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National Aeronautics and Space Administration	**Approved:** 2016-07-13 Superseding NASA-STD-7009 (Baseline)

STANDARD FOR MODELS AND SIMULATIONS

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DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Interim			2006-12-01	Initial Baseline Release
Baseline			2008-07-11	Baseline Release
Revision	A		2016-07-13	Restructure Section 4; Criticality, Credibility, & Risk Assessment updates & additions; Reporting updates; general reformat per NASA-NTSP-2A STD Instructions with numbering of all requirements and addition of Appendix A, Requirements Compliance Matrix; boilerplate update to section 1.2.

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FOREWORD

This NASA Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods endorsed as standard for models and simulations (M&S) developed and used in NASA programs and projects, including requirements for selection, application, and design criteria of an item. This NASA Technical Standard was originally developed to respond to Action 4 from the 2004 report "A Renewed Commitment to Excellence," with consideration also given to related findings as identified in the Columbia Accident Investigation Board (CAIB) Report. This first revision continues to evolve the concepts of the Baseline version from experiences in its implementation.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

This NASA Technical Standard establishes requirements and recommendations for the development and use (or operation) of M&S, as well as the analysis and presentation of the results from M&S. This also includes the proper training of M&S practitioners and the identification of recommended practices, while ensuring the credibility of the results from M&S is assessed and clearly conveyed, especially for critical decisions.

Requests for information should be submitted via "Feedback" at https://standards.nasa.gov. Requests for changes to this NASA Technical Standard should be submitted via MSFC Form 4657, Change Request for a NASA Engineering Standard.

Original Signed By:	***07-13-2016***
Ralph R. Roe, Jr.	Approval Date
NASA Chief Engineer	

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STANDARD FOR MODELS AND SIMULATIONS

1. SCOPE

This NASA Technical Standard establishes uniform practices in modeling and simulation to ensure essential requirements are applied to their design, development, and use, while ensuring acceptance criteria are defined by the program/project and approved by the responsible Technical Authority.

This NASA Technical Standard provides an approved set of requirements, recommendations, and criteria with which models and simulations (M&S) may be developed, accepted, and used in support of NASA activities. As the M&S disciplines employed and application areas involved are broad, the common aspects of M&S across all NASA activities are addressed. The discipline-specific details of a given M&S should be obtained from relevant recommended practices.

1.1 Purpose

The primary purpose of this NASA Technical Standard is to reduce the risks associated with M&S-influenced decisions by ensuring the complete communication of the credibility of M&S results. The requirements and recommendations contained herein provide a basic set of best practices applicable to any M&S. This NASA Technical Standard achieves this by establishing a minimum set of requirements for the key elements related to M&S, including development, maintenance, operation, results analysis, training, credibility assessment, and reporting. This NASA Technical Standard covers what needs to be accomplished and communicated, not how it is to be done. Discipline-specific recommended practice guides should be consulted for specific applications or methodologies.

1.2 Applicability

This NASA Technical Standard:

- Is applicable (relevant and appropriate) to all M&S used by NASA, its contractors, and its partners.
- Covers M&S used in design, development, manufacturing, ground operations, and flight operations.
- Is highly recommended for M&S used in critical decisions or functions.

Any required application of this NASA Technical Standard is to be specified in program/project/organization/office directives and may be tailored (refer to section 1.3 for tailoring requirements).

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[M&S 1] When conflicts exist between this NASA Technical Standard and voluntary consensus standards (VCS), this document shall take precedence, except in those cases where the VCS is invoked by applicable Government regulation.

This NASA Technical Standard is approved for use by NASA Headquarters and NASA Centers and Facilities and may be cited in contract, program, and other Agency documents as a technical requirement. It may also apply to the Jet Propulsion Laboratory and other contractors only to the extent specified or referenced in applicable contracts.

Verifiable requirement statements are numbered and indicated by the word "shall"; this NASA Technical Standard contains 39 requirements. Explanatory or guidance text is indicated in italics beginning in section 4. To facilitate requirements selection and verification by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix A.

1.3 Tailoring

[M&S 2] Tailoring of this NASA Technical Standard for application to a specific program/project/organization/office shall be formally documented as part of program/project/organization/office requirements and approved by the responsible Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.

2. APPLICABLE DOCUMENTS

2.1 General

The document listed in this section contains provisions that constitute requirements of this NASA Technical Standard as cited in the text.

2.1.1 [M&S 3] The latest issuances of cited documents shall be used unless otherwise approved by the assigned Technical Authority.

2.1.2 [M&S 4] Non-use of specifically designated versions shall be approved by the responsible Technical Authority.

The applicable document is accessible at https://standards.nasa.gov, may be obtained directly from the Standards Developing Body or other document distributors, or information for obtaining the document is provided.

2.2 Government Documents

National Aeronautics and Space Administration (NASA)

NPR 7120.5	NASA Space Flight Program and Project Management Requirements

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2.3 Non-Government Documents

None.

2.4 Order of Precedence

2.4.1 The requirements and standard practices established in this NASA Technical Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation.

2.4.2 [M&S 5] Conflicts between this NASA Technical Standard and other requirements documents shall be resolved by the responsible Technical Authority.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
ANOVA	Analysis of Variance
ASME	American Society of Mechanical Engineers
CAIB	Columbia Accident Investigation Board
CM	Configuration Management
COTS	Commercial-Off-The-Shelf
CPIAC	Chemical Propulsion Information Analysis Center
DoD	Department of Defense
FS	Factors of Safety
GOTS	Government-Off-The-Shelf
HDBK	Handbook
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
JANNAF	Joint Army-Navy-NASA-Air Force
M&S	Model and Simulation; or Models and Simulations
M&SCO	Modeling and Simulation Coordination Office
Mgt.	Management
MOTS	Modified-Off-The-Shelf
MUF	Model Uncertainty Factor
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NPR	NASA Procedural Requirements
Rec.	Recommendation
RPG	Recommended Practices Guide
RWS	Real World System
SAE	Society of Automotive Engineers
SME	Subject Matter Expert
STD	Standard
V&V	Verification and Validation

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VCS	Voluntary Consensus Standard
VV&A	Verification, Validation, and Accreditation

3.2 Definitions

The definitions listed below are those used in this document. Wherever possible, these definitions have been taken from official NASA documents. In some cases, after reviewing definitions of interest in the International Organization for Standardization (ISO), the Department of Defense (DoD) Modeling and Simulation Coordination Office (M&SCO), professional society publications, and English language dictionaries, some of these definitions were taken or adapted from these sources to achieve the goal and objectives stated in section 1.1. Some definitions may have alternate meanings in other documents and disciplines.

