1995.

6 Anderson, M. J., and Whitcomb, P. J., "DOE Simplified: Practical Tools for Effective Experimentation" Productivity Press, ISBN: J-56327-225-3, Alk. Paper, 231 pages. Published May 2000, copyright 2000, Productivity, Inc.

7 Anderson, M. J., and Whitcomb, P. J., "RSM Simplified: Optimizing Processes Using Response Surface Methods for Design of Experiments" ISBN: 1-56327-297-0, 292 pages Published November 2004, Copyright 2005, Productivity, Inc. Chudoba, B., Coleman, G., Huang, X., and Czysz, P.A., "Conceptual Design Assessment of a Suborbital Tourist Space Access Vehicle," No. 1135, Vol. 112, The Aeronautical Journal, September 2008.

8 Army Regulation 5–11, "Management of Army Models and Simulations," Department of the Army, Washington, DC, February 2005.

9 "ASAP Recommendations, Second Quarter 2010," Minutes from the April 30, 2010 NASA Aerospace Safety Advisory Panel (ASAP) public meeting, National Aeronautics and Space Administration, National Aeronautics and Space Administration, Washington, DC, May 2010.

10 ASME B89.7.3.1-2001, "Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications." American Society of Mechanical Engineers, ASME International, 2001.

11 ASME PTC 19.1-2005 (Revision of ASME PTC 19.1-1998) Test Uncertainty ASME PTC 19.1-2005 (Revision of ASME PTC 19.1-1998) Copyright ASME International Provided by IHS under license with ASME Licensee=NASA Technical Standards 4/9972545004, User=Green, Evelyn No reproduction or networking permitted without license from IHS Not for Resale, 09/07/2007 05:57:23 MDT.

12 ATEC Pamphlet 73-21, Test and Evaluation Modeling and Simulation Verification, Validation, and Accreditation Methodology," ATEC Pamphlet 73-21 Headquarters U.S. Army Test and Evaluation Command Alexandria, VA. April 2007.

13 Balci, O. and Nance, R.E., "Formulated Problem Verification as an Explicit Requirement of Model Credibility" Simulation, Vol. 45 (2), pp. 76-86, 1985.

14 Balci, O.: “Quality Assessment, Verification, and Validation of Modeling and Simulation Applications.” Proceedings of the 2004 Winter Simulation Conference. ed. by Ingalls, R.G.; Rossetti, M.D.; Smith, J.S.; Peters, B.A., pp. 122–129, Dec. 5-8, 2004, IEEE: Piscataway, NJ.

15 Balci, Osman: “Verification, Validation and Testing,” Handbook of Simulation, Chapter 10, ISBN 0-471-13403-1, Chapter 10, pp. 335-393, John Wiley & Sons, 1998.

16 Balci, Osman: “Verification, Validation, and Certification of Modeling and Simulation Applications,” Proceedings of the 2003 Winter Simulation Conference, S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, eds., pages 150 – 158, 2003.

17 Balci, Osman; Ormsby, William F.: “Quality Assessment of Modeling and Simulation of Network-Centric Military Systems,” presented at the Symposium on Modeling and Simulation Tool for Emerging Telecommunications Networks: Needs, Trends, Challenges, Solutions. September 8-9, 2005 Munich, Germany.

18 Balci, Osman; Saadi, Said D.: “Proposed Standard Processes for Certification of Modeling and Simulation Applications,” Proceedings of the 2002 Winter Simulation Conference, E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds., pages 1621 – 1627, 2002.

19 Baxter, M. J., “Techniques for Implementing an Efficient and Effective System of Systems Simulation Capability,” 2004 IEEE Aerospace Conference, 8 March 2004, IEEE paper no. 1075.]

20 Baxter, M.J., “A Methodology for Modeling, Simulation, and Analysis Support of DoD Space Acquisitions,” 2005 IEEE Aerospace Conference, 10 March 2005, IEEE paper no. 1043.

21 Blattnig, S.R.; Green, L.L.; Luckring, J.M.; Morrison, J.H.; Tripathi, R.K.; Zang, T.A.: “Towards a Credibility Assessment of Models and Simulations.” AIAA-2008-2156, 2008.

22 Brooks, R. J. and Tobias, A.M., “A Framework for Choosing the Best Model Structure in Mathematical and Computer Modeling.” Proceedings of the 6th Annual Conference AI, Simulation, and Planning in High Autonomy Systems. University of Arizona, pp. 53-60, 1996b.

23 Brooks, R. J. and Tobias, A.M., “Choosing the Best Model: Level of Detail, Complexity and Model Performance” Mathematical and Computer Modeling, Vol. 24 (4), pp. 1-14, 1996a.

24 Carnahan, B., Luther, H. A., and Wilkes, J. O., “Applied Numerical Methods,” John Wiley & Sons Publishing, New York NY, 1976.

25 Chairman of the Joint Chiefs of Staff Instruction 3170.01, “Joint Capabilities Integration and Development System,” May 1, 2007.

26 "Characteristics of good requirements,” http://en.wikipedia.org/wiki/Requirement#Characteristics_of_good_requirements, accessed June 7, 2010.

27 Code of Best Practice for C2 Assessment Decisionmaker's Guide NATO Research and Technology Organisation (RTO) sponsored Research Group (SAS-026), reprinted by the Command and Control Research Program (CCRP) under the auspices of the Assistant Secretary of Defense (C3I), 2002.

28 Columbia Accident Investigation Board Report. Vol. 1, August 2003 [URL: http://caib.nasa.gov/].

29 Cook, David, A.; Skinner, James M.: "How to Perform Credible Verification, Validation, and Accreditation for Modeling and Simulation," The Journal of Defense Software Engineering, pages 20 – 24, May 2005.

30 Cowdale, Alan, "Real World Data Collection for Model Validation." Proceedings of the 2009 Winter Simulation Conference M. D. Rossetti, R. R. Hill, B. Johansson, A. Dunkin and R. G. Ingalls, eds.

31 Czysz, P.A., Chudoba, B. and Rahaim, C., "A Hypersonic Aircraft Launch System Capable of Global and Space Access," ISABE Paper, ISABE-2009-1137, 19th ISABE Conference, Montreal, Canada, 7-11 September 2009.

32 DeLoach, Richard: "Analysis of Variance in the Modern Design of Experiments," AIAA 2010-1111, presented at the 48th AIAA Aerospace Sciences Meeting, 4 - 7 January 2010, Orlando, Florida.

33 DoD 5000.59-P, "Modeling and Simulation (M&S) Master Plan," Under Secretary of Defense for Acquisition Technology, October 1995.

34 DoD Directive 5000.01, "The Defense Acquisition System," May 12, 2003.

35 DoD Instruction 5000.2, "Operation of the Defense Acquisition System," December 8, 2008.

36 DoD Instruction 5000.59, "DoD Modeling and Simulation (M&S) Management," August 8, 2007.

37 DoD Instruction 5000.61, "DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A)," December 9, 2009.

38 DoD Modeling and Simulation Glossary, DOD 5000.59-M, Under Secretary of Defense for Acquisition Technology, January 1998.

39 Duncan, J., "The Really Easy Statistics Site (TRESS)" http://helios.bto.ed.ac.uk/bto/statistics/tress1.html#THE%20REALLY%20EASY%20STATISTICS%20SITE.

40 Fasanella, E.L.; Jackson, K.E.; Lyle, K.H.; Jones, L.E.; Hardy, R.C.; Spellman, R.L.; Carney, K.S.; Melis, M.E.; Stockwell, A.E.: "Dynamic Impact Tolerance of Shuttle RCC Leading Edge Panels Using LS-DYNA." AIAA-2005-3631, 2005.

41 Federal Acquisition Regulation Part 12, "Acquisition of Commercial Items."

42 Ferson, S. and T.F. Long: “Deconvolution can reduce uncertainty in risk analyses. Risk Assessment: Measurement and Logic,” M. Newman and C. Strojan (eds.), Ann Arbor Press, 1997.

43 Ferson, S: “Using approximate deconvolution to estimate cleanup targets in probabilistic risk analyses,” pages 239–248 in Hydrocarbon Contaminated Soils, P. Kostecki (ed). Amherst Scientific Press, Amherst, Massachusetts, 1995.

44 Ferson, Scott; Kreinovich, Vladik; Hajagos, Janos; Oberkampf, William; Ginzburg, Lev: “Experimental Uncertainty Estimation and Statistics for Data Having Interval Uncertainty,” SANDIA REPORT, SAND2007-0939, May 2007.

45 FIPS PUB 200, “Minimum Security Requirements for Federal Information and Information Systems,” L Information Processing Standards Publication, Computer Security Division, Information Technology Laboratory, National Institute of Standards and Technology, March 2006. [Green71

46 Fisher, R. A., “Statistical Methods for Research Workers,” ISBN 0050021702, Oliver and Boyd, Edinburgh England, 1925.

47 Fogg, B.J.; Tseng, H.: “The Elements of Computer Credibility.” Proceedings of CHI 99, pp. 80–87, ACM: New York, 1999.

48 GIANNOULIS, Constantinos, “Common Validation, Verification and Accreditation Framework for Simulation REVVA 2 Recommended Practice Guide,” EUROPA 111-104, EUROPA 111-104 Management Group REVVA2 Consortium.

49 Green, L.L., “Uncertainty Analysis of Historical Hurricane Data,” AIAA Paper 2007-1101, Reno, Nevada, January 2007.

50 Green, L.L.; Blattnig, S.R.; Luckring, J.M.; Tripathi, R.: “An Uncertainty Structure Matrix for Models and Simulations.” AIAA-2008-2154, 2008.

51 Gross, David C.: “Report from the Fidelity Implementation Study Group,” The Boeing Company, Huntsville, AL

52 Guide for Verification and Validation in Computational Solid Mechanics.” ASME V&V 10, ASME. New York, NY, 2006.

53 Guide for Verification and Validation of Computational Fluid Dynamics Simulation.” AIAA G-077, AIAA: Reston, VA, 1998.

54 Hale, J.P.; Hartway, B.L.; Thomas, D.A.: “A Common M&S Credibility Criteria-set Supports Multiple Problem Domains.” The 5th Joint Army-Navy-NASA-Air Force (JANNAF) Modeling and Simulation Subcommittee Meeting, CDJSC 49, May 2007, Johns Hopkins University: Columbia, MD.

55 Hall, Dave; Simecka, Karl; Terry, Ray: “What Makes A Simulation Credible? A Cost Effective Approach to Model and Simulation VV&A,” SURVICE Engineering Company, www.survice.com.

56 Harmon, S.Y.; Youngblood, S.M.: “A proposed model for simulation validation process maturity.” J. Defense Modeling & Simulation, vol. 2, no. 4, pp. 179–190, 2005. [Green33

57 Hemsch, M. J., “Statistical Analysis of CFD Solutions from the Drag Prediction Workshop,” AIAA Paper 2002-0842, 2002.

58 Hemsch, M. J.; Morrison, J. H., “Statistical Analysis of CFD Solutions from 2nd Drag Prediction Workshop,” AIAA Paper 2004-0556, 2004. [

59 Hooks, Ivy F.; Farry, Kristin A.: Customer-Centered Products, ISBN 0-8144-0568-1, Amacon American Management Association, New York, NY, 2001.

60 Houston, Dan; Keats, J. Bert: “The Cost of Software Quality: A Means of Promoting Software Process Improvement.”

61 IEEE Std 1058-1998, “IEEE Standard for Software Project Management Plans,” The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1998. [Green53

62 IEEE Std 1220-2005, “IEEE Standard for Application and Management of the Systems Engineering Process,” The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2005.

63 IEEE Std 610.12-1990(R2002), “IEEE Standard Glossary of Software Engineering Terminology,” The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2002.

64 IEEE Std 610.3-1989, “IEEE Standard Glossary of Modeling and Simulation Terminology, The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1989.

65 IEEE/IEA Guide Industry Implementation of International Standard ISO/IEC 12207: 1995 (ISO/IEC 12207) Standard for Information Technology – Software Life cycle processes – life cycle data,” IEEE/EIA 12207.1-1997, The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1996.

66 IEEE/IEA Standard Industry Implementation of International Standard ISO/IEC 12207: 1995 (ISO/IEC 12207) Standard for Information Technology – Software Life cycle processes,” IEEE/EIA 12207.0-1996, The Institute of Electrical and Electronics Engineers, Inc. New York, NY, 1996.

67 Intelligence Community Directive 105, “Acquisition,” August 15, 2006.

68 Intelligence Community Policy Guidance 105.1, “Acquisition,” July 12, 2007.

69 Johnson, R., “Elementary Statistics (7th Edition),” Duxbury Press/Wadsworth Publishing Company, Cincinnati, OH, 1996.

70 Kilikauskas, Michelle L.; Hall, David H.: “THE USE OF M&S VV&A AS A RISK MITIGATION STRATEGY IN DEFENSE ACQUISITION,” An Invited Paper for Foundations ’04: A Workshop for VV&A in the 21st Century Held at Arizona State University Tempe, Arizona (USA) October, 2004.

71 Law, A. M., “Simulation Model’s Level of Detail Determines Effectiveness” Industrial Engineering, Vol. 23 (10), pp. 16–18, 1991.

72 Law, A. M. and Kelton, W. D., Simulation Modeling and Analysis, 3rd ed. McGraw-Hill, New York. 2000.

73 Lin, J.; West, J. S.; Williams, R. W.; Tucker, P.K.: “CFD Code Validation of Wall Heat for a GO2/GH2 Single Element Combustor.” AIAA-2005-4524, 2005.

74 Mahadevan, Sankaran: “Uncertainty Quantification and Propagation using Variable Fidelity Multidisciplinary and Probabilistic Analyses,” Quarterly progress report submitted to NASA Langley Research Center from Vanderbilt University for Grant/Cooperative Agreement Number: NNX08AF56A S01, April 2010.

75 Mehta, U.B.: “Simulation Credibility Level.” The 5th Joint Army-Navy-NASA-Air Force (JANNAF) Modeling and Simulation Subcommittee Meeting, CDJSC 49, May 2007, Columbia, MD: Johns Hopkins University.

76 Mehta, U.B.: Guide to Credible Computer Simulations of Fluid Flows. J. Prop & Power, vol. 12, no. 5, pp. 940–948, 1996.

77 Miller, G.A.: “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information.” Psychological Rev., vol. 63, pp. 81–97, 1956.

78 Modeling and Simulation Verification, Validation, and Accreditation Implementation Handbook Volume I VV&A Framework, Department of the Navy, March 2004 Prepared by: Navy Modeling and Simulation Management Office, 2004.

79 Modeling and Simulation Verification, Validation, and Accreditation Implementation Handbook Volume I VV&A Framework,” Department of the Navy Navy Modeling and Simulation, March 2004.

80 Morris, W. T., On the Art of Modeling” Management Science, Vol. 13 (12), pp. B707-717, 1967.

81 Morrison, J. H.; Hemsch, M. J., “Statistical Analysis of CFD Solutions from the Third AIAA Drag Prediction Workshop,” AIAA Paper 2007-0254, 2007.

82 Muessig, Paul R.; Laack, Dennis R.; Wrobleski, John J.: “An Integrated Approach to Evaluating Simulation Credibility,” Naval Air Warfare Center, Weapons Division (Code 418000D).

83 Musselman, K. J., Conducting a Successful Simulation Project.” Proceedings of the 1992 Winter Simulation Conference (Swain, J.J., Goldsman, D., Crain, R.C. and Wilson, J. R., eds.) IEEE, Piscataway, NJ, pp. 115-121, 1992.

84 NASA Software Engineering Requirements, NASA Procedural Requirements NPR 7150.2A, Office of the Chief Engineer, NASA Headquarters, Washington DC, November 2009.

85 "NASA Systems Engineering Processes and Requirements," NASA Procedural Requirements NPR 7123.1A, Office of the Chief Engineer, NASA Headquarters, Washington DC, March 2007.

86 National Security Space Acquisition Policy 03-01, "Guidance for DoD Space System Acquisition Process," December 27, 2004.

87 NIST IR 7298, "Glossary of Key Information Security Terms," Richard Kissel, editor, April 2006.

88 NIST Special Publication 800-53 Revision 3, Recommended Security Controls for Federal Information Systems and Organizations Information Security," Joint Task Force Transformation Initiative, Computer Security Division, Information Technology Laboratory, National Institute of Standards and Technology, August 2009.

89 Oberkampf, W.L.; Pilch, M.; Trucano, T.G.: "Predictive Capability Maturity Model for Computational Modeling and Simulation." SAND2007-5948, Sandia National Laboratories, 2007.

90 Pace, D. K., "Development and Documentation of a Simulation Conceptual Model." Proceedings of the 1999 Fall Simulation Interoperability Workshop, 1999.

91 Pace, Dale K.: "Modeling and Simulation Verification and Validation Challenges," Johns Hopkins APL Technical Digest, Volume 25, Number 2 (2004), pages 163–172.

92 Pidd M., "Just Modeling Through: A Rough Guide to Modeling" Interfaces, Vol. 29 (2), pp. 118–132., 1999.

93 Pilch, M.; Trucano, T.G.; Peercy, D.E.; Hodges, A.L.; Froehlich, G.K.: "Concepts for Stockpile Computing." SAND2004-2479, Sandia National Laboratories, 2004 (Official Use Only document, not available electronically).

94 Pritsker, A.A.B., "Principles of Simulation Modeling." Handbook of Simulation (Banks, J., ed.), Wiley, New York, pp. 31–51, 1998.

95 Project Management Tips," http://pmtips.net/characteristics-good-requirement/, accessed June 7, 2010.

96 Return to Flight Task Group, Return to Flight Task Group Final Report, U.S. Government Printing Office, August 2005 [URL: http://returntoflight.org/assets/pdf/final_rtftg_report/RTF_TG_Final_Report_Lo-Res.pdf, July 2005.

97 Ridgeway, Debra; Dymond, Peggy: "Future Combat System Spinout1 Technical Field Test (FCS SO1 FT) Establishing and Implementing Modeling and Simulation (M&S) System of System (SoS) Verification, Validation and Accreditation (VV&A) Practices, Methodologies and Procedures," PEO I Case 09-9156, presented at the 2010 ITEA LVC Conference, November 2009.

98 Roache, Patrick J.: Verification and Validation in Computational Science and Engineering, ISBN 0-913478-08-3, Hermosa Publishers, Albuquerque, NM, 1998.

99 Roberts, K., Mixon, B., Chudoba, B., Huang, X., “A Unique Conceptual Design Approach: Generic Design Space Screening and Convergence of Hypersonic Vehicles,” AIAA Paper, AIAA-2006-1241, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 9–12 January 2006.Ferson, S., V. Kreinovich, and W.T. Tucker: “Untangling equations involving uncertainty: deconvolutions, updates, and backcalculations,” NSF workshop on Reliable Engineering Computing, Savannah, Georgia., 2004. http://www.gtsav.gatech.edu/workshop/rec04/presentations/Fearson.ppt[Green84

100 Robinson, Stewart; “Simulation Model Verification and Validation: Increasing the Users’ Confidence,” Proceedings of the 1997 Winter Simulation Conference, ed. S. Andradóttir, K. J. Healy, D. H. Withers, and B. L. Nelson, pages 53–59, 1997.

101 Robinson, S., “Simulation Projects: Building the Right Conceptual Model” Industrial Engineering, Vol. 26 (9), pp. 34–36, 1994.

102 Robinson, S., “Simulation: The Practice of Model Development and Use,” Wiley, Chichester, UK 2004.

103 Shannon, R.E., Systems Simulation: The Art and Science, Prentice-Hall, Englewood Cliffs, NJ 1975.

104 Simpkins , Scott D.; Paulo, Eugene P.; Whitaker , Lyn R.: “Case Study in Modeling and Simulation Validation Methodology,” Proceedings of the 2001 Winter Simulation Conference, B. A. Peters, J. S. Smith, D. J. Medeiros, and M. W. Rohrer, eds., 2001.

105 “Standard CMMI Appraisal Method for Process Improvement (SCAMPISM) A, Version 1.2: Method Definition Document.” CMU/SEI-2006-HB-002. Software Engineering Institute. 2006. http://www.sei.cmu.edu/library/abstracts/reports/06hb002.cfm. Retrieved 23 September 2006.

106 Standard for Models and Simulations, NASA-STD-(I)-7009, Dec. 1, 2006.

107 Standard for Models and Simulations, NASA-STD-7009, July 11, 2008.

108 Stat-Ease, Inc “Design, Analyze, and Optimize with Design-Expert” Analytical Chemistry, 2002 Volume 74, Number 7, Pages 222 A-223 A.

109 Teeuw, W. B. and van den Berg, H., “On the Quality of Conceptual Models.” Proceedings of the ER'97 Workshop on Behavioral Models and Design Transformations: Issues and Opportunities in Conceptual Modeling (S.W. Liddle, ed.). osm7.cs.byu.edu/ER97/workshop4/, 1997.

110 Tseng, S.; Fogg, B. J.: Credibility and computing technology. Comm. ACM, vol. 42, no. 5, pp. 39–44, 1999.

111 USD(AT&L) Memorandum, “Ballistic Missile Defense Program Implementation Guidance,” February 13, 2002.

112 VV&A Recommended Practices Guide, Defense Modeling and Simulation Office. http://vva.dmso.mil/. RPG Build 3.0.

113 Wang, R. Y. and Strong, D.M.: Beyond Accuracy: What Data Quality Means to Data Consumers. J. Mgmt. Info. Systems, vol. 12, no. 4, pp. 5–34, 1966.

114 Webster, D. B., Padgett, M.L., Hines, G.S. and Sirois, D.L., “Determining the Level of Detail in a Simulation Model – a Case Study” Computers and Industrial Engineering, Vol. 8 (3/4), pp. 215-225, 1984.

115 Wertz, J. R. and Larson, W. J., Space Mission Analysis and Design, 3rd ed., Springer London, Limited, London, 1999.

116 Willemain, T. R., “Insights on Modeling from a Dozen Experts” Operations Research, Vol. 42 (2), pp. 213–222, 1994.

117 Youngblood, Simone: “An Approach for Realizing a Risk-Based VV&A (RBA) Methodology,” NSAD-R-2010-020, Enclosure to: NSAD-L-2010-052, JNC04, The Johns Hopkins University Applied Physics Laboratory, March 2010.

118 Zaman, Kias; Mahadevan, Sankaran: “FireSat Uncertainty Quantification using High-fidelity and Low-fidelity Models,” pends publication from Vanderbilt University, Nashville, TN 37235.

119 Rodriquez, E. A., Report LA-14167, “Detailed Model Development, Verification, and Validation Process,” Los Alamos National Laboratory, October 2004.

120 Sargent, R. G., Simulation Model Validation. Simulation and Model-based methodologies: An integrative view, edited by Orn et al., Springer-Verlag, 1984.

Appendix A. Collected Recommended Practices

The following is a list of collected, recommended practices found within this document. The knowledgeable reader will note that this list is quite similar to, but expands upon, the fifteen verification, validation, and testing principles related to M&S, espoused by Dr. Osman Balci[14].

[R1] It is recommended that before a program M&S Plan is actually written, a phase of M&S planning be undertaken.

[R2] It is recommended that the M&S planning phase should allow for a significant amount of thought, discussion, and negotiation among the various stakeholders, participants, and customers, and a consideration of what is feasible, compared to what is desirable.

[**R3**] It is recommended that the purpose of M&S be considered as a means to gain significant, reasonable, or sufficient assurance that an approach or design will be able to meet the customer or user's needs, will function as desired, and will be a preferred approach.

[**R4**] It is recommended that the potential benefits of spending the time and money to produce, maintain, sustain, and use an M&S should always be evaluated against the costs of potentially designing, building, and testing a system, subsystem, or component that fails to function or perform as needed or desired.

[**R5**] It is recommended that Models and Simulations should only be as complicated as necessary to address the concern at hand with the desired fidelity.

[**R6**] It is recommended that at the initial stages of planning, the benefits versus the cost of Modeling and Simulation Efforts should be considered and integrated into the program risk reduction and planning discussions.

[**R7**] It is recommended that in both the planning and execution phases of M&S activities, it is crucial to ensure that the benefits gained in refining and testing a design, identifying an effective approach, reducing the risk, or in establishing requirements are sufficient to justify the cost.

[**R8**] It is recommended that assessment of the benefits versus the costs of conducting, modeling, and simulation should be tied to specific questions to be answered and the activities needed to obtain answers.

[**R9**] It is recommended that successful implementation of M&S in a complex space system program is characterized by use of the four basic elements identified in Table 1 and their implementation.

[**R10**] It is recommended that the M&S management team be considered to have two initial responsibilities: (1) to identify and document those sections of the reference documents (this guidance document included) that are applicable for this M&S effort, and (2) to identify and document the parties responsible for complying with the applicable guidance in this and other reference documents.

[**R11**] It is recommended that the M&S management team should also identify and document the critical decisions to be addressed with M&S and perform, or request, risk assessments to determine which M&S are within the scope of the applicable guidance.

[**R12**] It is recommended that the M&S management team also have the responsibility to identify and document the training requirements for personnel within the program, to identify and document the extent and level of formality of documentation needed to meet the documentation guidance in this and the other reference documents, and to ensure that: (1) risk assessments for any M&S used in critical decisions are documented, and (2) M&S that are within scope of the applicable guidance are identified and documented.

[**R13**] It is recommended that the M&S management team should likewise identify and document the acceptance criteria for M&S products, the intended use of the M&S, the safety, performance, cost and schedule metrics (all programmatic and technical metrics) relevant to the M&S effort, the requirements for verification, validation, and uncertainty quantification, the requirements for reporting of M&S information for critical decisions, the requirements for Configuration Management, the requirements for the program deviation/waiver process, and the specific person or groups responsible for complying with the specific applicable guidance in this and other documents.

[**R14**] It is recommended that a substantial effort be placed in the intended use definition activity.

[**R15**] It is recommended that, as a minimum, the following points about validation should be considered:

- Are experimental of flight results available for validation or only computational results (note that many people do not accept as validation the comparison of different computational results)?
- More generally, the type and quality of the referent.
- The sources for uncertainty information about the referent and the M&S.
- What quantities will actually be validated?

[**R16**] It is recommended that a risk/benefit analysis be performed to quantify the value of undertaking a formal accreditation program for a given M&S, weighed against the associated cost.

[**R17**] It is recommended that accreditation of M&S be considered, at a minimum, when the M&S meets one or more of the following conditions:

- The M&S is developed by one person and used by another.
- The results of M&S are used in mission- or budget-critical decisions.
- The M&S itself is a deliverable to the customer.
- The M&S is expected to be reused over multiple programs.

[**R18**] It is recommended that the following steps be considered as critical:

1. Identify the intended uses for M&S (to the extent currently known and updated as the program progresses). See Section 2.
2. Assign responsibility for each identified intended use to a M&S team lead.
3. Have the team lead identify the appropriate team members.
4. Define a general M&S process (like the one provided in Figure 5) and assign the resulting tasks (for example "validation") and work with the team members to define the actual work activities, products, required inputs, and needed resources. See Sections 5.1 – 5.5 above.
5. Determine when, to whom, and in what format and medium the results of the M&S activities are required by the program and integrate the M&S plan with the program plan and schedule. See Section 4.0.
6. Capture, document, communicate, and update each of the intended use sub-plans within the overall program M&S plan. See Section 6.0 below.

[**R19**] It is recommended that ***decisions should be made*** as whether specific the information needs to be addressed in the M&S Plan, at all, and if a topic is to be addressed, to what extent the information needs to be addressed, and whether that information is to actually appear in the M&S Plan document itself, or simply appear in the M&S Plan document as a reference to another accompanying document.

[**R20**] It is recommended that tasks such as verification should be decomposed into the simplest and smallest possible units that make physical sense and then re-assembled together to construct verification components, sub-assemblies, assemblies and systems.

[**R21**] It is recommended that a suite of verification test scripts be developed in parallel with the M&S itself to enable repeatable and self-documenting verifications.

[**R22**] It is recommended that VV&A not be considered as one or more separate sub-task(s) but rather, an iterative and essential part of the design process.

[**R23**] It is recommended that the level of risk associated with the use of M&S within a programmatic decision drive the level of effort put towards VV&A.

[**R24**] It is recommended that uncertainties in both the M&S outputs and experimental results (the referent) be accounted for statistically in the validation uncertainty quantification.

[**R25**] It is recommended that comprehensive uncertainty quantification requires the identification, categorization, and quantification of as many sources of uncertainties within a system as possible.

[**R26**] It is recommended that program adopt and exercise some means of assessing the credibility of their M&S to aid decision makers is using M&S results.

[**R27**] It is recommended that if an M&S is operated outside of the specified intended use range, the results should be appropriately flagged to alert decision makers reviewing the analysis.

[**R28**] It is recommended that analysis results always be presented in light of the reported validation uncertainties to communicate the appropriate confidence level.

[**R29**] It is recommended that some measure of uncertainty quantification for computational simulations be used when no experimental data is available.

[**R30**] It is recommended that the intended use statement of an M&S be considered as having the same characteristics as good requirements statements, but with additional information provided about the risks associated with violations of the intended use (see Appendix I).

[**R31**] It is recommended that programs attempt to determine the minimum, true cost associated with verification and validation of their M&S before undertaking such activities (see Appendix J).

Appendix B. Annotated M&S Plan Template

Appendix B –Annotated M&S Plan Template Guidance about the suggested content of many sections within this template can be found in other sources such as IEEE 1058-1998, IEEE 12207.0-1996, IEEE 12207.1, IEEE 12207.1, NASA STD-7009, NASA NPR 7123.1A and numerous Department of Defense documents. This document really only addresses M&S implemented within software or other accompanying documents (for example, conceptual, functional, algorithmic, logical descriptions); the user should consult an *accompanying document on Testbeds and Simulators* for considerations of hardware-oriented M&S

In all cases, a judgment should be made as to whether any subsequent section is needed at all for your particular application/M&S effort. If a section is deemed to be needed or desired, then another judgment should be made as to where the information should actually appear. For example, the suggested information could be included in this document explicitly (as is assumed in describing the template contents), or the relevant information could be referenced, and perhaps summarized, in this document but explicitly appears in a companion document. It is noted that, in most cases, the information described below should be considered someone within the program structure, even if a decision is made that the information need not appear in this M&S Plan.

1.0 Executive Summary

This section describes, very briefly, and at a very high level, the intent and major points of the document. The intent of this document is to provide a template for a program Modeling and Simulation (M&S) Plan and specific guidance about how that M&S Plan should be developed and implemented, as well as more general guidance about the nature of M&S and discussion about a typical M&S process.

This section should be independent of the rest of the document (i.e., this section can stand alone) and it is intended to provide a very quick overview of the rest of the document. This template arose from a superset combination of similar templates from several sources. This section fulfills two purposes:

1. It provides a quick overview of the document (this could be the only part of the document that some people read).

2. It provides enough detail so that others who contemplate reading some, or all, of the document understand clearly what might be expected to follow.

2.0 Introduction

This section begins to provide detail about the program and how M&S will be used within the program; further detail might be specified within later sections of this document such as Sections 2.7.1 and 2.7.2. In general, M&S might be used in several ways to support a program, such as to enable risk reductions within key decisions or to facilitate training. Any specifically identified purposes of M&S within the program should be described somewhere in this section.

2.1 Document Structure

This section describes how the rest of the document is organized. This should enable users of the document to quickly identify portions and features of it that may be of particular interest within very specific contexts.

2.2 Terminology/Notations Used in this Document

This section defines any terminology, notation, acronyms, use of fonts or symbols, etc. related to how the is document structured and how the presentation of information is made.

2.3 Mission

This section generally describes the program's mission, or may reference another higher-level document. In some cases, this section might describe the M&S Mission(s) within the program.

2.4 Vision

This section generally describes the program's vision, or may reference another higher-level document. In some cases, this section might describe the M&S Vision(s) within the program.

2.5 Objectives

This section describes the specific purposes of M&S within the program such as found in Section 2, the rationale for using M&S in specific situations (Section 1.1), the problem definitions for the M&S activities, etc. In particular, this section (or the next) should identify the number (N) and highest-level characteristics of the distinct M&S activities covered by this Plan. For example, if three distinct M&S activities are covered by this plan, a list might appear in this section to identify them by name or purpose. This information will provide a context for a recursive format that is adopted subsequently in this template to describe each identified M&S activity in more detail.

2.6 Strategy

This section describes the strategy behind using M&S in place of, or in combination with, other choices such as ground testing or flight experiments. The strategies for distinct M&S activities should be discussed separately. This section should include a description of how M&S results support programmatic decisions and schedule.

2.7 Program Overview

This section should discuss information such as highest level goals of the program. In addition, it should document the evolution of the program M&S Plan, including a history of the changes in the program M&S plan. Where possible, reference existing program documentation.

2.7.1 System Overview

This section describes and references the system or architecture concepts as it is currently understood or defined. To facilitate configuration management, reference existing program documentation when applicable.

2.7.2 System-Level Constraints and Limitations

This section lists any constraints or limits imposed on the system, including segment breakdown, cost, and performance constraints. During the early stages of system development parameters often adjust as the design solidifies. For this reason, it is recommended that this section of the M&S template reference the most current program requirements or interface documentation.

2.7.3 M&S Overview

This section describes the overall approach to be taken in determining intended uses and implementing M&S for any given intended use. This document provides illustrations of such an approach in sections 3.0 and 5.0.

2.7.4 To-Date List of Intended Uses (Decision/Evaluation/Risk Points) to be Addressed by M&S

This section lists the identified engineering problems for the system development effort and indicates which have been selected as M&S intended uses (i.e., candidates for the application of M&S techniques).

2.7.5 List of M&S Leadership Assignments/Responsibilities

This section lists the leadership assignments of each of the identified M&S intended uses.

3.0 Evolution of the program M&S Plan

This section describes the planned evolution of the M&S plan and provides a history of changes and modifications to the plan.

4.0 Applicable Documents

This section is the enumerated reference list for the M&S Plan. All relevant documents, specifications, standards, drawings, websites, and any other items of this nature that are referenced either explicitly or implicitly by the M&S Plan, and from all sources, should be listed in this section. Some templates break these references out as to those from government and non-government sources, but that organization may not be required or helpful.