Abstraction: The process of selecting the essential aspects of a source system or referent system to be represented in a model or simulation, while ignoring those aspects not relevant to the purpose of the model or simulation. Any modeling abstraction carries with it the assumption that it does not significantly affect the intended uses of the M&S.

Accepted Use: The successful outcome of a Use Assessment designating the M&S is accepted for a Proposed Use.

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

Actual Use: The specific purpose and domain of application for which an M&S is being, or was, used.

Aleatory Uncertainty: The inherent variation in the physical system; it is stochastic and irreducible without changes to the system or how it operates.

Analysis: The examination of a situation or problem in order to understand the item in question and make appropriate recommendations. Analysis spans the whole extent of the M&S process from the study of the Real World System (RWS) and/or its referents, the gathering and reduction of data from the RWS or accepted referents for incorporation into a model, the development of simulation scenarios, and the study and reduction of data from use of the M&S into recommendations for the RWS.

Artifact: Any tangible product produced by the project team, e.g., requirements, documents, help systems, code, executables, test documentation, test results, and diagrams.

Assumption: Asserting information as a basis for reasoning about a system. In modeling and simulation, assumptions are taken to simplify or focus certain aspects of a model with respect to the RWS or presume values for certain parameters in a model.

Calibration: The process of adjusting numerical or modeling parameters in the model to improve agreement with a referent. **Note:** Calibration can also be known as “tuning.”

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Caveat: "An explanation to prevent misinterpretation, or a modifying or cautionary detail to be considered when evaluating, interpreting, or doing something." (http://www.merriam-webster.com/dictionary/caveat)

Computational Model: The operational or usable implementation of the conceptual model, including all mathematical, numerical, logical, and qualitative representations. This may also be known as "simulation model."

Conceptual Model: The collection of abstractions, assumptions, and descriptions of physical components and processes representing the reality of interest, which includes the RWS, its environment, and their relevant behaviors. **Note:** The conceptual model provides the source information for conceptual validation with respect to the RWS, model construction, and model verification. It may consist of flow charts, schematic drawings, written descriptions, math models, etc., that explain the RWS and its interaction with the surrounding/interfacing environment. The conceptual model should be independent of any specific model implementation.

Conceptual Validation: The process of determining the degree to which a conceptual model (as defined in this NASA Technical Standard) or model design adequately represents the real world from the perspective of the intended uses of the model or the simulation.

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

Correlated (as in an M&S correlated with a RWS): The extent to which an M&S and RWS, or some aspect of an M&S and RWS, behave similarly due to a particular change in some set of input variables, parameters, perturbations, etc.

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

Critical Decision: The selection of a course-of-action related to design, development, manufacturing, ground, or flight operations that may significantly impact human safety or mission success, as measured by program/project-defined criteria.

Data Pedigree: A record of traceability from the data's source through all aspects of its transmission, storage, and processing to its final form used in the development of an M&S. (Any changes from the real-world source data may be of significance to its pedigree. Ideally, this record includes important quality characteristics of the data at every stage of the process.)

Design of Experiments (or Experimental Design): A series of tests in which purposeful changes are made to the input variables of a system or process and the effects on response variables are measured. It is applicable to both physical processes and computer simulation models.

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Deterministic: A term describing a system whose time evolution can be predicted exactly. **Note:** for comparison, see definition of "Probabilistic."

Domain of Validation: The region enclosing all sets of model inputs for which the M&S's responses compare favorably with the referent.

Domain of Verification: The region enclosing all sets of model inputs for which the solution is determined to be correct and satisfy requirements for computational accuracy.

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

Emulation: The use of an M&S to reproduce the function or action of another system.

Epistemic Uncertainty: A lack of knowledge of the quantities or processes identified with the system; it is subjective, is reducible, and comprises both model and parameter uncertainty.

Factor of Safety: A multiplicative factor applied to the parameters of an M&S (that is, in a model, in the input to a model, or in the output of a model) to ensure the adequacy of the RWS to meet specific requirements (adapted from NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware.)

Formal Training: Instructor-led training of at least the depth of a semester-long university course at the advanced undergraduate or graduate level.

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).

Input Pedigree: A record of traceability from the input data's source through all aspects of its transmission, storage, and processing to its final form when using an M&S. (Any changes from the real-world source data may be of significance to its pedigree. Ideally, this record includes important quality characteristics of the data at every stage of the process.)

Intended Use: The expected purpose and application of an M&S.

Key Input Data: Input to the model with high relevance to the analysis.

Limits of Operation: The bounding set of parameters for an M&S, based on the outcomes of verification, validation, and uncertainty quantification, beyond which the accuracy, precision, and uncertainty of the results are indeterminate.

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Margin: The allowances carried in budget, projected schedules, and technical performance parameters (e.g., weight, power, or memory) to account for uncertainties and risks (NASA-SP-2007, NASA Systems Engineering Handbook).

Mathematical Model: The mathematical equations, boundary values, initial conditions, and modeling data needed to describe the conceptual model (adapted from *ASME V&V 10, Verification and Validation in Computational Solid Mechanics*).

Mission Success Criteria: Specifications against which the program or project will be deemed to have achieved operational objectives.

Model: A description or representation of a system, entity, phenomenon, or process (adapted from Banks (1998). **Note:** 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 are considered part of the model.

Modeling: The act of creating a model, i.e., the act of creating a representation of a system.

Model Capability: The potential or ability (of a model) to represent an RWS, entity, phenomenon, or process.

Model Uncertainty: Variation in M&S results due to assumptions, formulas, and representations, and not due to factors inherent in the RWS.

Model Uncertainty Factor (MUF): A semi-quantitative (i.e., a quantitative magnitude based on past experience rather than data) adjustment, either additive or multiplicative or both, made to the results of an M&S-based analysis to account for uncertainty. **Note:** The MUF is also likely to have some associated confidence or coverage range.

Numerical Errors: Errors traceable to various sources, including but not limited to, floating point precision, inherent in all computer systems and leading to round off, underflow, and overflow; truncation of infinite series expansions; and approximations of exact solutions inherent in all numerical methods, e.g., approximation of derivatives and integrals by algebraic operations on sampled continuous functions.

Permissible Use: The purposes for which an M&S is formally allowed.

Probabilistic: Pertaining to non-deterministic events, the outcomes of which are described by a measure of likelihood.

Proposed Use: A desired specific application of an M&S.

Real World System: The reality of interest a model is representing, which may include relevant operating conditions or aspects of its environment. **Note:** The RWS may interact with its environment, i.e. a set of relevant elements external to the RWS, through the exchange of

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properties. The term RWS is used to differentiate between the "system represented" and the "modeling system" used for the analysis.