5.0 Definitions

This section should provide one or more definitions for any terms related to the development or implementation of the M&S Plan. These definitions are generally discipline-specific and may be quoted, or adapted from, widely available literature. In some cases, the definitions provided within widely available literature may not be suitable for the current application and new definitions for a given term may be put forward. Whenever possible, definitions from widely available literature are preferred, and a judgment needs to be made about the possible confusion that will arise from the use of a new definition for an otherwise familiar term, compared to the limitations that will arise within your context from the application of a less than ideal, but more widely accepted definition, of an otherwise familiar term within your special circumstances.

6.0 Related Program and M&S Documents

This section lists many documents related to the M&S Plan. Again, a judgment should be made as to whether all of these documents are needed at all for your particular application/M&S effort. If a particular document is deemed to be needed or desired, then another judgment should be made as to where the information should actually appear. For example, the suggested information could be included in this document explicitly as a distinct section, or the relevant information could be referenced, and perhaps summarized, in this document but explicitly appears in a companion document. It is noted that, in most cases, the information described below should be considered by someone within the program structure, even if a decision is made that the information need not appear in this M&S Plan.

6.1 Managerial Process Plans

These documents should describe how the program/System/M&S effort are envisioned to be managed at the outset of the program. The information may be updated as more information becomes available throughout the lifecycle of the program.

6.1.1 Project Start-Up Plans

This section describes the planned activities to initiate and begin the program's M&S activities, including identification of intended uses, assignment of team members, etc.

6.1.2 Work Plans

This section describes (as currently understood) the planned activities to support the development and deployment of M&S to address the intended use(s).

6.1.3 Controls Plans

This section details how the work plan activities will be monitored, and when needed, adjusted to successfully perform the identified M&S tasks.

6.1.4 Risk Management Plans

This section identifies the risks to the system and program associated with developing and relying upon M&S-based analysis to evaluate and design the system. It also captures the risk mitigation or management activities that will be employed to deal with these risks.

6.1.5 Project Closeout Plans

This section identifies when the M&S activities will be deemed completed and the associated tasks involved in finishing the related work, including documentation, delivery of products, and analysis and archival of development and analysis products.

6.2 Technical Plans

These documents should describe how the program/System/M&S effort are envisioned to function technically at the outset of the program. The information may be updated as more information becomes available throughout the lifecycle of the program. Section 6.2 and following subsections go into greater detail of how M&S activities will be implemented to support the intended use.

6.2.1 Process Model Description

This section discusses the M&S process that will be employed during the program (see Section 2 and 4 for an illustrative example).

6.2.2 Methods, Tools and Techniques Descriptions

This section identifies and discusses any specific methods (such as statistical analysis), tools (such as software or computer based environments) and techniques (such as agent based simulation). It also provides a cross reference between these items and the intended uses for which they will be employed.

6.2.3 Infrastructure Plan

This section describes the equipment, facilities, and other types of infrastructure that will be required and provided to support the identified M&S efforts.

6.2.4 Product Acceptance Plan

This section describes the criteria and procedures for acceptance/utilization of the results of M&S efforts including format and media.

6.2.5 M&S Integration Plan

This section describes the process for integrating the results of the M&S efforts into the program documentation, reviews, and gated events (milestones).

6.2.6 System Integration Plan

This section describes the process for integrating the results of the M&S efforts into the system concept, requirements, design/specifications, and risk management.

6.3 Supporting Process Plans

This section identifies the program processes (such as systems engineering and requirements development) that M&S will be used to support or enable.

6.3.1 Configuration Management Plan

This section describes the specific process to be used for configuration management (CM), as well as a detailed list of all the items subject to configuration control. There should be discussion as to how long items will be subject to CM, under what conditions the CM system is shut down, and what the disposition of items under configuration control will be when the CM system shuts down.

6.3.2 Verification Validation and Accredidation Plan(s)

This section describes the specific processes and timeline for planned VV&A activities.

6.3.3 Documentation Plan

This section identifies (to the current state of planning) what documentation will be produced and delivered as M&S products for each of the identified intended uses.

6.3.4 Quality Assurance Plan

This section details how (procedures and evaluation criteria) the products of the M&S activities will be judged successful in supporting the overall program objectives.

6.3.5 Reviews and Audit Plan

This section identifies what reviews and audits will be performed (and when they will be performed) to evaluate the M&S plans, accomplishments to date, and the M&S products.

6.3.6 Problem Resolution Plan

This section details the program's plan for dealing with M&S problems including schedule delays, inconclusive results, inaccurate results, etc.

6.3.7 Subcontractor Management Plan

This section describes how subcontractors will be integrated into the M&S activities.

6.3.8 Process Improvement Plan

This section describes how the program will identify and incorporate process improvements into the M&S activities for this and future programs.

7.0 Modeling and Simulation Specific Plan(s) for Each Identified Decision/Evaluation/Risk Point (i.e., intended use)

It should be noted that an M&S plan may contain multiple M&S specific plans, one for each intended use or modeling activity. In some cases, it might be appopriate for the contect of section 6, specifically the technical plans, to be placed in section 7.0 tailored to each modeling activity.

7.1 Specific M&S Intended Use (problem being addressed)

This section identifies and dicusses the intended use. In addition, it provides the rationale supporting the need to conduct an M&S effort including the uncertainties being addressed, assessment of the risk of not conducting the M&S effort, and the acceptable costs of pursing the associated M&S effort.

7.2 Uncertainties/Options/Alternaties/Tradespace

This section identifies and discusses the relevent subset of the following:

- **Uncertainties:** What unknowns will be explored and addressed using M&S. For space system programs these unknowns generally involve not knowing which approach to meeting a user's need is preferred, or what the requirements or design specifications should be in order to best assure that the user's needs are met. Examples include concept or notional architecture exploration, analysis of alternatives (system level or higher), and M&S in support of requirements analysis.

- **Options/Alternatives:** What object and interface options or alternatives have been identified for evaluation in terms of the user's needs and the resulting decomposed requirements and design specification. Examples include different systems, subsystem, component, software and interface options/alternatives.

- **Tradespace:** What requirement or specification values or object (system, subsystem, component, etc.) properties will be varied to assess the ability of the object of interest (system, etc.) to meet the users needs or the resulting decomposed requirements or design specifications. It will also provide technically sound rationale for varying these values and the bounds on the variations. Examples include (utility, effectiveness, performance, technical peformance measures, cost, and risk metrics).

7.3 Limits, Constraints and Requirements (Objectives and Thresholds)

This section identifies and discusses the known limits and constraints on the identied tradespace. It also captures the resulting selection of specifications (on objects and interfaces) and the selection of requirements (including thresholds and objectives) identified through the associated M&S effort.

7.4 Expected Return on Investment and Risk Reduction

This section identifies and discusses the expected or achieved benefits as well as the expected or expended costs of the M&S effort on the associated intended use. It should also be used to track the current assessment of both the benefits and costs of the M&S effort on this intended use. In addition, it should discuss what the anticpated range of consequences and possible liklihood of failing to meet the requirements could be of not assessing the alternatives or carrying the uncertainty further. Such assessments are often based on expert opinion or experience and sometimes historical data.

7.5 Conceptual/Logical/Algorithmic Models

This section should identify the current state of knowledge and planning of the objects, functions, concept of operations, logical and mathematical models to be developed and used to address the identfied M&S intended use. Where applicable, it should reference their source or identify the lead developers.

7.6 Environments and Scenarios

This section should identify and reference the environmental models. It should also list, describe, and as relevent, reference any scenarios used in this M&S intended use effort.

7.7 Computational Models and Tools

This section should identify and describe any computational models to be used or developed to support this M&S intended use effort. References should be provided to the actual tools, especially software, including the applicable versions and manuals.

7.8 Verification and Validation Approaches

This section documents the verification and validation procedures and the associated pass/fail criteria to be applied to the models and simulations for the M&S intended use.

7.9 M&S Products

This section identifies and describes the anticipated or delivered results of each M&S intended use effort including format and media and references to the applicable reports and databases.

7.10 Delivery Schedule and Dependent Activities

This section identifies the program schedule events supported by the M&S intended use effort including documentation, reviews, and gated events. It also identifies which program activities provide inputs into the M&S effort or which program activities require the M&S effort results as inputs.

7.11 Activities, Resources and Assignments

This section provides a detailed breakdown or list of the activities that will be conducted in support of the M&S intended use activitiy as well as the resources and personnel required to support each activity.

7.12 Certification and Accreditation Plan

This section describes the procedures, criteria, and reviewing organizations to be used in seeking (or having successfully passed) certification and accreditation of the tools used in conducting the M&S intended use effort.

7.13 M&S Report List

This section provides a list of the reports produced during the M&S intended use effort.

8.0 Plan Annexes

This section provides a place for any supporting material not appropriate for the main body of the M&S plan.

8.1 Bibliography

A list of the supporting references used in the M&S plan.

8.2 Acronym List

A list of the acronyms used in the M&S plan.

8.3 Glossary

A list of the terms and associated definitions as used in the M&S plan.

Appendix C. Definitions

Abstraction: The process of selecting the essential aspects of a reference system to be represented in a model or simulation while ignoring those aspects that are not relevant to the purpose of the model or simulation (adapted from Fidelity ISG Glossary, Vol. 3.0).

Acceptability Criteria: The criteria that the M&S needs to meet to be acceptable for its intended use.

Acceptance: The decision to use the results produced by an M&S for an intended use.

Accreditation: The official management decision given by a senior agency official to authorize operation of an M&S and to explicitly accept the risk to agency operations (including mission, functions, image, or reputation), agency assets, or individuals, based on the implementation of an agreed-upon set of requirements (Adapted from NISTIR-7298[87]; SOURCE: SP 800-53[88]; FIPS 200[41]). This includes gaining official acceptance of the modeling and simulation products.

Accuracy: The difference between a parameter or variable (or a set of parameters or variables) within a model, simulation, or experiment and the true value or the assumed true value.

Activity: A set of tasks that consumes time and resources and whose performance is necessary for the execution of the M&S development and execution process

Analysis: Any post-processing or interpretation of the individual values, arrays, files of data, or suites of executions resulting from a simulation.

Artifact: Any tangible product that is produced by the project team, i.e., requirements documents, help systems, code, executables, test documentation, test results, diagrams, etc.

Calibration: The process of adjusting numerical or modeling parameters in the model to improve agreement with a referent.

Certification: A comprehensive assessment of the management, operational, and technical actions, made in support of an accreditation decision, to determine the extent to which the requirements are implemented correctly, the M&S is operating as intended, and producing the desired outcome with respect to intended purpose of the M&S (Adapted from NISTR-7298; SOURCE: SP 800-53; FIPS 200). Also, the process of verifying the correctness of a statement or claim and issuing a certificate as to its correctness (SOURCE: FIPS 201). This includes acceptance of the modeling and simulation products by the M&S customer.

Computational Model: The numerical representation of the mathematical model.

Conceptual Model: The collection of abstractions, assumptions, and descriptions of physical processes representing the behavior of the reality of interest from which the mathematical model or validation experiments can be constructed (adapted from ASME V&V 10).

Configuration Management (CM): A management discipline applied over the product's life cycle to provide visibility into, and to control changes to performance, functional, and physical characteristics (NPR 7120.5D, NASA Space Flight Program and Project Management Requirements).

Constructive Simulation: M&S that involve simulated people operating simulated systems. Real people stimulate (make inputs) to such simulations, but are not involved in determining the outcomes.

Credibility: The quality to elicit belief or trust in M&S results.

Critical Decision: Those technical decisions related to design, development, manufacturing, ground, or flight operations that may impact human safety or mission success, as measured by program/project-defined criteria.

Emulation: The use of an M&S to imitate another system, so that the M&S behaves like or appears to be the other system.

Human Safety: The condition of being protected from death, permanently disabling injury, severe injury and several occupational illnesses. In the NASA context this refers to safety of the public, astronauts, pilots, and the NASA workforce (adapted from NPR 8000.4 and the NASA Safety Hierarchy).

Intended Use: Engineering problems or uncertainties identified during the course of program execution and to which the program has decided to apply M&S resources.

Limits of Operation: The boundary of the set of parameters for which an M&S result is acceptable based on the program/project-required outcomes of verification, validation, and uncertainty quantification.

Live Simulation: M&S involving real people operating real systems.

Mathematical Model: The mathematical equations, boundary values, initial conditions, and modeling data needed to describe the conceptual model (ASME V&V 10).

Mission Success Criteria: Standards against which the program or project will be deemed a success. Mission success criteria may be both qualitative and quantitative, and may cover mission cost, schedule, and performance results as well as actual mission outcomes (NPR 7120.5C, NASA Program and Project Management Processes and Requirements).

Model: A description or representation of a system, entity, phenomena, or process (adapted from Banks, J., ed. [1998]. Handbook of Simulation. New York: John Wiley & Sons). (A model may be constructed from multiple sub-models; the sub-models and the integrated sub-models are all considered models. Likewise, any data that goes into a model is considered part of the model. A model of a model [commonly called a meta-model], e.g., a response surface constructed from the results of M&S, is considered a model.)

Program: A strategic investment by a Mission Directorate or Mission Support Office that has a defined architecture and/or technical approach, requirements, funding level, and a management structure that initiates and directs one or more projects. A program defines a strategic direction that the Agency has identified as critical. (NASA NPR 7120.5D)

Project: A specific investment identified in a program plan having defined requirements, a life-cycle cost, a beginning, and an end. A project yields new or revised products that directly address NASA's strategic needs. (NASA NPR 7120.5D)

Referent: Data, information, knowledge, or theory against which simulation results can be compared (adapted from ASME V&V 10). A codified body of knowledge about a thing being simulated.

Risk: The combination of the probability that a program or project will experience an undesired event and the consequences, impact, or severity of the undesired event, if it were to occur. Both the probability and consequences may have associated uncertainties (adapted from NPR 7120.5D).

Sensitivity Analysis: The study of how the variation in the output of a model can be apportioned to different sources of variation in the model input and parameters (adapted from Saltelli and others, 2000).

Simulation: The imitation of the characteristics of a system, entity, phenomena, or process using a computational model.

Stimulation: The description of a type of simulation whereby artificially generated signals are provided to real equipment in order to trigger it to produce the result required for verification of a real-world system, training, maintenance, or for research and development.

Subject Matter Expert: An individual having education, training, or experience in a particular technical or operational discipline, system, or process and who participates in an aspect of M&S requiring expertise.

Tailoring: The documentation and approval of the adaptation of the processes and approach to complying with requirements according to the purpose, complexity, and scope of a NASA program or project (NPR 7123.1A, NASA Systems Engineering Processes and Requirements).

Uncertainty: (1) The estimated amount or percentage by which an observed or calculated value may differ from the true value (The American Heritage Dictionary of the English Language, 4th ed.). (2) A broad and general term used to describe an imperfect state of knowledge or a variability resulting from a variety of factors including, but not limited to, lack of knowledge, applicability of information, physical variation, randomness or stochastic behavior, indeterminacy, judgment, and approximation (adapted from NPR 8715.3B, NASA General Safety Program Requirements).

Uncertainty Quantification: The process of identifying all relevant sources of uncertainties, characterizing them in all models, experiments, and comparisons of M&S results and experiments, and of quantifying uncertainties in all relevant inputs and outputs of the simulation or experiment.

Validation: The process of determining the degree to which a model or a simulation is an accurate representation of the real world from the perspective of the intended uses of the model or the simulation.

Virtual Simulation: M&S involving real people (i.e., simulation player/puckster) operating simulated systems. Virtual simulations inject Human-in-the-Loop in a central role by exercising motor control skills (e.g., flying an airplane), decision making skills (e.g., committing fire control resources to action), or communication skills (e.g., as members of a C4I team).

Verification: The process of determining that a computational model accurately represents the underlying mathematical model and its solution from the perspective of the intended uses of M&S.

Waiver: A documented authorization intentionally releasing a program or project from meeting a requirement (NPR 7120.5D). Deviations and exceptions are considered special cases of waivers.