Recommended Practices: Guidelines developed by professional societies, best practices documented for specific simulation codes, and NASA handbooks and guidebooks.

Referent: Data, information, knowledge, or theory against which simulation results can be compared (adapted from ASME V&V 10, *Guide for Verification and Validation in Computational Solid Mechanics*). **Note:** A referent may be the RWS to which the analysis is directed, a similar or analogous system (whereby the closeness of the referent to the RWS becomes pertinent), or a higher-fidelity model.

Regression Testing: Selective checking of the quality, performance, or reliability of an M&S system or component to verify that modifications have not caused unintended effects and that the M&S still complies with its requirements (adapted from ISO/IEC/IEEE 24765:2010 Systems and software engineering--Vocabulary). **Note:** This term is in no way related to statistical regression analysis.

Responsible Party: The group or individual identified as accountable for complying with requirements in this NASA Technical Standard. **Note:** different parties may be identified for the various requirements.

Results Robustness: The characteristic whereby the behavior of (result from) an M&S does not change in a meaningful way to relatively slight variations in parameters. The results from an M&S are robust if they are relatively stable (do not change in a meaningful way) with respect to changes in the parameters or input variables of the M&S. Key sensitivities are parameters and variables shown to produce large changes in results with relatively small perturbations to input.

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

Scenario: The description or definition of the relevant system and environmental assumptions, conditions, and/or parameters used to drive the course of events during the run of a simulation model. It may include, but is not limited to, the set of initial conditions, a set of assumptions, the values of relevant parameters (including system and environmental conditions, locations and quantities of objects, entities, or resources), or a sequence of actions, which may be specified in the model itself. **Note:** Running the model with the given scenario is the simulation.

Sensitivity Analysis: The study of how variation in the output of an M&S can be apportioned to different sources of variation in the model input and parameters. **Note:** The results robustness of an M&S-based analysis is obtained via sensitivity analysis (adapted from Saltelli, 2005).

Simulation: The imitation of the behavioral characteristics of a system, entity, phenomenon, or process.

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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 RWS, training, maintenance, or for research and development.

Stochastic: Involving or containing a random variable or variables. Pertaining to chance or probability. (http://mathworld.wolfram.com/Stochastic.html)

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 their expertise.

Tailoring: The process used to adjust or modify a prescribed requirement to better meet the needs of a specific program/project task or activity.

Uncertainty: (a) The estimated amount or percentage by which an observed or calculated value may differ from the true value; (b) 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 8715.3, NASA General Safety Program Requirements); (c) Non-negative parameter characterizing the dispersion of values attributed to a measured quantity.

Uncertainty Characterization: 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 either qualifying or quantifying uncertainties in all relevant inputs and outputs of the simulation or experiment.

Unit Testing: Any type of software testing conducted on the smallest meaningful, testable fragments of code to ensure the code behaves exactly as intended under various conditions. For procedural programming languages, such code fragments are generally functions or subroutines.

Use Assessment: The process of determining if an M&S is accepted for a Proposed Use.

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 M&S.

Verification: The process of determining the extent to which an M&S is compliant with its requirements and specifications as detailed in its conceptual models, mathematical models, or other constructs.

Voluntary Consensus Standards (VCS): Standards developed or adopted by VCS bodies, both domestic and international, that include provisions requiring that owners of relevant intellectual property have agreed to make that intellectual property available on a non-discriminatory, royalty-free, or reasonable royalty basis to all interested parties. (Source: OMB Circular No. A-119.)

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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.

4. REQUIREMENTS

This NASA Technical Standard establishes a minimum set of requirements and recommendations for M&S influencing or supporting decisions, particularly critical decisions.

Decisions based entirely or partially on M&S are usually made within the context of a program or project. The risk assumed by the program or project is often incorrectly estimated due to a number of factors that may occur throughout the development and use of an M&S, not the least of which is an inadequate assessment of uncertainties. This NASA Technical Standard establishes practices to help reduce, assess, and communicate risk by making the factors leading to M&S credibility more apparent. As such, this NASA Technical Standard contains a number of assessments that occur during the life cycle of an M&S. This NASA Technical Standard provides a general M&S life cycle process, which parallels the NASA program/project management life cycle, as a basis for understanding the application of the requirements and recommendations it contains (see Appendix F – M&S Life Cycle). These requirements and recommendations emphasize documentation and control of M&S processes and products to enforce transparency, repeatability, and traceability and also encourages the appropriate training and experience base for key M&S personnel.

The requirements and recommendations in this NASA Technical Standard are generic in nature because of their broad applicability to all types of M&S. Implementation details should be addressed in discipline-specific recommended practices, program/project/program management plans, etc. Specific requirements applicable to M&S implemented in software are found in the NASA Software Engineering Requirements (NPR 7150.2).

The following organizational structure is employed in this NASA Technical Standard:

4.1 M&S Programmatics, including:

- *Planning across the M&S Cycle.*
- *Identification and Use of Recommended Practices.*
- *Training.*

4.2 M&S Development, including:

- *Verification.*
- *Validation.*
- *Uncertainty Characterization.*

4.3 M&S Use (Operations), including:

- *Uncertainty Characterization.*
- *Sensitivity Analyses.*

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- *Assessing the Credibility of M&S Results.*
- *Reporting Results to Decision Makers.*

In many instances, the modeling, simulation, and analysis activities are interwoven, particularly during the development, verification, and validation phases, but also may occur during the use (or operation) of an M&S. This NASA Technical Standard is intended to be inclusive of all these possibilities.

Program and project management have the responsibility to identify and document the parties responsible for complying with the requirements in this NASA Technical Standard. The actual person identified to fulfill the role of the "responsible party" in specific requirements will likely vary depending upon the context of the requirement. 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. Additionally, program and project management in collaboration with the Technical Authority have the responsibility to identify and document the extent and level of formality of processes (including any assessments) and documentation needed to meet the requirements in this NASA Technical Standard. Furthermore, the Technical Authority has the particular responsibility to assure appropriate outcomes of [M&S 8], [M&S 23], and [M&S 31].

The documentation requirements do not imply that either the activity in question is required or that a new document for the model, simulation, or analysis is needed. The intent is, however, to document what about the activity was either accomplished, or not accomplished. Also, if some evidence or artifact of the relevant activity is available, then a reference to that evidence (e.g., a journal article, a technical report, an M&S development/test document or computer file, an M&S user/operator guide, or a program/project document) may suffice, provided that all the required details are contained therein and that specific locations of the required information is given.

The responsibility party is to provide a rationale why any requirement (or recommendation, if imposed by tailoring or direction) is not met.