Appendix D. Acronyms

ADP	Algorithm Development Plan
ANOVA	Analysis of Variance
ASAP	Aerospace Safety Advisory Panel
ASP	Analysis and Simulation Plan
ATP	Authority to Proceed
BIST RR	Baseline Integrated Test Readiness Review
BRR	Build Readiness Review
C&A	Certification and Accreditation
CCB	Configuration Control Board
CD	Drag Coefficient
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CM	Configuration Management
CMMI	Capability Maturity Model Integration
CONOPS	Concept of Operations
DMSO	Defense Modeling and Simulation Office
DOD	Department of Defense
EO	Electro-Optical
FRR	Flight Readiness Review
ICD	Interface Control Document
ICR	Initial Checkout Review
KDP	Key Decision Points
LSD	Least Significant Difference
M&S	Modeling and Simulation
MAIW	Mission Assurance Improvement Workshop
MRR	Mission Readiness Review
OFAAT	One Factor at a Time
PDR	Preliminary Design Review
PER	Pre-Environmental Review
PSR	Pre-Ship Review
RA	Reliability Analysis
RFP	Request for Proposal
RR	Requirements Review
RVP	Requirements Verification Plan
SME	Subject Matter Expert
STK	Satellite Toolkit
SVP	System Verification Plan
Tb&S	Testbeds and Simulators
TECR	Test Evaluation Campaign Review
TOR	Technical Operating Report
TPM	Technical Performance Measure
UQ	Uncertainty Quantification
V&V	Verification and Validation
VV&A	Verification, Validation, and Accreditation
WCA	Worst Case design Analysis
WP	Work Products

Appendix E. M&S Process Details

E.1 M&S Generic Implementation Process Additional Detail

E.1.1 Intended Use Definition (Problem Definition)

Having ascertained the type of Engineering Problem appropriate to the phase or phases of interest, the actual structuring and decision-critical information must be identified and developed to fully define the Engineering Problem. Human beings in general do not invent new objects or processes, rather they tend to assemble new systems out of familiar objects, use objects to perform different but still familiar functions and to seek to improve how well objects or systems perform. In this fashion, people tend to identify Engineering Problem solution alternatives or options by consulting their own experience, the experience of knowledge area experts, by analogy and simply piling up ideas (brain storming).

Generally, the alternatives or options are sought by asking the question of "to do what" to achieve a higher level solution. For instance "to achieve wide area surveillance," a capability, one possible alternative is "to capture and transmit images," a functional solution, while at the next level two possible architectural solutions might be "from an airborne platform" and "from a space borne platform." The second part of the Engineering Problem definition consists of picking the evaluation metrics. This part generally consists of determining what aspects of the current situation are unacceptable, undesirable, or could be improved in the opinion of the people who fund the development of a new system (senior decision makers), the individuals that will be using the system (users or consumers in the case of commercial space systems) and individuals familiar with the associated knowledge domain (scientists, engineers, strategists, and tacticians in the case of military space systems).

System level models (and simulations) should contain the performance features to allocate a system requirement down to its lower level requirements. For example, a communication link budget that models the satellite transmission and ground reception must include features such as antenna size, efficiency, gain and transmit power in order to produce adequate results. These models can trade the space borne antenna size and transmit power with the ground antenna gain and receiver sensitivity (refer to Figure E-1). At this phase, margin should be provided to account for future variations in space and/or ground capabilities.

Transmission	Frequency	**2,000.0 MHz**	
	Data Rate	**2500 Kbps**	
	Modulation	**BPSK**	
	Transmit Power	**5.0 W**	
	Antenna Diameter (cm)	**30.48**	36 ° Beamwidth
	AntennaEfficiency	**55%**	
	Antenna Gain	13.5 dB	
	Transmitter Loss	-3.0 dB	
	EIRP	**17.5 dB**	
Emission Path	Altitude	625 km	
	Elevation Angle	5.0°	
	Horizon Angle	65.1°	
	Slant Range	2,389 km	
	Range Loss	-166.0 dB	
	Atmospheric Loss	-2.0 dB	
	Rain Attenuation	0.0 dB	
	Polarization Loss	-0.5 dB	
	Path Loss	**-168.5 dB**	
Reception	Antenna Diameter (m)	**6**	
	AntennaEfficiency	**55%**	
	Antenna Gain	39.4 dB	
	Receiver Loss	-1.5 dB	
	Reception Gain	37.9 dB	
	Received Signal	**-113.1 dBW**	
17.1 dB/k G/T	System Temperature	120K	
	Noise Power	-140.8 dB	
	Received SNR	**27.7 dB**	
Link	SNR	27.7 dB	
	Coding Gain	0.0 dB	
	Available SNR	**27.7 dB**	
	BER	**2.73E-257**	
	MARGIN for 1E-6	**17.1 dB**	

Transmission	Frequency	**2,000.0 MHz**	
	Data Rate	**2500 Kbps**	
	Modulation	**BPSK**	
	Transmit Power	**5.0 W**	
	Antenna Diameter (cm)	**30.48**	36 ° Beamwidth
	AntennaEfficiency	**55%**	
	Antenna Gain	13.5 dB	
	Transmitter Loss	-3.0 dB	
	EIRP	**17.5 dB**	
Emission Path	Altitude	625 km	
	Elevation Angle	5.0°	
	Horizon Angle	65.1°	
	Slant Range	2,389 km	
	Range Loss	-166.0 dB	
	Atmospheric Loss	-2.0 dB	
	Rain Attenuation	0.0 dB	
	Polarization Loss	-0.5 dB	
	Path Loss	**-168.5 dB**	
Reception	Antenna Diameter (m)	**6**	
	AntennaEfficiency	**55%**	
	Antenna Gain	39.4 dB	
	Receiver Loss	-1.5 dB	
	Reception Gain	37.9 dB	
	Received Signal	**-113.1 dBW**	
17.1 dB/k G/T	System Temperature	120K	
	Noise Power	-140.8 dB	
	Received SNR	**27.7 dB**	
Link	SNR	27.7 dB	
	Coding Gain	0.0 dB	
	Available SNR	**27.7 dB**	
	BER	**2.73E-257**	
	MARGIN for 1E-6	**17.1 dB**	

Figure E-1. RF link closure model for command and control.

E.1.2 Conceptual Models

One of the first steps in model development is the creation of a Conceptual Model. A Conceptual Model is a high level, informal description of the system that describes the simulation concept and its pieces. This includes assumptions, algorithms, relationships, and data that define the behavior of the components of the simulation. The Conceptual Model can be used to communicate among the stakeholders (i.e., developers, analysts, SMEs, system engineers) the expectations of the simulation in terms of its context, elements, and concept.

A suggested approach for conceptual model development includes four basic steps.

1. Collect authoritative simulation context information including constraints and boundaries
2. Identify entities and processes that will be modeled through functional decomposition
3. Develop Simulation Elements for the entities previously identified
4. Address Relationships among simulation elements

The M&S Plan should include conceptual model documentation for the Models and Simulations to be used in the development program. This documentation should include representations of the models in the form of text, causal diagrams, block diagrams, pseudo-code, etc.

Conceptual models consist of representations that describe and provide for the communication of system, subsystem, or component elements, their arrangement and organization and their interrelationships or interfaces. Examples of conceptual models are shown in Figure E-10 as the Architectural and Functions models. Conceptual models are a precursor to the development of other types of models and should be built in a systematic fashion as a guide for the development of the other types and as a way to ensure that all the features and aspects that need to be modeled have been identified and evaluated.

E.1.3 Logical/Algorithmic Models

Logical and algorithmic models generally should be built on top of (with parameters, decision mechanisms, and decision actions allocated to elements and interfaces) conceptual models. An example of a logical model is also shown in Figure E-10 and the performance model example in the same figure is an example of an algorithmic model. This set of models tends to be the types M&S professionals tend to focus on, however the proper use of conceptual models to guide their construction is often critical to success.

E.1.4 Mathematical Models

Mathematical Models of a system are equations and logical expressions that predict the end products of a process or outputs of a function. A mathematical model describes a system by a set of equations and variables that predict the behavior of the system. The variables represent properties of the system and the model is the set of functions that describe the relationships between variables.

It is important to identify and document the definition of mathematical models used in the M&S Plan so that fidelity assessments and "reuse" decisions can be made regarding use of the model in system development activities.

E.1.5 Computational Models and Simulations, Environments, and Scenarios

Computational models and simulations capture the essential elements of both conceptual and logical/algorithmic models in a form where calculations or outputs can be produced from inputs. The interactions and responses of the models to input conditions, environments, and scenarios can be generated and evaluated. Such captures may include simple equations, software/code, physical representations or some combination of modeling mediums.

E.1.6 Environments and Scenarios

In the development of M&S products, the modeler has generally defined a boundary between the object or system being modeled and everything else. The conditions, states, and inputs external to the model (or simulation) which affect the states or behavior of the model of interest constitute the environment (or environments). Scenarios go a step further, and beyond, and consist of the changes in states and the actions of entities and systems within the environment that have occurred in time and lead up to the point in time when the model or simulation is initialized. It is critical in conducting effective and accurate modeling and simulation that both the environments and any scenarios used in the conduct of M&S be defined, subject to VV&A scrutiny and be documented.

A scenario can be viewed as a documented description of events involving the system that is focused on some specific function or output of the system. A scenario can be used in conjunction with models to perform experiments that answer "what if" questions in order to assess how the system would behave in a particular instance. Scenarios are useful during all stages of development as they can be applied to validate system performance as the fidelity of the system models matures.

A scenario can be considered a form of data input and is generally defined during the initial concept development phase of the program. Documentation of the scenarios as part of the M&S Plan ensures consistency of data inputs as fidelity and functionality of the models are developed. It is critical that the scenarios be under configuration management along with the rest of the M&S elements to ensure that changes in simulation results can be predicted and attributed to the intentional modifications that are being made as part of the M&S development.

E.1.6 Verification, Validation, and Accreditation

E.1.6.1 Overview

"Verification and Validation cannot prove that a model is correct and accurate for all possible scenarios, but, rather, it can provide evidence that the model is sufficiently accurate for its intended use." -

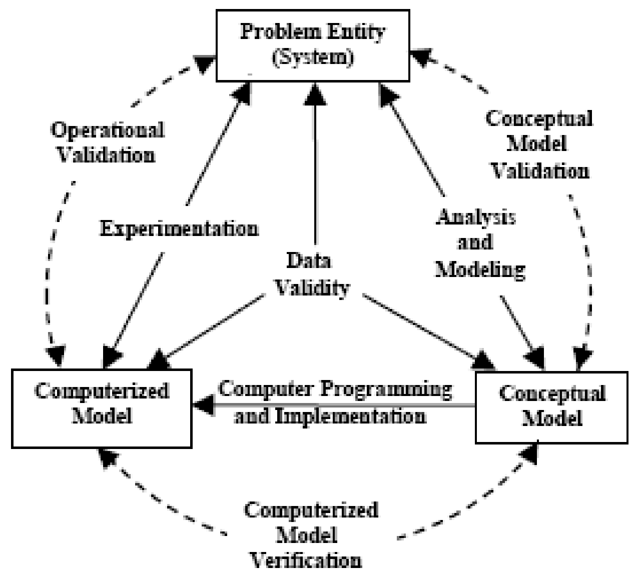
"The expected outcome of the model V&V process is the quantified level of agreement between experimental data and model prediction, as well as the predictive accuracy of the model."

(Concepts of Model Verification and Validation, Los Alamos National Laboratory, LA-14167-MS)[119]

The verification and validation literature is rich with guidelines and recommendations established by a number of different organizations including NASA, the Department of Energy, the Department of Defense, the American Society of Mechanical Engineers, and others. This section comprises a summary of these general recommendations as applied to spaceborne remote sensing systems.

Information on accreditation is easily found in documents pertaining to information assurance or information security. Unfortunately, as noted previously, there is not a commonly accepted definition for accreditation within the modeling and simulation community. It is highly recommended that M&S

practitioners discuss with their customer the expectations and understanding of accreditation prior to creating an M&S plan.



© Sargent, R. G. (c. 1980).

Figure E-2. Simplified view of the model verification and validation process[120].

The verification activity may be split into two distinct efforts:

1. **A logical verification,** in which all the numerical operations (additions, subtractions, multiplications, etc.) and logical branching effects could be quickly performed and verified, using much smaller, yet representative, databases that yielded approximately correct trajectory results.

2. Following the first, a **numerical verification**, in which the actual force and moment values from large databases were used to accurately and independently compute and verify the full set of trajectory results.

This technique allows time intensive verification exercises to be satisfactorily completed on time. Hence, [**R20**] it is recommended that tasks such as verification should be decomposed into the simplest and smallest possible units that make physical sense and then re-assembled together to construct verification components, sub-assemblies, assemblies, and systems. This has two benefits:

1. It helps to ensure that every aspect of the M&S system gets its own verifications applied to it (nothing slips through the cracks as untested or undetected due to other effects).

2. It enables a verification program that is just the right size, using resources most needed at the time.

Further, [**R21**] it is recommended that a suite of verification test scripts be developed in parallel with the M&S itself to enable repeatable and self-documenting verifications.

E.1.6.2 VV&A Objectives

VV&A is part of the design process. Modeling and simulations are useless unless they produce reasonably accurate results. The steps involved in verification and validation assist the practitioner in developing a viable model which produces accurate simulation results. All too often VV&A is put off until the end of the M&S effort or, worse yet, just prior to a design review where the customer will inevitably ask for verification and validation outcomes. Entertain the idea of overseeing the design and deployment of a FireSat payload[115]. Chances are, you would not randomly select a sensor, attach it to the bus, cross your fingers and hope for the best. Proceeding this way would be foolish. In regard to this approach, some form of verification and validation are recognized as "good common sense." Rather, you would probably spend some time collecting equations that would help you determine the swath size, orbital period, ground resolution, and data rates. After realizing that you need to make tradeoffs in the design you decide to create a simple script that automatically recalculates these values, but before evaluating the different tradeoffs you would probably confirm that the equations were entered correctly into the script. When all tradeoffs are evaluated instead of jumpstarting the design you would probably insure that the script outcomes are in agreement with test data collected on a previous mission. While this example is over simplistic, it contains elements of verification, validation, and accreditation. From this perspective, [**R22**] it is recommended that VV&A not be considered as one or more separate sub-task(s) but rather, an iterative and essential part of the design process. Furthermore, before starting a modeling and simulation effort it is recommended to develop a plan that details how VV&A will be completed. The following sections attempt to provide a conceptual framework of VV&A and direct the reader to several resources that go into greater detail.

E.1.6.3 VV&A One Size Does Not Fit All

Prior to developing a VV&A plan one should gain an understanding of the context to which the M&S will provide data. Going back to the FireSat example[115], the level of effort spent on collecting the equations and generating a model is dependent upon the complexity and potential implications of the results being wrong. The amount of testing or calculation put towards a mission critical system would be very different than an auxiliary system. One size does not fit all. The approach to VV&A should be dependent upon the context, expertise, and the ramifications of the M&S producing inaccurate results.

The following questions should be addressed before starting M&S and its corresponding VV&A tasks. The answers will impact how to proceed with VV&A.

System Overview Questions

- What type of system am I trying to model?
- How mature is the architecture or system specifications?
- How will my model be used? What is the region of interest? What are the scenarios or use cases that my model will be used to predict?
- What are key parameters or metrics?
- How will the simulation results be used?
- What type of Model is most appropriate? How will the team be able to verify it?
- What type of data or measurements can I use to validate the modeling and simulation results?

Potential Risk Assessment

[**R23**] It is recommended that the level of risk associated with the use of M&S within a programmatic decision drive the level of effort put towards VV&A[9,107]. The NASA Standard 7009 addresses risk by accessing the consequences of a decision and potential influence of M&S upon that decision. This information is placed in a matrix to rank M&S priorities. Key questions to consider when evaluating risk are:

- If the modeling and simulation endeavor generates inaccurate results, what are the resulting consequences to the mission? Catastrophic, Critical, Moderate, or Negligible?
- What influence will the results have on decision making processes? Controlling, Significant, Moderate, Minor, or Negligible?
- How accurate should the model be to insure simulation results are meaningful?

Assessing Available Resources

- Does the team have sufficient resources to complete VV&A appropriately? Training, Computational Tools, and Equipment.
- How much time is allotted in the schedule for M&S +VV&A?
- Does the team have the right expertise?
- Who are the subject matter experts that could review the VV&A plan?
- Has another team or group completed a similar M&S + VV&A task? Have I looked for lessons learned or white papers published on the subject to be modeled?

E.1.6.4 Verification

While verification has a number of definitions from a broad systems engineering perspective, for the purposes of M&S, we adopt the standard definition accepted in the VV&A literature. That is, verification is the process of determining that a computational model or simulation and its associated data accurately represent the underlying conceptual model and mathematical description. In essence, verification assesses whether a computational model has been implemented properly, but does not determine the validity of model results when compared to reality.

As a model follows a development process such as the one shown in Figure E-3, an initial conceptual model is transformed into a mathematical model, which is then further developed into a computational model typically in the form of software. Verification occurs throughout the development cycle and not just at the end. This ongoing process consists of two fundamental subprocesses: code verification and calculation verification.

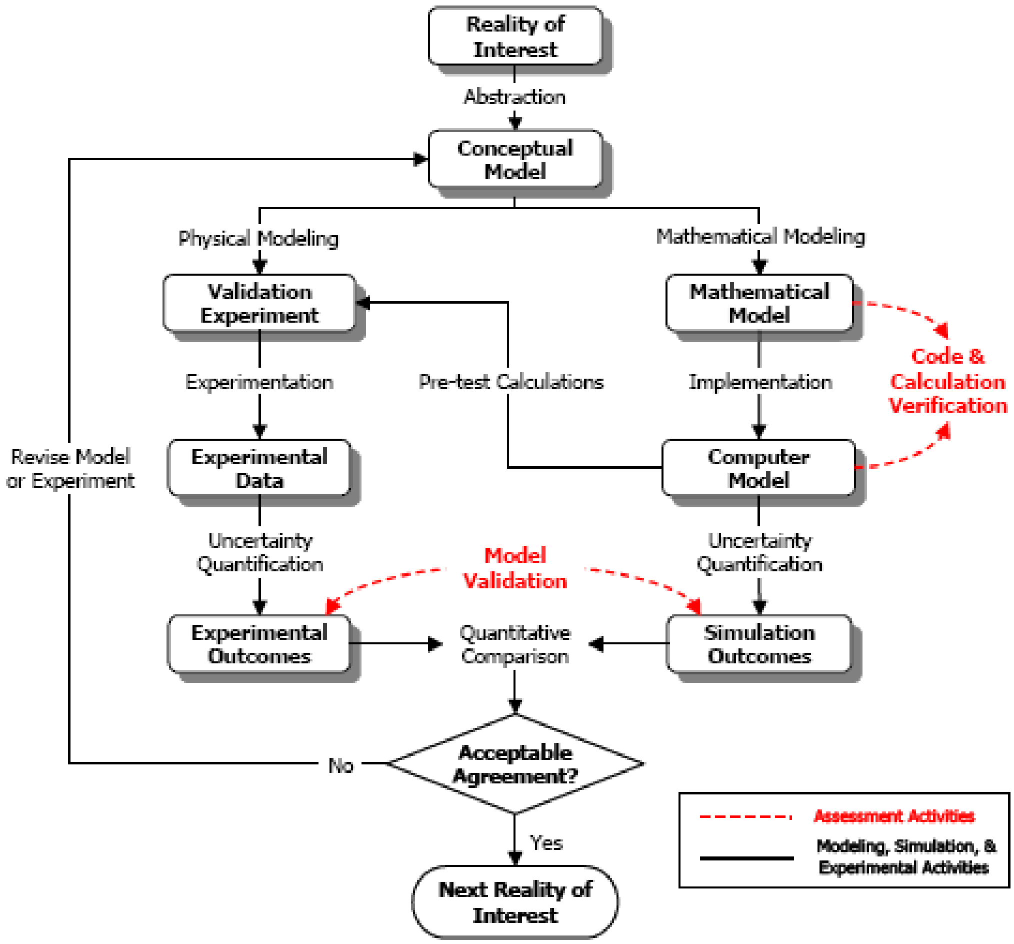


Figure E-3. Detailed model development, verification, and validation process[119].

Code Verification. Code verification confirms that the M&S practitioner's original concept and mathematical description of that concept is properly implemented in software. In other words, it ensures that the software works as originally intended.

Early in the M&S effort, a program identifies and establishes appropriate software assurance processes to monitor and control M&S software development. These include, but are not limited to, program-appropriate levels of configuration management, documentation of software requirements, coding standards, independent peer reviews, test procedures, verification datasets, and so on. Depending on the planned usage of the model, software assurance may also need to confirm that code can be properly implemented on different platforms using different compilers. The processes are carefully followed throughout the lifecycle of the software with proper documentation along the way to improve the fidelity and credibility of the model. As development progresses, models can be tuned with higher fidelity input data as it becomes available.

In addition, code verification assesses the implementation of numerical algorithms in software. Carefully constructed test cases with known analytical solutions allow a developer to identify, isolate, and remove coding errors through techniques such as regression testing. The test cases must consider the intended range of use of the model to ensure that the algorithmic implementation functions properly. Often, analytical solutions are far too complex for direct computation and comparison with software model predictions. In such cases, the method of manufactured solutions described in the VV&A literature offers a technique to provide analytical solutions that are sensitive to algorithm and software errors.

Calculation Verification. The next step in the verification process is calculation verification, which estimates the errors associated with the computational implementation of a model. Since software models provide only an approximation of an ideal analytical solution, calculation verification determines the accuracy of model results due to numerical and algorithmic errors. Errors may arise for a number of reasons including convergence effects, discrete sampling, numerical precision, mathematical or algorithmic approximations, and others. Early in the development cycle, acceptance criteria are established based on uncertainty allocations for inherent model calculation errors.

While errors arise from the software implementation process, they may also result from the way that the model is operated. For example, a user may select a different temporal, spatial, or spectral sampling scheme that changes the errors in model outputs. Consequently, calculation verification is the responsibility of not just the model developer, but also model users. Parameter-dependent errors must be understood over the range of possible operating conditions so that input-dependent calculation errors are not underestimated. This implies that proper specification of the domain of the verification is just as important as the numerical verification results.

Calculation verification methods, tests, and results must be properly documented for model credibility assessments. Quantified and recorded verification results form an important input to the uncertainty quantification process described later.

E.1.6.5 Validation

Validation in M&S determines how well a computational model represents reality in the context of the intended use of the model. This is achieved ***at a limited number of points***[89,93,107], by comparing model simulation results with referent data based on independent experimental results. A program establishes acceptance criteria early in the development cycle that are used to determine whether validation results are satisfactory or if additional revisions are required in the conceptual model to improve performance. Validation is an ongoing, iterative process that only concludes when a model demonstrates satisfactory performance compared to referent datasets.

Frequently, programs begin their M&S validation efforts after the model development ends leading to inefficiency, late identification of issues, and lower quality validation. In contrast, Figure E-3 illustrates that validation ideally occurs in parallel with model development enabling a “test as you go” approach to validate the model at different levels of maturity. The parallel process keeps the software development and validation experiment development focused on end objectives, which improves overall efficiency and end product quality.

Validation Metrics. In order to assess the validity of a model, validation metrics must be established that clearly and quantitatively measure the performance of a model in the context of its intended use. Typically, the metrics are derived from system performance requirements so that model validation is tied directly to system objectives. Validation metrics are often measures of statistical agreement between a particular parameter output by model simulations and the associated referent data. The metrics are defined early in the conceptual model development phase along with associated acceptance criteria for use during validation efforts.

Depending on the M&S application, it is also often useful to include supporting metrics that provide additional information during the validation process. These metrics may not be tied directly to requirements or top-level performance of a model, but are often valuable for diagnosing problems when unacceptable discrepancies arise between model simulation results and referent data. Supporting metrics can include initial or intermediate model parameters that provide measures of internal performance.

Validation Experiments. Successful validation relies on the identification of appropriate referent data derived from experiments for comparison with model predictions. The experiment results represent a proxy for "ground truth" data and offer a measuring stick for the model's ability to correctly emulate the physical processes of interest. Consequently, the proper identification of validation experiments is just as critical as the development of the model itself. Use of accurate experimental results improves credibility of a model and reduces the risks associated with using it to make programmatic or technical decisions.

Ideal experimental results are rarely achievable, which is often the reason for creating a model of a physical process in the first place. However, validation "experiments" still must be developed and used in some form to provide confidence that the model performs as intended. Validation experiments and results can take a number of different forms such as the following:

- Independent input and output datasets from similar systems
- Laboratory or field measurements of component, subsystem, or system hardware
- Results of other validated models or sub models

When properly designed and executed, these and other approaches offer independent referent data for comparison with model results. [**R24**] It is recommended that uncertainties in both the M&S outputs and experimental results (the referent) be accounted for statistically in the validation uncertainty quantification[§§].

Another important consideration in the design and execution of experiments is proper sampling of a model's input and output domains. The domain of the experiments will define the limits of the validation and has implications for how a model can be confidently applied to predict system performance under other conditions. As a result, the models input and output domains must be clearly identified early in the development cycle and the validation experiments must be design to provide sufficient sampling of those domains. "Sufficient sampling" is highly dependent on each particular M&S application.

Experiments and models involving stochastic variability should also include appropriate levels of data redundancy to enable a proper assessment of statistical performance in the validation. Statistical errors in computed validation metrics typically decrease as sample sets grow.

Uncertainty quantification. A critical element of model validation is the uncertainty quantification that provides measure of how well the model performs over a specified range of conditions. Accurate uncertainty quantification provides a measure of the confidence in model results, which is important as M&S is used as a tool for making programmatic or technical decisions. [**R25**] It is recommended that comprehensive uncertainty quantification requires the identification, categorization, and quantification of as many sources of uncertainties within a system as possible.

The first step in the uncertainty quantification process is the identification of as many sources of uncertainties within a system as possible. For each application, the sources of error will vary widely. Example areas from which model uncertainties may originate include:

- Inherent modeling errors due to approximations and assumptions
- Code implementation errors discussed in the verification section above
- Uncertainty of model input parameters
- Uncertainty of experimental results used as referent data

[§§]See references 11, 32, 44, and 49 in Section 6.

Most models rely on simplifying assumptions or approximations in the initial conceptual formulation of a model. These inherent errors propagate through the mathematical design and computational implementation of a model. They often cause systematic errors that can be reduced if the fundamental conceptual model of the physical process of interest is improved.

Code implementation errors represent discrepancies due to the intended conceptual model and the algorithmic/numerical implementation. These errors must also be accounted for in the final uncertainty estimate for the model. The verification section above noted a number of possible sources of these types of errors.

Variations in model input parameters can also cause uncertainty in simulation results. These must first be quantified and then propagated through the model to determine model simulation output uncertainties. This can be accomplished through such techniques as Monte Carlo analysis or sensitivity-based approaches.

The referent data derived from experimental test results also includes inherent uncertainties. These, too, are a fundamental part of the overall uncertainty quantification process. Figure E-3 shows that the validation experiment and model development portions of the M&S process both include uncertainty quantification. The discrepancies between model simulation results and experimental results inherently contain uncertainties from both sides of the comparison. Such uncertainties must be understood to properly assess overall model uncertainty.

Once the uncertainties have been properly identified, each term is then categorized as irreducible (aleatory) or reducible (epistemic). The amount of uncertainty from each source is then described either quantitatively (e.g., ±0.003 or ±15 percent), or qualitatively (e.g., the uncertainty in item A is bigger than that for item B). Irreducible uncertainties arise from natural, unpredictable variations in the performance of a system under study. These uncertainties cannot be reduced by obtaining additional information about the system, though additional information may help in quantifying the uncertainty. On the other hand, reducible uncertainties result from a lack of knowledge about the behavior of the system that is conceptually resolvable. These uncertainties can, in principle, be reduced with sufficient study and analysis.

Uncertainty source classification allows M&S managers and developers to focus resources in areas that are more likely to improve model performance. For irreducible uncertainties, the development effort can focus on having a more robust design to handle the variability and to enlist resources to better characterize the uncertainties. For reducible terms, management can allocate resources to improve the knowledge of model behavior with the objective of reducing the uncertainty.

Validation hierarchy. Models often consist of a hierarchy of subsystem and component models. While it is sometimes possible to validate a system model end-to-end, this approach limits a developers ability to identify, isolate, and mitigate errors at lower levels of the model. A more thorough approach consists of validating models in each tier of the overall model hierarchy with output uncertainties of one model serving as the input uncertainties of another.

As the validation hierarchy is traversed from bottom to top (component or unit level to complete system), a M&S practitioner must carefully consider statistical correlation of model uncertainties. Due to the underlying physical processes involved, uncertainties associated with individual lower level models may exhibit correlation that must be accounted for as higher level model uncertainties are estimated. Such correlations can amplify or attenuate end-to-end model error estimates. The validation process must conduct a sequence of increasingly larger validation experiments to ensure that these effects are properly addressed.

E.1.6.6 Accreditation

Accreditation is the process of determining that a model, associated simulations, and data are acceptable for use for a specific purpose. While verification and validation provides a quantitative assessment of model mathematical and physical accuracy, overall credibility of model results depends on other important factors that cannot always be directly quantified. For example, the training and experience of model users can play a significant role in the success of model simulations. Consequently, the accreditation process includes inherently subjective elements that should be clearly defined for each individual modeling application to improve accreditation rigor and value.

Accreditation can be viewed as a two step process. First, the M&S practitioner makes an assessment of specific model results. Second, an identified accreditation authority infers the credibility of the model given the particular scenario of interest. The decision is based on factors that contribute to or detract from the believability of model results for the desired application. M&S management establishes accreditation criteria based on the risks associated with using the model in the decision making process. If the risk is low, the criteria can be set accordingly. If the risk is high (such as possible mission failure due to decisions made based on erroneous model predictions), then more stringent accreditation criteria are set.

To provide some rigor and increased objectivity to the accreditation process, NASA Standard 7009[107] presents an ***M&S credibility assessment scale*** consisting of eight factors grouped into three categories as shown in Figure E-4. The factors all fall into the categories of M&S Development, M&S Operations, and Supporting Evidence. The M&S Development factors examine the results of verification and validation efforts to ensure that the model represents the reality of interest within established limits. M&S Operations factors consider the confidence level in model inputs, outputs, and perceived sensitivities. Supporting Evidence factors looks at the broader picture of a model's usage history, the management process used in model development, and the expertise of model developers and users. Each of these factors are rated on a scale of 0 to 4 and the overall credibility scores are compared against the predefined criteria. The reader is referred to NASA Standard 7009[106] for greater detail on the credibility assessment scale and the associated metrics. The reader is reminded that Aerospace Safety Advisory Panel strongly endorsed the kind of multi-factor M&S Credibility Assessment approach described in[107] during its recent meeting in Washington DC on April 30, 2010[9]). **[R26]** It is recommended that programs adopt and exercise some means of assessing the credibility of their M&S to aid decision makers in using M&S results.

Accreditation also frequently includes formal certification. For many programs, certification is the culmination of accreditation consisting of a written guarantee that a model and the associated simulations comply with specified requirements and are acceptable for use for a specific purpose. Others view certification as the process leading to accreditation. The independent accreditation/certification authority, usually a customer representative, makes the final certification decision based on VV&A results.

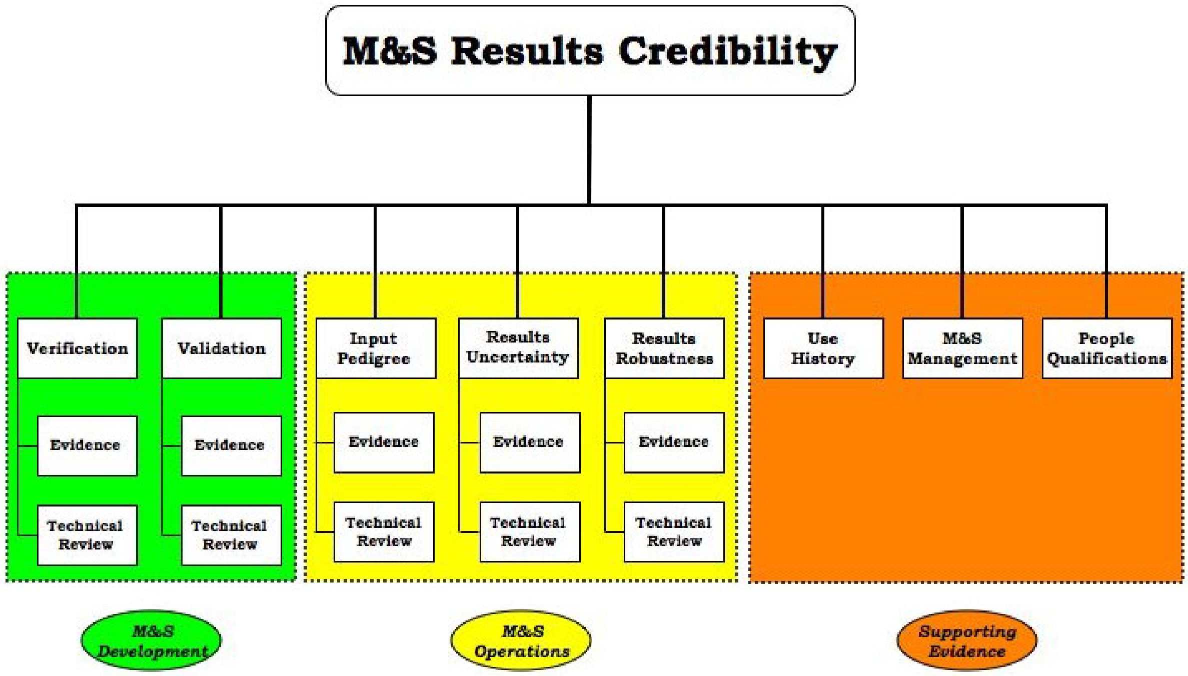


Figure E-4. NASA credibility assessment scale (NASA Standard 7009).

E.1.7 M&S Analysis

M&S Analysis as defined in NASA Standard 7009, M&S analysis is any post-processing or interpretation of the individual values, arrays, files of data, or suites of executions resulting from a simulation. In this context, models are used through simulations to produce results that are then analyzed further for specific program purposes. Analysis is the final segment in the overall endeavor to provide technical information required to make technical and programmatic decisions. A disciplined, rigorous analysis approach ensures accurate and appropriate interpretation of model simulation results.

A broad range of general model-based analyses exist in aerospace systems. Examples include, but are certainly not limited to, the following:

- Requirements derivation, allocation, and flow down
- Design feasibility studies
- Design trade studies
- System performance prediction/requirements verification
- Performance sensitivity analyses
- Technical risk analysis and mitigation
- Support for hardware/software test operations
- Concept of operations simulations
- Simulation of flight data products
- Hardware anomaly resolution (ground and flight)

These high level examples demonstrate the potential value of M&S in performing critical analyses that affect technical and programmatic decisions. In every case, model simulation results must be interpreted and applied consistent with the intended use and the designed capability of the model. Model users must avoid a “black box” mentality that can lead to inappropriate use of a model and inaccurate interpretation of its results.