4.1 M&S Programmatics

The overarching topics of determining M&S criticality, defining basic objectives, requirements, and recommendations for M&S development and use, and understanding the results from any technical reviews performed related to the M&S are considered programmatic activities. One key task when moving toward the creation of a new M&S is defining its intended use, that is, the expected purpose and application of an M&S. This provides the initial basis of development and feeds into the concepts of "accepted use" at the end of development (section 4.2) and "proposed use" at the beginning of M&S use (section 4.3).

Program and project management in collaboration with the Technical Authority have the responsibility to identify and document the critical decisions to be addressed with M&S and to determine which M&S are in scope, based upon the criticality of the situation addressed by the proposed use of the M&S. Appendix D describes a representative M&S criticality assessment matrix for this purpose.

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4.1.1 General M&S Programmatics

The responsible party performs the following:

a. [M&S 6] Shall perform and document the criticality assessment for the M&S.

[Rationale: The criticality assessment ensures communication of the amount of influence an M&S has on a particular situation relative to the consequences of that situation.]

Appendix D describes a representative method for assessing criticality. The method used, either Appendix D as is or modified, or another method, should be documented.

b. [M&S 7] Shall identify and document if the M&S is in scope of this NASA Technical Standard.

[Rationale: Identifying that an M&S is in scope of this standard (including any tailoring) ensures clarity to M&S developers, users, and analysts as to what they are required to accomplish in their development or use of the M&S.]

All M&S used to support critical decisions, as determined by the outcome of compliance with [M&S 6], are in scope of this NASA Technical Standard. Beyond that, at the discretion of program/project management and the Technical Authority, any other M&S may be deemed in scope of this NASA Technical Standard.

c. [M&S 8] Shall define the objectives and requirements for M&S products including the following:

(1) The acceptance criteria for M&S products, including any endorsement for the M&S.

(2) Intended use.

The intended uses may be updated throughout the model development.

(3) Metrics (programmatic and technical).

(4) Verification, validation, and uncertainty characterization (see [M&S 15-16], [M&S 17-18], [M&S 19-21]).

(5) Reporting of M&S information for critical decisions (see [M&S 32-39]).

(6) Configuration management (CM) (artifacts, timeframe, processes) of M&S.

[Rationale: Defining objectives and requirements for M&S products informs developers and users about what is required of the specific M&S during development and use for the items important to M&S listed and particular to the requirements and practices of a program, project, organization, or office.]

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d. [M&S 9] Shall document any technical reviews accomplished in regard to the development, management (control), and use of the M&S.

[Rationale: Documenting any technical review shows how, and what aspects of, M&S development or use were reviewed and the outcome of the reviews, as support for acceptance of the M&S and the results from its use.]

Refer to NASA-HDBK-7009, NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009, for more on this topic.

4.1.2 General M&S Programmatic Recommendations

Recommendations for general M&S practices are that responsible parties:

a. Should develop a plan (including identifying the responsible organization(s)) for the acquisition, development, operation, maintenance, or retirement of the M&S.

b. Should document M&S waiver processes.

c. Should document the extent to which an M&S effort exhibits the characteristics of work product management, process definition, process measurement, process control, process change, and continuous improvement, including CM and M&S support and maintenance.

4.1.3 M&S Best Practices Recommendations

This NASA Technical Standard addresses general issues with respect to the use of M&S and does not discuss implementation details specific to individual programs, projects, disciplines, or processes. The implementation details are addressed in relevant recommended practices (e.g., guidelines developed by professional societies, such as AIAA G-077, Guide for the Verification and Validation of Computational Fluid Dynamics Simulations, and ASME V&V 10, Guide for Verification and Validation in Computational Solid Mechanics, other best practices documented for specific simulation codes, and NASA handbooks and guidebooks.

This section lists the recommendations for the identification of recommended practices.

Recommendations for the identification of recommended practices are that responsible parties:

a. Should identify and document any recommended practices that apply to M&S for the program/project.

b. At a minimum, recommended practices for the following should be considered:

(1) Data and M&S input verification, validation, and pedigree.

(2) An auditing method of tracking adherence to recommended practices.

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(3) Verification and validation processes for the M&S.

(4) Uncertainty characterization methods for the M&S.

(5) Sensitivity analysis methods for the M&S.

(6) Understanding of the disciplines incorporated in the M&S.

(7) Analyzing and interpreting the M&S results, including documentation of inference guidelines and statistical processes used.

(8) Recognizing and capturing the need for any changes or improvements in the M&S.

(9) Reporting procedures for results.

(10) Best practices for user interface design to constrain the operation of the M&S to within its limits of operations.

4.1.4 M&S Training Recommendations

Training refers to providing instruction on the proper development and use of M&S so an individual can develop, operate, or analyze the relevant M&S.

Recommendations for training are that responsible parties:

a. Should determine the depth of required training or equivalent experience (i.e., qualifications) for developers, operators, and analysts.

b. Should document the following:

(1) Training topics required for developers, operators, and analysts of M&S, which should include the following:

A. The limits of operation for M&S, with implications and rationale.
B. CM requirements.
C. Documentation requirements and recommendations as specified in this NASA Technical Standard.
D. How to recognize unrealistic results from simulations.
E. Feedback processes to improve M&S processes and results, including providing feedback for results that are not credible, are unrealistic, or defy explanation.
F. Sensitivity analysis.
G. Uncertainty characterization.
H. Verification and validation.
I. How to report simulation results to decision makers.
J. Statistics and probability.

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K. Discipline-specific recommended practices. Other applicable Agency policy, procedural requirements, and standards.

L. Basic modeling structures, mathematics, assumptions, and abstractions.

(2) *Process and criteria for verifying that training requirements are met.*

4.2 M&S Development

The M&S development processes vary depending on the intended use and may be referred to as modeling activities. This phase in the life cycle (see Appendix F) of an M&S begins by specifying the intended use of the model and by establishing an understanding of the existing or envisioned system to be modeled. This is followed by developing the concept for the model (including conceptual, mathematical, or computational diagrams or models), continues with choosing application methods and platforms for implementing and testing (both verifying and validating) the model, and ends with releasing the model for use. The permissible uses for the M&S are determined during development with an understanding of the abstractions taken in development, the assumptions for model use, the constraints of implementation methods used, and the limits of operation based on the completeness and success of both verification and validation.

4.2.1 General M&S Development

For model and simulation development, the responsible party performs the following:

a. [M&S 10] Shall document the relevant characteristics, including data, about the RWS used to develop the model, including its pedigree (see Data Pedigree in Appendix E).

[Rationale: Documenting the relevant characteristics of the RWS provides the basis for M&S design, conceptual validation, development, and use.]