Analysts using M&S tools must first be adequately trained in a model's design, functionality, limits, operation, and VV&A. This requires proper documentation generated during the development phase covering these and other model-specific topics. As noted in a previous section, proper user training is a key factor in the overall accreditation process. If a user is not properly trained, even the best models may produce poor results.

Another critical element of M&S analyses is a keen understanding of the limits (or intended use) of a model (see additional guidance for the intended use statement in Appendix I). During the development phase, the developer should have clearly identified the limits of operation including the domains of input and output data as well as the range over which the limits were validated. A user is responsible to understand those limits and to interpret simulation results within that context. [**R27**] It is recommended that if an M&S is operated outside of the specified intended use range, the results should be appropriately flagged to alert decision makers reviewing the analysis. [**R28**] It is recommended that analysis results always be presented in light of the reported validation uncertainties to communicate the appropriate confidence level.

Documentation of procedures, approaches, and results are also important in M&S analysis. Analysis reports must include sufficient information to enable an independent analyst to reproduce the results should the need arise. Report content includes items such as the purpose/rationale for the analysis, model version numbers, analysis assumptions, input parameters, execution warning messages, anomalies encountered, output results, post-processing analysis details, and so on. NASA Standard 7009 provides additional detailed documentation requirements for M&S analyses.

E.2 General/Generic Representation of Models

In defining a general M&S process, a number of basic types of models have been identified: Conceptual (also Architectural), Functional, Logical, Mathematical, Algorithmic, and Computational. In addition, several specific applications of these models have been put forward including: Conceptual Modeling, Logical/Algorithmic Modeling, Concept of Operations and Environments and Scenarios. Graphical examples are provided of the basic types of models in Figure E-5, below. The category of conceptual models simply includes the object and function (noun and verb) symbolic representations used in defining designs. The Logical/Algorithmic category addresses the mathematical (variables and operations on variables) types of models used to quantify decision-based behavior, metrics, and observable/quantifiable properties. The Concepts of Operations category is essentially a set of models that determine and define how a "black box," the system, subsystem, or component of interest will be used and employed. Environment and Scenarios consists of the basic model types but is made up of those models external to, but affecting, the behavior and performance of the system, subsystem, or component model of interest. Computational models are those models that have been translated into a medium in which computations and behavior may be exercised, often into software.

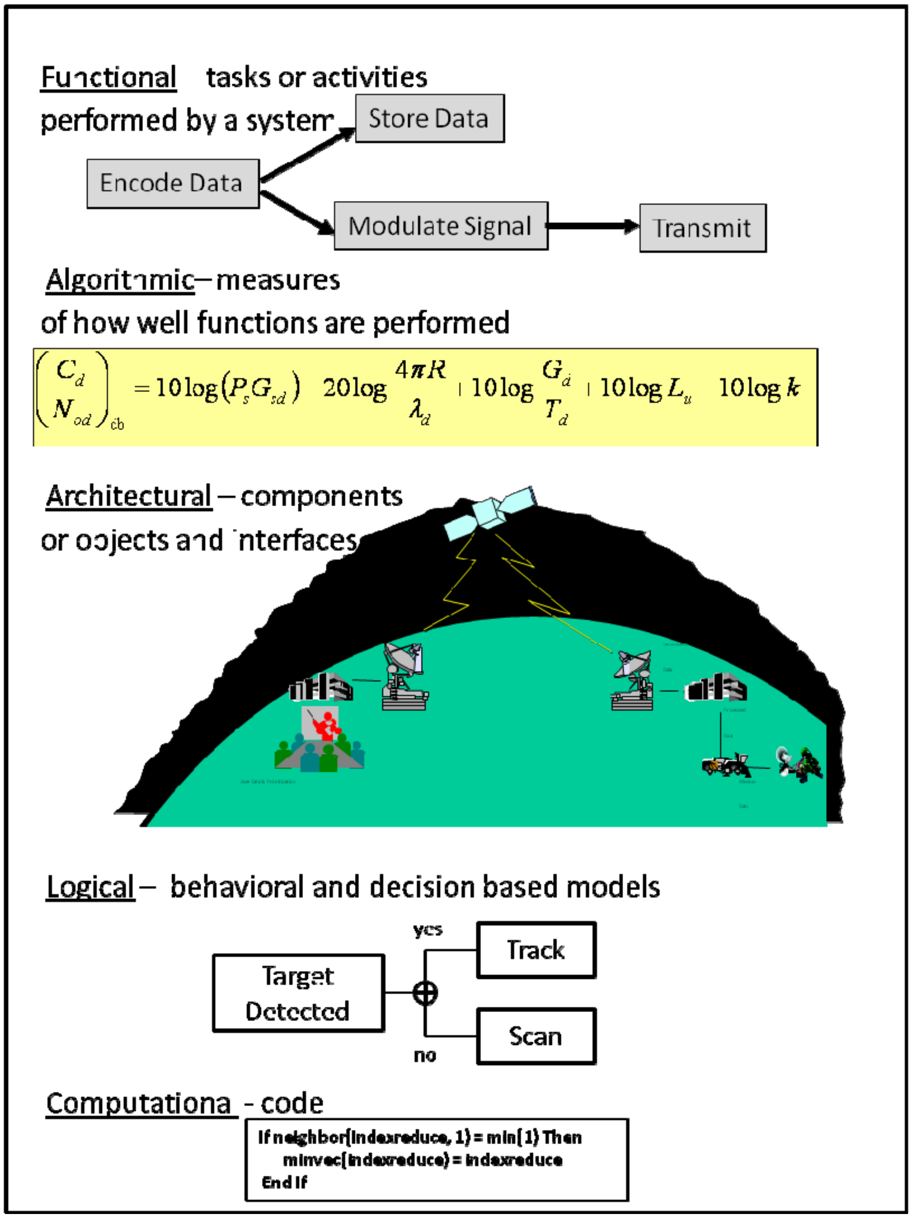


Figure E-5. Basic model types.

Appendix F. Description of Key M&S Characteristics

Two key characteristics of M&S are:

1. The concept of an intended use.
2. The representation of components, assemblies, systems, and processes to satisfy an intended use.

These two characteristics go hand-in-hand and contribute to several other key characteristics of M&S:

- Uncertainty quantification, propagation and management
- Verification
- Validation
- Robustness
- Sensitivities
- Risk
- "-ilities"

The intended use of an M&S is a concept or a mental image, a single statement or set of statements that encapsulate what the M&S is expected to do (or what the M&S should not be expected to do). The intended use should be a shared vision by those involved with developing, executing, and analyzing the M&S, and the customers for whom the M&S produces information (including decision makers that must act on the results of an M&S execution). The intended use should be initially defined and agreed upon before any real work is done to develop or exercise an M&S. Quite likely, the intended use will iteratively evolve over time as more knowledge about the system is developed, uncovered, and synthesized. The intended use will also evolve as the customer's requirements, and their implications for the design, are better understood. The intended use statement can be specified in one of two ways: positively (i.e., the intended use is …) or negatively (i.e., the intended use is not …; that is, as a set of constraints) or some combination of these two approaches. A decision maker must understand that there is some risk the intended use statement of a given M&S has not been stated, or conveyed, correctly or sufficiently (lack of proper understanding of the intended use). The risk associated with the proper specification of the intended use is diminished in proportion to how, and how much, the M&S has been used previously. The following points offer some guidance as to how to rate this risk, ranging from 1 (less risk) to 5 (more risk):

1. M&S has successfully been used in formal optimization under uncertainty studies or successfully coupled with a probabilistic driver
2. M&S has been successfully used in formal optimization studies, coupled with an optimizer
3. M&S has been successfully used in formal trade studies of related calculations/simulations
4. M&S has been successfully used only in discrete and unrelated calculations/simulations
5. M&S has no prior successful usage

Likewise, the decision maker must understand there are unique consequences and risks, related to the importance of the decisions that must be made based upon the results of M&S. These consequences and risks are associated with any violations of each of the intended use constraints imposed on the M&S. These consequences and risks can best be assessed and categorized by those involved with developing, executing, and analyzing the M&S. The following points offer some guidance as to the level of consequence associated with violating a particular portion of the intended use statement, ranging from 1 (less risk) to 5 (more risk):

1. M&S will fail and not produce a result
2. M&S will produce a result, along with a warning message in response to a known and detected limitation violation
3. M&S may/will produce a result that has not been verified or validated
4. M&S may/will produce a result where validation is not possible (no validation set available, and on facility exists to produce validation data, the result cannot be validated on earth, etc.)
5. M&S may/will produce a result that violates a known law of physics

Finally, the following questions should be asked relative to any intended use specification:

- How accurately are the true limitations of the intended use described by the set of constraints?
- How well are the limitations understood by the user?
- How accurately must the limitations be respected?
- How accurately will the current state vector of variables within the intended use domain be known?
- Is there a way from inside the intended use domain to determine that one is approaching the limitation boundary, or to detect that the M&S has crossed the limitation boundary?
- Will a violation of the intended use boundary lead to discontinuous behavior (fall off a cliff) or gradual deterioration (walking down a gentle hill)?

The representation of components, assemblies, systems, and processes includes aspects such as the adequacy, fidelity, consistency and completeness of the M&S for the intended use. This group of characteristic impacts all the other M&S characteristics to some extent. Ideally, these representational characteristics of the M&S will improve significantly over the lifecycle of a program as the design and the understanding of the customer's requirements mature. However, it is possible that in the very final stages of the development, and into testing and deployment, that high-fidelity response surfaces may be substituted for elaborate high-fidelity M&S tools, simply to achieve real-time performance requirements that may greatly exceed the capability of the high-fidelity M&S tools. The choices to be made related to the representational characteristics are obviously controlled by the budget allocations with the program, but these may also be dictated by customer requirements and by the knowledge of those involved in developing, executing, and analyzing the results of the M&S.

Perhaps the most significant considerations within the areas of adequacy, consistency, and completeness have to do with the representation of any required interfaces and functionality. It is wise to remember that every input to any component, assembly, system, or process is the output from another component, assembly, system, or process; these functions must be modeled correctly or the system behavior will be lacking. Likewise, the interfaces (and the information passed across the interfaces) must be correct. It is recommended that functional development and testing of the M&S be initiated at the interface level, using representative "shells" for the components, assemblies, systems, or processes involved; these shells are rigged so as to pass the right kinds of information between them from the start. This type of testing can generally be accomplished at very low costs, early in the program lifecycle, and long before all the details have been firmly established or implemented about the means for developing the actual information to be passed across the interfaces. To this end, it is further recommended that an owner be identified for each interface, as it is identified; this owner must be informed of, and approve, any changes on either side of the interface that will affect its form or function; likewise, the interface owner will act as the arbitrator when differences arise about changes to interface form or function. Again, one would expect that the knowledge about the interface definitions and functionality will increase throughout the lifecycle of the program, primarily through the control of those involved in developing, executing, and analyzing the results of the M&S.

Uncertainty quantification, propagation, and management are also important characteristics of M&S which distinguishes it from other kinds of software engineering projects. A model is a description or representation of a system, entity, phenomena, or process; a simulation is the imitation of the characteristics of a system, entity, phenomena, or process using a computational model. Hence, M&S is an imperfect approximation to the real world; it is this aspect of approximation which is subject to the practices of uncertainty quantification, propagation, and management. Ideally, the system level uncertainties will be reduced throughout an M&S program lifecycle, but it is possible that only the uncertainty about the system level uncertainties may be reduced through the M&S program lifecycle. That is to say, that, at a minimum, the confidence with which we describe the system level uncertainties should increase throughout the program lifecycle, even if the system level uncertainties themselves do not decrease. It is even quite possible that through learning more about the system level uncertainties (gaining more confidence about their magnitudes), that the estimation of their bounds and potential impact may grow, rather than decrease.

The uncertainty characteristics described above are closely related to the notion of ***accuracy***. A real statement of accuracy is a statement of achievement, compared to some known benchmark (a validation case). A meaningful statement of accuracy should always include these three parts:

1. A mean value
2. A plus or minus uncertainty bound
3. A confidence percentage associated with the uncertainty bounds

For example, the following is a potentially meaningful and complete statement of accuracy: 17 ±2.3 to 95 percent confidence. In this statement, the value 17 is the mean difference between the M&S and the referent or real world answer; this value has the same units associated with it the units of the response in question. The value 2.3 (in this case, a symmetric upper and lower uncertainty measure) is the amount that must be added to, and subtracted from, the mean value in order to obtain upper and lower bounds on the mean value; this value also has the same units associated with it the units of the response in question. Finally the value of 95 percent is an expression of the confidence associate with the accuracy statement. The statement is interpreted to mean (without any additional qualifications) that, given a sufficiently large sample of points (a statistically significant sample), the true answer will, 95 percent of the time, lie between 14.7 and 19.3 (17 – 2.3 and 17 + 2.3). It is recommended that a statement of accuracy without the three portions, described subsequently, be considered as incomplete. The validation effort associated with such a statement should not be underestimated, for the statement assumes normal distribution behavior, which may or may not be true, and requires a sufficiently large sampling of point (could be billions) to either confirm or deny the statement. In some cases, the customer requirements may specify a certain level of accuracy to be achieved, but this should only be considered as a goal for validation points that cannot be strictly enforced or demonstrated for prediction points. Furthermore, the desired accuracy goal may not be attainable at all, or may not be attainable within the resources allocated to the program.

Robustness is characteristic of the M&S, the system being simulated, or of the M&S process. When existing M&S (computational tools and/or processes) under configuration management are reused, their robustness should be constant throughout the lifecycle of the program, as provided to the current M&S effort from prior usage. It may be the case that the current usage will uncover new aspects of the M&S robustness, simply because the current application is different from prior uses. It is generally expected that one is trying to determine the robustness of the system being developed to changes in its operating conditions; in this case, one might hope that the system robustness will improve throughout the lifecycle of a program. Designing robustness into a system is a recommended best practice in order to cover “known unknowns” as well as “unknown unknowns”. For a new M&S being developed along with a new system, the robustness of the M&S tools and process as well as the system might be expected to improve throughout the program lifecycle. The M&S robustness is generally controlled by those developing the M&S and the customer requirements. The system robustness may be controlled by real world and by customer requirements.

Sensitivities are additional pieces of information, as compared to the functional values, about the system behavior as significant input variables change. Sensitivities are generally an uncertain characteristic of the system being simulated, governed by the physics of the system within in its operational context. The true values of the system sensitivities are unknowable until the system is operating; hence, the system sensitivities are approximately determined through M&S by sensitivity analysis. In contrast, margin sensitivity is purely a construct of the M&S process, since the concept of a margin is irrelevant to an operating system. Although the true values of the operating sensitivities are fixed by the real world, knowledge about the true values of the operating system sensitivities should improve throughout the M&S effort; the degree to which this knowledge is revealed is generally under the control of those involved in the development and analysis of the M&S. Since sensitivity analysis may lead to an improved prioritization of resource allocation during the system development, it is a recommended practice.

Risk is generally a highly uncertain characteristic of the system being developed; while there may be risk involved in the development or execution of the M&S itself, this generally is small in comparison to the deployed system (real world) risk. Like sensitivities, risk has a true value that is unknowable. It is recommended that the risk of a system be frequently analyzed by different means and by different practitioners throughout the life cycle of a program. These multiple efforts to assess the system should then be used as an ongoing approximate bounding of true risk. Even once the system has been deployed and is operational, the true risk of the system to its owners, users, and the general public, may have never been accurately estimated, as evidenced by any number of unexpected catastrophes throughout history. Risk is generally described by:

1. The likelihood of an event occurring.
2. The consequence of an event occurring.
3. The uncertainties associated with both the likelihood and consequence.

This definition leads to two specific recommendations:

1. Do not only consider “worst case events”; for every event of a given likelihood and consequence that might occur, there are surely many more lower consequence and more likely events in the same category that surely will occur.

2. Do not fail to consider the effect of uncertainty in the likelihood and consequence ratings.

From a statistical point of view, likelihoods of a very infrequent nature (i.e., 1 in 10,000 or 1 in 100,000) require millions to billions of samples (Monte Carlo analyses) in order to have 90 percent or greater confidence associated with the likelihood assessment; in contrast, the use of the probabilistic techniques known as First- and Second-Order Reliability Methods (FORM and SORM, respectively) should require fewer analyses in order to establish high confidence probability of failure estimates. Ideally, the system risk (or at least the uncertainty about the system risk) will decline over time due to the wise influences of the customer requirements, those involved with the analysis and management of the M&S, and the decision makers involved.