RWS can be interpreted as narrowly or broadly as necessary, that is, from a single specific system to a whole class of systems, depending on the intended use of the M&S.

b. [M&S 11] Shall document the assumptions and abstractions underlying the M&S, including their rationales.

[Rationale: Documenting assumptions and abstractions clarifies areas where the M&S differs from the RWS or where limits of implementation mechanisms may cause the M&S's response to differ from that of the RWS. This also provides an understanding needed for V&V, the specification of permissible uses, and the acceptance of proposed uses of the M&S. Failure to clearly identify, understand and communicate assumptions and abstractions introduces risks throughout development and use of the M&S.]

c. [M&S 12] Shall document the basic structure and mathematics of the model (e.g., equations solved, behaviors modeled, and conceptual models).

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[Rationale: Verification cannot be accomplished without an understanding of the basic structure and mathematics of the M&S.]

For Commercial-Off-The-Shelf (COTS), Government-Off-The-Shelf (GOTS), Modified-Off-The-Shelf (MOTS), and legacy M&S, some of the documentation required in [M&S 11-12] and may be available in published user guides; a reference to the user guides will suffice for this part of the documentation.

d. [M&S 13] Shall document the limits of operation (e.g., boundary conditions) of models.

[Rationale: Documenting the limits of operation of an M&S provides specific parameter or variable ranges (operating conditions) where the M&S use is known to produce acceptable results as determined by M&S design and V&V.]

e. [M&S 14] Shall document the permissible uses of the M&S.

[Rationale: Documenting the permissible uses of an M&S at the end of M&S development aggregates the latest available information about the intended uses, limiting assumptions & abstractions, and V&V'd limits of M&S use. The permissible uses are the basis for performing the use assessment of [M&S 23].]

When a model's development is completed, the permissible uses are determined by the intended use [M&S 8(2)]; the model's assumptions and abstractions [M&S 11]; the limits of operation [M&S 13]; the domain of verification [M&S 16]; and the domain of validation [M&S 18]. Furthermore, the permissible uses are the criteria by which the proposed use is assessed [M&S 22].

4.2.2 General M&S Development Recommendations

a. Should document data sets and any supporting software used in model development.

b. Should document units and vector coordinate frames (where applicable) for all input/output variables in the M&S.

c. Should document any methods of uncertainty characterization and the uncertainty in any data used to develop the model or incorporated into the model.

d. M&S should be designed and constructed so that, in the event of a failure, messages detailing the failure mode and point of failure are provided.

This feature helps to prevent the inappropriate use of potentially misleading results.

e. Should document guidance on proper use of the M&S.

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Guidance on proper use of a model includes descriptions of appropriate practices for set-up, execution, interfaces with other models when the model is used as part of either a linked or coupled model, and analysis of results.

f. Should document any parameter calibrations and the domain of calibration.

g. Should document updates of the model (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.

h. CM records should contain test cases that span the limits of operation for the M&S defined by the program or project.

"Test cases" are defined as benchmark input/output sets used to verify proper execution of the M&S.

i. Should document obsolescence criteria and obsolescence date of the model.

Obsolescence refers to situations where changes to the real system invalidate the model.

j. Should provide a feedback mechanism for users to report unusual results to model developers or maintainers.

k. Should maintain (conceptual, mathematical, and computational) models and associated documentation in a controlled CM system.

l. Should maintain the data sets and supporting software referenced in Rec. "a" of this section and the associated documentation in a controlled CM system.

m. Should document any unique computational requirements (e.g., support software, main memory, disk capacities, processor, and compilation options).

n. Developers should convey serious concerns about M&S to project managers (and decision makers, if appropriate) as soon as they are known.

4.2.3 M&S Verification

The process of testing a model takes two distinct forms: verification and validation. While both these activities test the model, they do so for different reasons. Verification is testing with respect to model design (specification). While verification is usually meant to occur prior to validation, that precedence is not necessarily required and the two often occur in a cyclical or mixed manner depending on many factors in the overall model development process, and the success or failure in the testing process. These two aspects of model testing are separately discussed because their purposes are different and should never be confounded.
For verification, the responsible party performs the following:

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a. [M&S 15] Shall verify all models.

[Rationale: Verifying the model ensures it is implemented in accordance with its design.]

b. [M&S 16] Shall document the domain of verification of all models.

[Rationale: Documenting the domain of verification for the model provides operational criterion for which it is known to produce results within the capabilities for which it was constructed.]

See Appendix E for more on this topic.

4.2.4 M&S Verification Recommendations

Recommendations for verification of M&S are that the responsible party:

a. Should document any verification techniques used.

NASA-HDBK-7009 has further information regarding specific verification techniques.

b. Should document any numerical error estimates (e.g., numerical approximations, insufficient discretization, insufficient iterative convergence, finite-precision arithmetic) for the results of the computational model.

c. Should document the verification status of (conceptual, mathematical, and computational) models.

d. Should document any aspects of M&S that have not been verified.

4.2.5 M&S Validation

Testing a model with respect to the system the model is representing (i.e., the referent) is called validation. (See discussion of verification in section 4.2.3.)

For validation, the responsible party performs the following:

a. [M&S 17] Shall validate all models.

[Rationale: Validating the model ensures it produces results acceptably similar to the RWS it represents.]

b. [M&S 18] Shall document the domain of validation of all models.

[Rationale: Documenting the domain of validation for the model provides operational criterion for which it is known to produce results acceptably similar to the RWS it represents.]

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See Appendix E for more on this topic.

4.2.6 M&S Validation Recommendations

Recommendations for validation of M&S are that the responsible party:

a. Should document any techniques used to validate the M&S for its intended use, including the experimental design and analysis. NASA-HDBK-7009 has further information regarding specific validation techniques. Should document any validation metrics and referents, and data sets used for model validation.

b. Should document any studies conducted and results of model validation.

c. Should document any aspects of M&S that have not been validated.

4.2.7 Uncertainty Characterization in M&S Development

No M&S is a perfect replica or imitator of the RWS for which the model is used to study. Characterizing the uncertainty in M&S results is, therefore, at least one way to qualify those results. Factors influencing that uncertainty may occur in any part of the M&S life cycle, from the initial understanding of the RWS and the earliest conceptualization of the model through all aspects of model development, testing, and use. When little actual information is available, this characterization may itself be qualitative, or may be quantified if data are or become available. The requirements and recommendations in this section are related to the handling and incorporation of uncertainties during M&S development.

For uncertainty characterization, the responsible party performs the following:

a. [M&S 19] Shall document any processes and rationale for characterizing uncertainty in the referent data.