Validation is an uncertainty quantification and management process for M&S. Validation requires a comparison to the real world. The validation campaign is under the primary control of the customer or sponsor (funder of the program) but will also be very reflective of the knowledge of the analyst whose job it is to conduct validation testing in critical areas of the domain of interest and for critical inputs and responses. Other involved in the M&S development and testing process for the M&S will also contribute the validation effort. In preparing for a validation campaign, the following aspects should be considered:

- Will the validation be done in a deterministic or non-deterministic (probabilistic, possible, etc.) way?
- Will the validation consider function values, functional sensitivities, functional uncertainties, and functional sensitivity uncertainties?
- Will the sources for uncertainty quantification information include a single subject matter expert, multiple subject matter experts, a single higher-fidelity source, or multiple higher-fidelity sources?
- Does the referent data include a single data point, a small set of data points, a large set of data points, multiple large sets of data points, or some mix of these referents?
- Is the quality of the referent data known? If so, is the referent of high quality? Can some statistical confidence metrics be stated about the quality of the referent?
- Does the referent set consist of a single output or response or are many responses available for comparison? If many responses are available, is there any statistical correlation between them?
- Are the responses used for validation the true responses desired for validation or are they surrogates? That is, does the validation involve deduction or inference?
- Does the referent set cover the domain of interest for the system being developed or are the regions where the referent set does not provide useful comparisons with the current system?

Verification is a means to demonstrate the correctness of a given M&S implementation, compared to its programmatic requirements and numerical best practices. Verification recursively compares the functional model to its requirements from the conceptual model, the logical model to its requirements from the conceptual and functional models model, the mathematical model to its requirements from the conceptual, function, and logical models, etc. Verification includes the aspects of repeatability and reproducibility and also carries over from a comparison of the ensemble model of the system to the intended real world system. Within computational M&S, verification includes the two branches of: (1) code verification and (2) solution verification. The former aspect of verification (code verification) measures the degree to which the M&S code and numerical algorithms have been tested for errors. Code verification consists of software quality assurance activities such as version control, configuration management, documentation, regression testing, and numerical algorithm testing. Numerical algorithm testing focuses on the correctness of specific implementations of the numerical algorithms using test cases such as exact analytical solutions. Note: since it is not generally possible to prove a code correct, code verification is an ongoing activity to develop confidence; multiple application-relevant test problems should be developed with coverage for the M&S execution domain of interest. The latter aspect of verification (solution verification) measures the level of confidence of the M&S results based on estimates of numerical error associated with the M&S. Examples of numerical errors for M&S results include discretization error, iterative error, round-off error, and statistical sampling errors. The acceptable level of numerical error should be specified before the M&S is performed. Verification is under the primary control of the M&S developers and testers, subject to funding provided by the customer or sponsor of the program. For the aspects addressing system verification, one is interested in demonstrating that the system will perform in the same, correct way given the same input set at different times.

The “-ilities” (e.g., usability, reusability, testability, traceability, portability, flexibility, extensibility, modularity, reliability, supportability, maintainability) are a set of uncertain, desirable characteristics (but generally not required characteristics) that are frequently subject to design trades and which generally fall into two groups. The first group (usability, reusability, testability, traceability, portability, flexibility, extensibility, and modularity) are those characteristics for which the primary focus is for the M&S itself; the second group (reliability, supportability and maintainability) are those for which the primary focus is the system being developed. Those “-ilities” in the first group are generally under the control of the M&S developer and might be inferred from customer requirements. These are more likely to benefit the M&S developer’s organization in future M&S efforts unless the M&S itself is a deliverable to the customer. In the case where the M&S itself is a deliverable, the knowledge gained of how the M&S was constructed will, as a minimum, be helpful to inform future M&S efforts. The “-ilities” in the second group will be more explicitly defined within the customer requirements for the system, but again are frequently subject to trade for the benefit of increased system performance or lower system cost. Estimation of these quantities for the customer should be done within the context of these being uncertain quantities.

Appendix G. Interaction of M&S with Key Life Cycle Work Products

G.1 The Analysis and Simulation Plan (ASP)

The Analysis and Simulation Plan (ASP) is obviously the place where most people would think to look for the use of M&S within the program. This document is intended to describe all the M&S that will be performed specifically to design the customer's product. Specifically expected to be discussed in this document are calculations, interpolations, extrapolations, interpretations, comparisons, simulations, and calibrations. This document is created by the time the SRR occurs; it is updated by PDR, baselined by CDR, and finalized by the BRR. The document should address each of the eight generic M&S topics noted above. Of particular note for discussion in this document would be:

- How the system and subsystem representations will change over time
- How uncertainties estimates or distributions will be obtained and propagated between the various subsystems and between the subsystems and the system level analyses throughout the various lifecycle phases
- How sensitivities will be obtained and utilized
- How the system-level risk will be evaluated
- What are the specific validation sets that will be utilized and quality assessments of such
- How system-level verification will be performed
- How the system reliability/supportability/maintainability estimates will be obtained
- What, if any, M&S usability/reusability/testability/traceability/portability/flexibility/ extensibility requirements must be met and how such will be met

G.2 The Requirements Verification Plan (RVP)

The Requirements Verification Plan (RVP) defines the sequence by which hardware and software are combined into a functioning and unified higher-level element with all interfaces working. The plan identifies the processes, tasks, and actions used for verifying a delivered system's requirements. This document is created for the SRR; it is updated by PDR, baselined by CDR, revised by BRR, and finalized by, at, or before, the FRR. At first, this document may not seem relevant to the use of M&S, but more requirements are being stated in a probabilistic manner and M&S may be used to interpret or verify these kinds of requirements. Additionally, some requirements are specifically verified by either analysis or simulation. For other requirements subject to verification by demonstration, analysis, and/or test, it is likely that only a subset of the actual products may be verified and one may resort to arguments based on M&S in order to justify verification claims for those not subjected to strict verification. Any such usage of M&S within this context should be described and rationale provided for such choices.

G.3 Reliability Analyses (RA)

Reliability Analyses (RA) are a set of products resulting from the planned efforts described above in the ASP. These reports document what was actually done to obtain subsystem- and system-level reliability estimates; any discrepancies with the planned activities should be explained. Also, obviously, the results of the reliability analyses that were performed should be documented here. These documents are created for the SRR; it is updated by PDR, baselined by CDR, revised by BRR, and finalized by, at, or before, the FRR. As with any uncertain numbers, the reliability estimates that are obtained from these efforts should be stated as a mean values, plus or minus some interval, and having a confidence interval associated with the interval.

G.4 The Worst Case Design Analyses (WCA)

The Worst Case Design Analyses (WCA) demonstrate that at end of life for the product, all components (by incorporating margins) will meet their intended function both for application and for the environment used. This document is created for the SRR; it is updated by PDR, baselined by CDR, revised by BRR, and finalized by at or before the FRR. The document should address any use of M&S or probabilistic studies used to derive or justify the WCA conclusions. Of particular note in this document would be to highlight where one-factor-at-a-time (OFAAT) studies have been exclusively used to develop any conclusions, and more importantly to highlight where studies other than OFAAT studies have been used to develop the conclusions. It is well known in the statistical community that OFAAT studies may not reveal the actual worst set of combined conditions when multiple factors change together within the system or environment, particularly if the distributions of possible values for the factors involved are non-normal. It is therefore recommended that techniques such as Analysis of Variance (ANOVA[***]) be used to draw statistically meaningful conclusions for instances when multiple factors change together, whether the changes statistically correlated, or not.

G.5 The Algorithm Development Plan (ADP)

The Algorithm Development Plan (ADP) describes the algorithm architecture and relationship to hardware and software. The plan should, in particular, address any calibration aspects. This document is created for the SRR; it is updated for both the by PDR and CDR, baselined by the BRR, and finalized by, at, or before, the FRR. Any M&S used for calibration purposes should be described. In addition, the document should address any uncertainty or issues related to M&S performance on specific hardware platforms or units.

G.6 The Error Budgets and Allocation Analysis

The Error Budgets and Allocation Analysis describes how performance budgets are allocated to key subsystems and units, including how the tolerances imposed by design, fabrication, assembly and environmentally-induced uncertainties impact the system’s ability to meet its top-level requirements. This document is created and updated for the SRR; it is baselined for PDR, revised for CDR and BRR, and finalized for, at, or before, the FRR. While the error budget allocation may initially be done based upon historical trends, at some point, it is likely that M&S will be used assess at lower levels in the product design if the component can live with the error budget it has been given by the assembly, and if not, to suggest changes to error budget allocation that must be fed back up to the assembly, subsystem, or system and the entire error allocation scheme may need to be re-evaluated. A major M&S issue in this negotiation is how the various product levels are represented to other components, assemblies, and subsystems when the error allocation is performed. Too little detail in the representation of lower-level entities to higher-level entities may result in optimistic expectations for the error budget allocation, whereas too much detail in the representation of lower-level entities to higher-level entities may result in an impractical effort to determine a reasonable error allocation strategy. It should go without saying, because it is so obvious, that the error budget negotiation and allocation may have to necessitate changes in the customer requirements in order to allow for a feasible system design. Any use of M&S to inform the decisions made regarding the error budget formulation from customer requirements and its allocation to lower-level entities should be documented.

[***] See references 6, 7, 24, 32, 39, 46, 69, and 108 in Section 6.

G.7 The Concept of Operations (CONOPS)

The Concept of Operations (CONOPS) describes the general expectations for operations of a specific concept definition. Several CONOPS may be developed to represent different points of view, for example the usage and maintenance CONOPS would likely be distinct. This document is created, updated, and baselined for the SRR; it is revised for PDR, and finalized for CDR. Any M&S used for studies in the following areas, for example, should be documented:

- Fault management
- Health and status monitoring/reporting
- Anomaly resolution
- On-orbit configuration changes (software updates, system/subsystem state changes)
- Calibrations
- Maintenance
- Simultaneous operations
- On-board data and command processing
- Operational modes

Appendix H. Guidance for Writing an Intended Use Statement

An intended use statement is generally a way for either the customer to specify an M&S need to the M&S developer, or for an M&S developer to specify to potential or actual customers an existing capability. An intended use statement will likely evolve throughout the program life cycle as greater understanding of the needs and capabilities emerges. An intended use statement may take the form of a description (typically for a need) or a specification (typically for capability)[66]. Two aspects that are critical for an intended use statement are that it accurately specifies the need or capability, and that this information be clearly communicated to the user.

An intended use statement of an M&S should be considered as similar to a requirement statement. Thus, it should have the same characteristics as a good requirement. In the simplest form, the characteristics of a good requirement are that it is **necessary**, **verifiable**, and **attainable**[95]. But the intended use statement must also possess clarity. To expand upon these characteristics, each portion of a good intended use statement should include the following characteristics[26]:

- **Unitary (Cohesive):** addresses one thing and one thing only.
- **Complete:** fully stated in one place with no missing information.
- **Consistent:** does not contradict any other portion and is fully consistent with all authoritative external documentation.
- **Non-Conjugated (Atomic):** does not contain conjunctions (and/or); these should be written as two separate statements.
- **Traceable:** meets all or part of a business need as stated by stakeholders and authoritatively documented.
- **Current:** has not been made obsolete by the passage of time.
- **Feasible:** can be implemented within the constraints of the project.
- **Unambiguous:** concisely stated without recourse to technical jargon, acronyms (unless defined elsewhere in the statement), or other esoteric verbiage. It expresses objective facts, not subjective opinions. It is subject to one interpretation and one interpretation only. Vague subjects, adjectives, prepositions, verbs, and subjective phrases are avoided. Negative statements and compound statements are prohibited.
- **Mandatory:** represents a stakeholder-defined characteristic the absence of which will result in a deficiency that cannot be ameliorated. An optional requirement is a contradiction in terms.
- **Verifiable:** implementation can be determined through one of four possible methods: inspection, demonstration, test, or analysis.

Because decision-makers will use the results of M&S in support of critical decisions, there are also risks associated with the violation of an intended use statement. There is a risk that the intended use domain has not been accurately (or accurately enough) described to prevent misuse and there is a risk that the intended use statement has not been correctly interpreted or correctly implemented. Finally there is a risk the violations to the constraint set may not be properly detected while using the M&S. [**R30**] It is recommended that the intended use statement of an M&S be considered as having the same characteristics as good requirements statements, but with additional information provided about the risks associated with violations of the intended use.

The risk associated with proper specification of the intended use is diminished in proportion to how, and how much, the M&S has been used previously. The following points offer some guidance as to how to rate this risk, ranging from 1 (less risk) to 5 (more risk):

1. M&S has successfully been used in formal optimization under uncertainty studies or successfully coupled with a probabilistic driver.
2. M&S has been successfully used in formal optimization studies, coupled with an optimizer.
3. M&S has been successfully used in formal trade studies of related calculations/simulations.
4. M&S has been successfully used only in discrete and unrelated calculations/simulations.
5. M&S has no prior successful usage.

The following points offer some guidance as to the level of consequence associated with violating a particular portion of the intended use statement, ranging from 1 (less risk) to 5 (more risk):

1. M&S will fail and not produce a result.
2. M&S will produce a result, along with a warning message in response to a known and detected limitation violation.
3. M&S may/will produce a result that has not been verified or validated.
4. M&S may/will produce a result where validation is not possible (no validation set available, and on facility exists to produce validation data, the result cannot be validated on earth, etc.).
5. M&S may/will produce a result that violates a known law of physics.

Finally, the following questions should be asked relative to any intended use specification:

- How accurately are the true limitations of the intended use described by the set of constraints?
- How well are the limitations understood by the user?
- How accurately must the limitations be respected?
- How accurately will the current state vector of variables within the intended use domain be known?
- Is there a way from inside the intended use domain to determine that one is approaching the limitation boundary, or to detect that the M&S has crossed the limitation boundary?
- Will a violation of the intended use boundary lead to discontinuous behavior (fall off a cliff) or gradual deterioration (walking down a gentle hill)?

For the considerations noted above, the most useful form of an intended use statement might take the form of a set of constraints (much like those used with an optimization package) that evolves along with the M&S development, which are intended to prevent the user from going beyond the intended uses boundaries, and which includes some measure of the risk consequences associated with violations included.

Appendix I. Guidance for Determining the Minimum Cost of M&S

The space industry routinely faces situations where validation of predicted performance is difficult or impossible until the vehicle is actually on-orbit. These situations constitute the minimum set of conditions for which M&S should be used. Many other situations (e.g., concept exploration, subsystem design trades, requirements derivation, etc.) may arise within the satellite design process, or within the program management activities, for which the use of M&S is desirable. ***The following guidelines are provided to help the program management understand the potential true cost of M&S verification and validation within their program, and also the impact that their decisions have in driving the cost of the M&S validation within their program.*** [**R31**] It is recommended that programs attempt to determine the minimum, true cost associated with verification and validation of their M&S before undertaking such activities.

First, the cost of verification is most easily thought of as being driven by the number of computational units, as illustrated in Figure I-1. A computational unit may range from a single line of executable code (or a single line of data within an input file) to a logical block of statements grouped within a decision branch, to subroutines or functions, to whole executable codes. In general, computational units interface with other computational units (of the same or different scope) and each unit must be first verified in a stand-alone mode for proper execution or description of the inputs, and each interface must be verified to ensure proper (bi-directional?) interaction and communication flow between the units. Also, a hierarchy of verifications must be considered from the simplest units and interfaces through true multidisciplinary integration of numerous subsystem M&S. If the tools to be used for your M&S have been previously verified, little may need to be done in this area, but it is recommended that at least spot checks for correct execution among key units and interfaces be performed with every potential M&S application. If the tools to be used in your M&S are all developed new from scratch, or "substantially modified" from prior uses, you should assume that a full verification of all units and interfaces must be performed and you should question people that indicate a lack of need for this. The term "substantially modified" is unfortunately vague because it is possible that even innocuous changes may have far reaching, unintended consequences by overwriting the memory of a computer where prior data (or worse, code) has been stored. Finally, it is recommended that a single person be in charge of all verification activities for each unit and each interface, that is, one person is identified for each unit and each interface. Failure to identify a person with each interface is asking for trouble. The Figure I-2 illustrates in notional form the increasing cost of verification as the number of units and interfaces grows. It is recommended that the program management discuss this figure with their M&S developers and the people that will do the M&S verification.

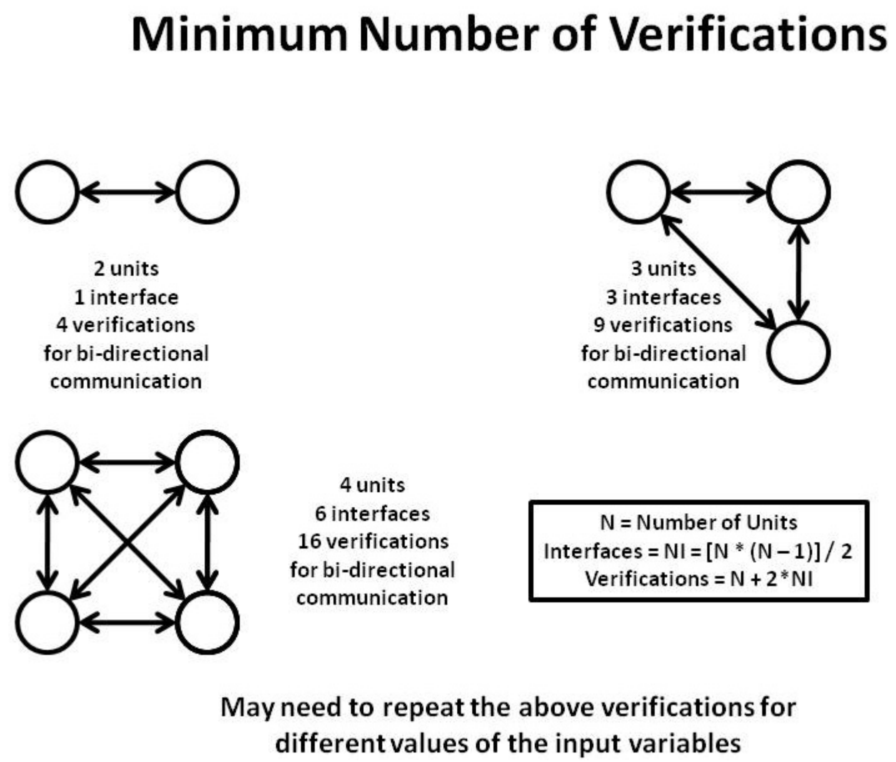


Figure I-1. The minimum number of verifications required.