[Rationale: Documenting how and why referent data uncertainty is analyzed ensures a rational basis for comparison with M&S results uncertainty (i.e., referent data uncertainty is not simply notional). Referent data uncertainty is a partial basis for M&S validation [M&S 17-18].]

b. [M&S 20] Shall explain and document any mechanisms or constructs related to the incorporation or propagation of uncertainty in the model.

[Rationale: Explaining and documenting how M&S uncertainty is incorporated in, and propagated through, an M&S ensures rational consideration was given to the effects of uncertainty during M&S development.]

c. [M&S 21] Shall document any uncertainties (qualitatively described or quantitative) incorporated into the M&S.

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[Rationale: Documenting the uncertainties in an M&S ensures an understanding of the type and magnitude of uncertainties that propagate through an M&S and affect the results.]

4.2.8 Uncertainty Characterization in M&S Development Recommendation

a. The responsible party should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.

4.3 M&S Use (Operations)

The use (or operation) of an M&S and the processing of the results from the use are simulation and analysis activities. This phase in the life cycle (see Appendix F) of an M&S begins with a specific use being proposed and the assessment of the proposed use against the M&S's permissible uses. Once the use is accepted as appropriate for the M&S, the process of M&S setup and explicit scenario definition (e.g., design of experiments) begins, followed by the actual use (e.g., running) of the M&S, reviewing and analyzing the output results, and developing conclusions and recommendations for the RWS or situation under study.

4.3.1 M&S Use Requirements

For M&S use, the responsible party performs the following:

a. [M&S 22] Shall document the proposed use(s) of the M&S.

[Rationale: Documenting the proposed use of an M&S ensures a clear communication of how the M&S is to be used, which is the subject of the use assessment required in [M&S 23].]

b. [M&S 23] Shall perform and document an assessment of the appropriateness of the M&S relative to its proposed use.

[Rationale: The use assessment compares the proposed uses against the permissible uses to determine if the M&S is appropriate and if the use is within or outside the known acceptable uses of the M&S.]

Determining the appropriateness of an M&S for a proposed use, referred to as a use assessment, is obtained by comparing the proposed use [M&S 22] to the permissible use [M&S 14]. The result of the use assessment is that either the M&S is or is not accepted for the proposed use.

c. [M&S 24] Shall document data used as input to the M&S, including its pedigree (see Input Pedigree in Appendix E).

Rationale: Documented input data, including its pedigree, ensures an understanding of scenarios or experiments run with an M&S. These, coupled with associated M&S results, provide a documented basis for conclusions drawn from the M&S use.]

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d. [M&S 25] Shall document the rationale for the setup and execution of the simulation and analysis.

[Rationale: Documented rationale for M&S setup and execution ensures evidence is available for consideration and adjustment as needed.]
Setup and execution rationale includes any assumptions made when using the M&S.

e. [M&S 26] Shall do either of the following:

(1) Ensure that simulations and analyses are conducted within the limits of operation of the models, or

(2) Placard the simulation and analysis results with a warning that the simulation may have been conducted outside the limits of operation and include the type of limit that may have been exceeded, the extent that the limit might have been exceeded, and an assessment of the consequences of this action on the M&S results.

[Rationale: Placarding M&S results if used outside established permissible uses provides a warning to the consumers of that information.]

f. [M&S 27] Shall document and explain any observed warning and error messages resulting from the execution of the computational M&S.

[Rationale: Unexplained warning or error messages are a cause for concern (increase risk) in accepting the results of an M&S use.]

4.3.2 M&S Use Recommendations

Recommendations for M&S Use are that responsible parties:

a. Should document the relevant characteristics of the system that is the subject of the M&S-based analysis.

b. Should document which computational models were used (including revision numbers) in the simulation/analysis.

c. Should document any parameter calibrations and the domain of calibration.

d. Should document data sets and any supporting software used in input preparation.

e. Should document the processes for conducting simulations and analyses for generating results reported to decision makers.

f. Should document the versions of M&S results.

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g. Should document any use history of M&S, in the same or similar applications, which are relevant for establishing the credibility of the current M&S application (see Appendix E.4.3.1, M&S History Factor).

h. Should document and explain all failure modes, points of failure, and messages indicating such failures.

4.3.3 Uncertainty Characterization in M&S Use

As mentioned in section 4.2 (M&S Development), the characterization of uncertainty in M&S results may be influenced in any part of the M&S life cycle, including its use and the post-processing of results. The requirements and recommendations in this section are related to the incorporation, handling, and documentation of uncertainties during M&S use (operations).

For uncertainty characterization in M&S use, the responsible party performs the following:

a. [M&S 28] Shall document any processes and rationale for characterizing uncertainty in:

(1) The input to an M&S.

(2) The results from an M&S.

(3) The quantities derived from M&S results.

[Rationale: Documenting how and why M&S uncertainties are input to, and handled in the results of, an M&S ensures a rational basis for inclusion and analysis when an M&S is used (i.e., input and results uncertainty is not simply notional).]

b. [M&S 29] Shall document any uncertainties (qualitatively described or quantitative) in:

(1) The input to an M&S.

(2) The results from an M&S.

This includes any MUFs incorporated into the M&S as well as any Factors of Safety (FS) that are intended to cover uncertainties in the model or simulation. The uncertainties those factors are intended to address should also be documented.

(3) The quantities derived from M&S results.

[Rationale: Documenting the uncertainties in the input to and results from an M&S ensures an understanding of the type and magnitude of uncertainties that propagate through an M&S and show in the results.]

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4.3.4 M&S Uncertainty Characterization in M&S Use Recommendation

a. Responsible parties should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.

4.3.5 M&S Sensitivity Analysis

Sensitivity analysis is the study of an M&S's response to variations in input parameters to determine which parameters are key drivers to the M&S's results. If the response is negligible, then the M&S (at least in the experimental domain), and by inference the RWS (as validated), are considered insensitive to that parameter. Understanding the sensitivity to input parameters is key to determining the robustness of the M&S (see Results Robustness factor in Appendix E). On the other hand, if the response is not negligible, particularly to minor variations in the input parameters, the M&S is considered sensitive and that parameter is a key driver to the model results.

Assessing the similarity of M&S sensitivity with that of the RWS is one of the tasks of M&S validation with the goal that M&S and RWS sensitivities are correlated.

[M&S 30] The responsible party shall document the extent and results of any sensitivity analyses performed with the M&S.

[Rationale: Documenting the extent of sensitivity analyses ensures an understanding of how well the sensitivities were investigated and provides an understanding of the stability of M&S results to input (scenario) perturbations.]