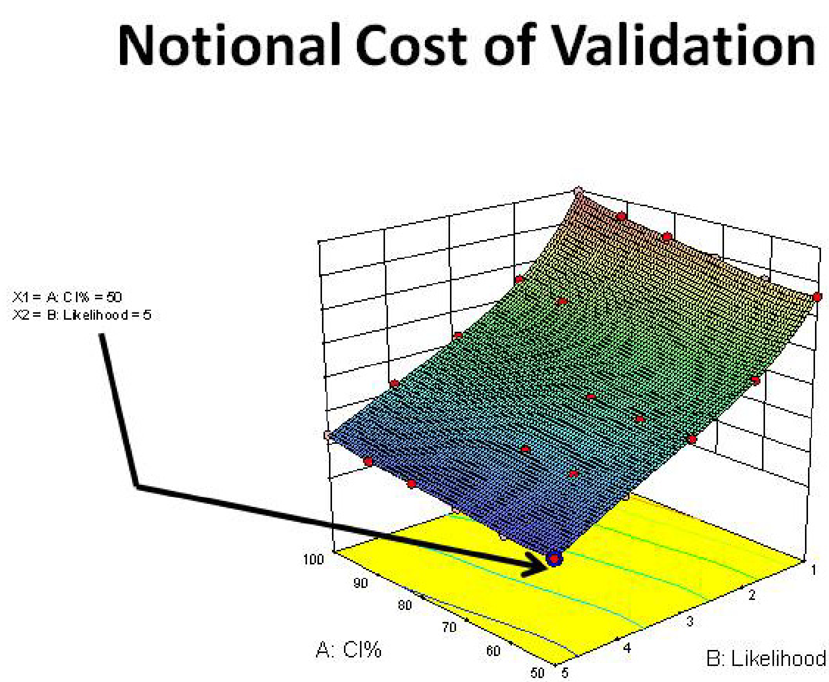


Figure I-2. The increasing cost of validation confidence.

Next, the cost of validation is most easily thought of as being driven by two factors: (1) the probability of the event being predicted, and (2) the level of confidence required by the decision maker about the event being predicted. The true cost of validation can be a significant portion of a program budget and few programs do a sufficient effort in validation; the cost of good validation is usually assumed to be a luxury that can be arbitrarily cut when other demands arise. The relationship between the probability (or likelihood) of the event being predicted and the decision maker's required confidence interval (CI%) level is notionally illustrated in Figure I-2, based on unpublished work of Green. In this figure, it is seen that event probability is a more significant cost driver than is the decision maker's confidence, but the validation of any low probability event at a high confidence interval will be a costly venture. The highlighted point in the figure is the baseline cost associated with a high likelihood of occurrence and low level of confidence required.

In actuality, the cost of validation depends upon many factors including:

- If the validation be done in a deterministic or non-deterministic (probabilistic, possibility, etc.) way
- If the validation only considers function values, or also functional sensitivities, functional uncertainties, and functional sensitivity uncertainties
- If the sources for uncertainty quantification[†††] information include a single subject matter expert, multiple subject matter experts, a single higher-fidelity source, or multiple higher-fidelity sources
- If the referent data include a single data point, a small set of data points, a large set of data points, multiple large sets of data points, or some mix of these referents?
- If the quality of the referent data known and if so, is the referent of high quality and if some statistical confidence metrics be stated about the quality of the referent
- If the referent set consist of a single output or response or many responses and if many responses are available, if any statistical correlation between them
- If the responses used for validation the true responses desired for prediction or are they surrogates and if the validation involves deduction or inference
- If the referent set cover the domain of interest for the system being developed or are the regions where the referent set does not provide useful comparisons with the current system?

Sometimes M&S preparation is the most time consuming event and numerous executions and analyses can be conducted with a single setup effort; other times, the execution or the analysis of the execution results will be the most time consuming aspect of the a given M&S. It is recommended that an M&S count be established based upon the most time consuming event in a given M&S activity and that a separate analysis count be established for each M&S activity to indicate how many time a given code will execute or the results be analyzed.

[†††]See references 11, 32, 44, and 49 in Section 6.

The following questions[‡‡‡] are intended to be discussion starters with the people responsible doing the M&S execution/analysis/validation to help the program management determine the true cost of validation.

1. How many program decisions involve or more of the following?
    a. No ground facility exists to test the combined on-orbit physical conditions (e.g., near-zero gravity, low and high temperature cycles due to exposure to sunlight, and radiation)
    b. The cost or scheduling of a suitable existing ground facility to test the combined on-orbit physical conditions results is prohibitive
    c. Other programmatic situations requiring M&S (risk reduction, etc.)

The answer to the above question provides a lower bound to the number of M&S that must be under taken (N1). Within each M&S activity, a number of analyses need to be performed to provide the information needed by decision makers. The answers to the following un-prioritized list of questions will likely increase the number of M&S executions and /or analyses that must be undertaken:

2. Do you wish to have a quantified confidence level for each solution for the N1 decisions?
3. If the answer to question 2 is yes, what confidence interval (CI) do you wish to obtain? This choice or requirement is usually given as a percentage between 0 and 100% and is shown in Figure I-2 as CI%. If the answer to question 2 is yes, then at least two distinct M&S (or analysis) must be undertaken for each of the N1 decisions (N2 = 2 * N1) at the same conditions. If two M&S are undertaken at the same conditions using different codes, a standard deviation and least significant difference can be developed for the set of solutions. This allows for the prediction of the CI% bounds required here.
4. Do you wish to have any information about how the answer to each of the N1 decisions might change due to uncertainty or variability of conditions (sensitivities)?
5. If the answer to question 4 is yes, is a linear approximation of the changes sufficient, or is a non-linear approximation required? If the answer to question 4 is yes, then at least one M&S (or analysis) must be executed at two different conditions. This enables the development linear finite difference sensitivities. If a non-linear approximation is required (question 5), then at least on M&S must be executed a minimum of three times.
6. If the answer to question 2 is yes, do you wish to be able to validate the confidence level associated with question 3? This validation of the stated confidence level will a costly venture for low probability events for which a high confidence level is required by the decision maker.
7. How many disciplines must be represented to provide solutions for each of the N1 decisions enumerated above? Each discipline will have to be independently validated, much like computational units are verified above, and then validated as an integrated system. Interdisciplinary executions and validations should occur only after disciplinary executions and validations have been completed.
8. Is the required fidelity of each discipline M&S known, a priori, to answer the N1 decisions? If not, some experimentation will likely be needed to establish sufficient fidelity and to demonstrate fidelity independence of the predicted solution.
9. Is a certain accuracy of the solutions required or desired? This may or may be achievable; it is possible that no available tool can produce the required accuracy, or that the required accuracy may entail representational fidelity that is cost prohibitive. Accuracy requirements also imply

[‡‡‡]See references 1, 14, 17, 21, 28, 29, 30.40, 47, 50, 54, 55, 56, 60, 73, 75, 76, 77, 82, 89, 91, 93, 96, 100, 104, 106, 107, 110, and 113 in Section 6.

that the accuracy can be measured, which is generally only true for validation points, not for prediction points. Still, it is good to know if someone expects to obtain a specific level of accuracy.

10. Do you wish to have field properties (graphics, pressure coefficient, element stresses, point wise descriptions of conditions along a trajectory, etc.) for the decision solution, or are integrated results sufficient? The need for field solutions means that having done lots of work in the neighborhood of the final solution, that the M&S must be actually executed at the exact conditions for which the field properties are required; this may necessitate further iteration to achieve the exact conditions required.
11. Is the M&S prep time greater than the M&S execution time? If so, count M&S preps, if not, count M&S executions. Does one M&S prep service multiple M&S executions, or each M&S execution needs a distinct M&S prep?
12. Has the chosen M&S been recently used? If not, there will likely be a need one or more start-up executions to see if the M&S is still working as expected, especially if the current application uses a different computer platform, operating system, or compiler and libraries than the previous execution.
13. Is the current user familiar with the M&S? If not, there will likely be a need for one or more start-up executions to get user up to speed.
14. Is the best M&S user available to help with this application? If not, the current user may have to demonstrate their capability to generate results consistent with prior uses.
15. How many flight conditions need to be simulated? A typical scenario might need to consider various off-nominal situations, such as pad abort, launch, first-stage separation, second stage operation, beginning of life on orbit, on-orbit maneuver situations and de-orbit conditions.
16. Is event risk quantification required? Event risk quantification may require M&S executions to assess both likelihood and consequence; the likelihood assessment requires the use of some form of probabilistic analysis, possibly performed with a lower fidelity M&S than the actual event prediction, plus one or more anchoring solutions to establish the UQ bounds for the predicted event likelihood. Event UQ analysis typically requires a minimum of 10 executions to establish a statistically significant sample set.
17. How many additional verification/validation/accreditation cases are required by other aspects of the program?
18. Is the M&S known to be robust; that is the M&S never fails? If not, it may be necessary to “sneak up” on the desired solutions.
19. Does this M&S application involve new M&S grids, methods, conditions, loads, etc. or is there some reuse possible? This effects how much verification and M&S setup time may be required.
20. Are there any known uncertainties in the mechanical, material, environmental properties?
21. Are different material choices possible?

Appendix J. Annotated Bibliography of M&S to Support M&S Planning (courtesy W. Tucker)

J.1 M&S Program Planning

Surprisingly few publications are available to guide program level M&S planning, although the need to do such planning is well documented. The documentation that is available focusing on the planning needs of the government program office, rather than the program. To a great extent planning for M&S is similar to any other kind of planning, but the unique needs of M&S must be addressed.

- Simulation Support Planning and Plans DA PAM 5-12
  http://www.army.mil/usapa/epubs/pdf/p5_12.pdf
- Modeling and Simulation Support Plan
  http://www.dtic.mil/ndia/2007systems/Tuesday/PM/Track5/5603.pdf

The Defense Acquisition University in Modeling and Simulation in Systems Engineering course includes an overview level segment on M&S planning

Defense Acquisition University course CLE011 at https://learn.dau.mil/html/clc/Clc1.jsp

J.2 M&S Development Processes

This is a foundational paper about M&S development methods and tools.

Simulation Model Development Framework - Nance
http://eprints.cs.vt.edu/archive/00000056/01/TR-87-08.pdf

Most recent discussion about M&S development processes are focused on and driven by verification and validation processes. These publications emphasize the need for integration between development and Verification and validation processes.

- High level developmental process description http://vva.msco.mil/Diagram/process-new/process-new.htm
- Verification and Validation of Simulation Models – Sargent
  http://delivery.acm.org/10.1145/1170000/1162736/p130-sargent.pdf?key1=1162736&key2=4794734721&coll=GUIDE&dl=GUIDE&CFID=89056290&CFTOKEN=51914650

This paper provides general guidance for planning M&S development based on a wide scope literature search.

Recommended Practices for Homeland Security Modeling and Simulation, Jain and MacLean,
http://www.informs-sim.org/wsc09papers/279.pdf

This paper provides a pragmatic view of the simulation development process, emphasizing the need for understanding of both the intended use and the system to be simulated.

What are the fundamental steps in building a Simulation?
http://www.imcva.com/simulation_4.htm

J.3 M&S Life Cycles

Because M&S is used to support the system life cycle in many ways, at different times in the program, supporting very different levels of maturity of the underlying system's design, and with different required confidence levels; no single life cycle model is always best. The selection of the life cycle for a given M&S development should consider the development timeframe, required level of confidence, availability, and maturity of the needed data, and the maturity and predicted change rate of the M&S requirements. Since the data and requirements are rarely stable, some type of spiral development is often applied to M&S development

Development Paradigms http://vva.msco.mil/ , select Special Topics, then Development paradigms

J.4 M&S Need Statements (intended uses)

Although there is wide agreement about the need to document the intended use for a simulation, very little data is available to describe how to do so. DA PAM 5-11, while Army centric suggests content of need statement (pg. 8) and provides some example (pg 44). It also provides a useful overview of M&S development, VV&A, and application processes, and provides outlines for relevant documents

Department of the Army Pamphlet 5-11 -Verification, Validation, and Accreditation of Army Models and Simulations
https://acc.dau.mil/GetAttachment.aspx?id=25731&pname=file&aid=3169&lang=en-US

Page 3 of this Department of Defense Modeling and Simulation Coordination Office reference document describes the creation of a need statement

A Practitioner's Perspective on Simulation Validation
http://vva.msco.mil/Ref_Docs/Val_Lawref/Val-LawRef-pr.pdf

Page 12-16 of this MSCO reference document provides a set of criteria by which M&S requirements quality can be judged

V&V Agent Role in the V&V of legacy Simulations
http://vva.msco.mil/Role/VVAgentLegacy/vv-leg-pr.pdf

J.5 M&S Conceptual Model

The following references were created based on experience in validating conceptual models for very large, complex simulations, but even fairly simple conceptual models should touch on most of the suggested areas. The Need Statement (intended use) references above also describe conceptual modeling.

- Development and Validation http://vva.msco.mil/Special_Topics/Conceptual/conceptual-pr.pdf

- Conceptual Model Template http://vva.msco.mil/Templates/conceptual_template/conceptual_template_pr.pdf

J.6 M&S Verification, Validation, and Accreditation

The Department of Defense VV&A Recommended practice guide is the most broad based and most widely cited description of VV&A available.

Defense Modeling and Simulation Coordination Office VV&A Recommended Practice Guide http://vva.msco.mil/

Verification, Validation, and Accreditation(VV&A) of Federations, Final Report of Modeling and Simulation

Group 019 / Task Group 016, RTO Technical Report TR-MSG-019, April 2008.

Not all problems with VV&A have been solved. This article provides an overview of the issues involved, and includes an extensive set of references.

Modeling and Simulation Verification and Validation Challenges, Pace, http://www.jhuapl.edu/techdigest/td2502/Pace.pdf

J.7 Other useful resources

- Fidelity Implementation Study Group Report http://vva.msco.mil/Ref_Docs/Ref_Docs/99s-siw-167.pdf

- The Certified Modeling and Simulation Professional Program http://www.scs.org/magazines/2010-01/index_file/Files/article_Lewis-Rowe.pdf

J.8 M&S Text Books

There are many M&S textbooks available – Amazon.con claims to have over 3000. This short list is intended to provide an introduction to this very broad subject.

- Cloud and Rainey, Applied Modeling and Simulation, An Integrated Approach to Development and Operation, McGraw Hill, 1998
- Banks, J. (ed), Handbook of Modeling and Simulation, John Wiley, 1998
- Birta and Arbez, Modeling and Simulation, Springer, 2007
- Law & Kelton Simulation Modeling and Analysis, McGraw Hill, New York, 2000
- Ziegler, Praehofer, and T-G. Kim, Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems, Academic Press, 2000
- Zipfel, Modeling and Simulation of Aerospace Vehicle Dynamics, AIAA, 2007

J.9 M&S Education resources

The following Universities offer academic degrees in Modeling and Simulation and have M&S related institutes or research centers

- Old Dominion University – Virginia Modeling and Simulation Center *www.vmasc.odu.edu*
- University of Alabama at Huntsville – Center for Modeling, Simulation, and Analysis *cmsa.uah.edu*
- University of Central Florida – Institute for Simulation and Training *www.ist.ucf.edu*

Many universities and commercial companies offer M&S continuing education or short course opportunities.

J.10 M&S-Related Organizations

- DoD Modeling and Simulation Coordination Office: http://www.msco.mil
- Army modeling and Simulation Office: http://www.amso.army.mil
- Navy Modeling and Simulation Office: https://nmso.navy.mil/
- Air Force Agency for Modeling and Simulation: http://www.afams.af.mil
- DoD M&S Information Analysis Center (MSIAC): www.dod-msiac.org
- DoD Survivability/Vulnerability Information Analysis Center (SURVIAC): http://www.bahdayton.com/surviac/
- American Institute for Aeronautics and Astronautics - Modeling and Simulation Technical Committee https://info.aiaa.org/tac/ASG/MSTC/default.aspx
- ACM Simulation Special Interest Group www.sigsim.org
- InterService/Industry Training and Simulation Conference http://www.iitsec.org
- NDIA Systems Engineering Division M&S Committee: http://www.ndia.org/divisions/modeling
- Simulation Interoperability Standards Organization: http://http://www.sisostds.org
- Society for Modeling and Simulation International http://www.scs.org/
- Winter Simulation Conference www.wintersim.org