4.3.6 M&S Results Credibility Assessment

Having an established process for assessing the credibility of M&S results helps to ensure a clearer and more complete communication of the important aspects of an M&S beyond just the results. The assessment of credibility discussed in Appendix E does not purport to determine credibility directly, but merely to assess key factors that contribute to a decision-maker's credibility assessment. The assessment of these factors is focused on the results produced by the M&S; however, the completeness and rigor of all the activities throughout the life cycle of the M&S contribute to it. This is why there are both developmental and operational factors for credibility. The decision makers can then make their own credibility assessment based upon this information in the context of the decision at hand.

This NASA Technical Standard itself levies no requirements with respect to what levels to achieve (the sufficiency threshold levels), merely that the levels be determined and reported.

[M&S 31] The responsible party shall assess the credibility of M&S results for each of the factors described in Appendix E.

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[Rationale: The assessment of each credibility factor ensures a discussion the achievements and shortcomings of the M&S use beyond just the results, and provides a rational basis for either acceptance or rejection of the M&S results.]

4.3.7 M&S Results Credibility Assessment Recommendations

Recommendations for credibility assessments in M&S use are that responsible parties:

a. Should set credibility sufficiency threshold levels for each factor as described in Appendix E.5.

b. Should justify and document the credibility assessment for each of the factors referenced in [M&S 31].

c. Should gain additional insight into the credibility of M&S results by applying the process in Appendix E.5 to determine and report any gaps between the achieved scores and the program/project-defined threshold scores for each of the factors.

4.3.8 M&S Results Reporting

Because of the inexact nature of all M&S in replicating any given RWS, more information than just the results are needed to provide a decision maker with a more complete understanding of the situation. This includes (1) the best estimate of the results, (2) a statement on the uncertainty in the results, (3) the assessment of the credibility of results (Appendix E), (4) any explicit caveats accompanying the results (e.g., the use of the M&S in violation of its assumptions or limits of operation), and (5) the risks associated with accepting the results of the M&S. This allows the decision makers to make their own conclusions about the quality or credibility of the results based upon all of this information, in the context of the decision at hand.

These requirements and recommendations provide for reporting a high-level synopsis of M&S outcomes relevant to the current use.

For reporting M&S results to decision makers, the responsible party performs the following:

a. [M&S 32] Shall include explicit warnings for any of the following occurrences, accompanied by at least a qualitative estimate of the impact of the occurrence:

(1) Any unachieved acceptance criteria (as specified in [M&S 8] (1)).

(2) Violation of any assumptions of any model (as specified in [M&S 11]).

(3) Violation of the limits of operation (as specified in [M&S 13]).

(4) Execution warning and error messages (see [M&S 27]).

(5) Unfavorable outcomes from the proposed use assessments (described in [M&S 23]).

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(6) Unfavorable outcomes from any setup/execution assessments (described in [M&S 25]).

(7) Waivers to any of the requirements in this NASA Technical Standard.

[Rationale: Reporting warnings for negative aspects of M&S development or use helps to ensure the inappropriate acceptance of M&S results, if the results are negatively impacted.]

In the absence of documentation for any of the requirements referenced in [M&S 32 (1)-(6)], a warning is to be provided.

b. [M&S 33] Shall include an estimate of results uncertainty, as defined in [M&S 29 (1)-(3)], in one of the following ways:

(1) A quantitative estimate of the uncertainty in the M&S results, or

(2) A qualitative description of the uncertainty in the M&S results, or

(3) A clear statement that no quantitative estimate or qualitative description of uncertainty is available.

[Rationale: Reporting an estimate of uncertainty, or lack thereof, for the M&S results ensures an understanding that the results are estimates (not exact) within assessed boundaries. Results without an estimate of uncertainty may differ vastly from those shown.]

For [M&S 33] , a complete quantitative uncertainty estimate would provide uncertainty intervals about the M&S results and confidence statements based on analysis, whereas a qualitative uncertainty estimate would be provided only in linguistic terms, e.g., small, medium, or large, rather than in numeric terms. Qualitative uncertainty estimates would still require justification, for example, by the descriptive phrasing of a subject matter expert (SME) or by resort to analogy with the quantified sensitivity of similar problems.

c. [M&S 34] Shall include a description of any processes used to obtain the estimate of uncertainty as defined in [M&S 28 (1)-(3)].

[Rationale: Reporting the processes used to obtain the estimate of uncertainty ensures the communication of how the uncertainties in the results occurred (or accumulated).]

d. [M&S 35] Shall include the assessment of credibility for the M&S results for each factor specified in [M&S 31].

[Rationale: Reporting the credibility assessment ensures communication of how well those aspects (factors) of M&S development and use were accomplished, which can affect the acceptance of the M&S results.]

e. [M&S 36] Shall include the findings from any technical reviews accomplished in regard to the development, management (control), and use of the M&S.

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[Rationale: Reporting findings from any technical reviews ensures the communication of supportive or unsupportive information related to what aspect of the M&S effort was reviewed.]

Refer to NASA-HDBK-7009 for more on this topic.

f. [M&S 37] Shall include the qualifications of the developers of the M&S and the users, operators, and/or analysts involved in producing the results from the M&S, including, but not limited to, their relevant education, training, and experience.

[Rationale: Reporting the qualifications of the developers, users, operators, and/or analysts involved in producing the M&S, or results therefrom, ensures clarity in qualifications. Specific topic areas that constitute qualification depends on the type and application of the M&S (the recommendations of sections 4.1.3 and 4.1.4 may be consulted).]

g. [M&S 38] Shall show what aspects of modeling and simulation are documented, as shown in Appendix A.

[Rationale: Reporting what aspects of modeling and simulation are documented ensures clear evidence of what was actually accomplished in M&S development and use.]

Appendix A lists all the requirements and Appendix B lists all the recommendations in a "compliance type" table with "if," "how," and "where" it is documented.

h. [M&S 39] Shall include an assessment of and rationale for the risks associated with the use of the M&S-based analysis.

[Rationale: Reporting assessment of and rationale for the risks associated with the use of the M&S-based analysis ensures the open communication of possible issues with the M&S, or use thereof, and may inform program/project risk management processes.]

These risks may be due to factors inherent to the M&S, or associated with the specific application or use of the M&S. Compliance with the reporting requirements [M&S 32-38] yields information to inform applicable program/project risk management processes and procedures.

4.3.9 M&S Results Reporting Recommendations

Recommendations for reporting results from M&S use are that responsible parties:

a. Should include concluding remarks stating whether the M&S results are credible enough for the actual use.

b. Should identify how to access more detailed backup material, including high-level descriptions of the models used and key assumptions for limits of validity.

c. Should place M&S results in the CM system.

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d. Should summarize deviations from established recommended practices.

e. Should include dissenting technical opinions regarding the credibility of the results or any recommended actions.

f. Should convey serious concerns about M&S or its use to project managers (and decision makers, if appropriate) as soon as they are known.

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APPENDIX A

REQUIREMENTS COMPLIANCE MATRIX

A.1 Purpose

This appendix provides a listing of requirements contained in this NASA Technical Standard for selection and verification of requirements by programs, projects, organizations, or offices. *(Note: Enter "Yes" to describe the requirement's applicability to the program or project; or enter "No" if the intent is to tailor, and enter how tailoring is to be applied in the "Rationale" column.)*

NASA-STD-7009A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
1.2	Applicability	[M&S 1] When conflicts exist between this NASA Technical Standard and voluntary consensus standards (VCS), this document shall take precedence, except in those cases where the VCS is invoked by applicable Government regulation.		
1.3	Tailoring	[M&S 2] Tailoring of this NASA Technical Standard for application to a specific program/project/organization/office shall be formally documented as part of program/project/organization/office requirements and approved by the responsible Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.		
2.1.1	Applicable Documents	[M&S 3] The latest issuances of cited documents shall be used unless otherwise approved by the assigned Technical Authority.		
2.1.2	Applicable Documents	[M&S 4] Non-use of specifically designated versions shall be approved by the responsible Technical Authority.		
2.4.2	Order of Precedence	[M&S 5] Conflicts between this NASA Technical Standard and other requirements documents shall be resolved by the responsible Technical Authority.		

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NASA-STD-7009A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.1.1a	General M&S Programmatics	[M&S 6] Shall perform and document the criticality assessment for the M&S.		
4.1.1b	General M&S Programmatics	[M&S 7] Shall identify and document if the M&S is in scope of this NASA Technical Standard.		
4.1.1c	General M&S Programmatics	[M&S 8] Shall define the objectives and requirements for M&S products including the following: (1) The acceptance criteria for M&S products, including any endorsement for the M&S. (2) Intended use. *The intended uses may be updated throughout the model development.* (3) Metrics (programmatic and technical). (4) Verification, validation, and uncertainty characterization (see [M&S 15-16], [M&S 17-18], [M&S 19-21]). (5) Reporting of M&S information for critical decisions (see [M&S 32-39]). (6) Configuration management (CM) (artifacts, timeframe, processes) of M&S.		
4.1.1d	General M&S Programmatics	[M&S 9] Shall document any technical reviews accomplished in regard to the development, management (control), and use of the M&S.		
4.2.1a	General M&S Development	[M&S 10] Shall document the relevant characteristics, including data, about the RWS used to develop the model, including its pedigree (see Data Pedigree in Appendix E).		
4.2.1b	General M&S Development	[M&S 11] Shall document the assumptions and abstractions underlying the M&S, including their rationales.		
4.2.1c	General M&S Development	[M&S 12] Shall document the basic structure and mathematics of the model (e.g., equations solved, behaviors modeled, and conceptual models).		
4.2.1d	General M&S Development	[M&S 13] Shall document the limits of operation (e.g., boundary conditions) of models.		
4.2.1e	General M&S Development	[M&S 14] Shall document the permissible uses of the M&S.		
4.2.3a	M&S Verification	[M&S 15] Shall verify all models.		

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NASA-STD-7009A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.2.3b	M&S Verification	[M&S 16] Shall document the domain of verification of all models.		
4.2.5a	M&S Validation	[M&S 17] Shall validate all models.		
4.2.5b	M&S Validation	[M&S 18] Shall document the domain of validation of all models.		
4.2.7a	Uncertainty Characterization in M&S Development	[M&S 19] Shall document any processes and rationale for characterizing uncertainty in the referent data.		
4.2.7b	Uncertainty Characterization in M&S Development	[M&S 20] Shall explain and document any mechanisms or constructs related to the incorporation or propagation of uncertainty in the model.		
4.2.7c	Uncertainty Characterization in M&S Development	[M&S 21] Shall document any uncertainties (qualitatively described or quantitative) incorporated into the M&S.		
4.3.1a	M&S Use Requirements	[M&S 22] Shall document the proposed use(s) of the M&S.		
4.3.1b	M&S Use Requirements	[M&S 23] Shall perform and document an assessment of the appropriateness of the M&S relative to its proposed use.		
4.3.1c	M&S Use Requirements	[M&S 24] Shall document data used as input to the M&S, including its pedigree (see Input Pedigree in Appendix E).		
4.3.1d	M&S Use Requirements	[M&S 25] Shall document the rationale for the setup and execution of the simulation and analysis.		
4.3.1e	M&S Use Requirements	[M&S 26] Shall do either of the following: (1) Ensure that simulations and analyses are conducted within the limits of operation of the models, or (2) Placard the simulation and analysis results with a warning that the simulation may have been conducted outside the limits of operation and include the type of limit that may have been exceeded, the extent that the limit might have been exceeded, and an assessment of the consequences of this action on the M&S results.		

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NASA-STD-7009A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.3.1f	M&S Use Requirements	[M&S 27] Shall document and explain any observed warning and error messages resulting from the execution of the computational M&S.		
4.3.3a	Uncertainty Characterization in M&S Use	[M&S 28] Shall document any processes and rationale for characterizing uncertainty in: (1) The input to an M&S. (2) The results from an M&S. (3) The quantities derived from M&S results.		
4.3.3b	Uncertainty Characterization in M&S Use	[M&S 29] Shall document any uncertainties (qualitatively described or quantitative) in: (1) The input to an M&S. (2) The results from an M&S. *This includes any MUFs incorporated into the M&S as well as any Factors of Safety (FS) that are intended to cover uncertainties in the model or simulation. The uncertainties those factors are intended to address should also be documented.* (3) The quantities derived from M&S results.		
4.3.5	M&S Sensitivity Analysis	[M&S 30] The responsible party shall document the extent and results of any sensitivity analyses performed with the M&S.		
4.3.6	M&S Results Credibility Assessment	[M&S 31] The responsible party shall assess the credibility of M&S results for each of the factors described in Appendix E.		
4.3.8a	M&S Results Reporting	[M&S 32] Shall include explicit warnings for any of the following occurrences, accompanied by at least a qualitative estimate of the impact of the occurrence: (1) Any unachieved acceptance criteria (as specified in [M&S 8 (1)]). (2) Violation of any assumptions of any model (as specified in [M&S 11]). (3) Violation of the limits of operation (as specified in [M&S 13]). (4) Execution warning and error messages (see [M&S 27]). (5) Unfavorable outcomes from the proposed use assessments (described in [M&S 23]). (6) Unfavorable outcomes from any setup/execution assessments (described in [M&S 25]). (7) Waivers to any of the requirements in this NASA Technical Standard.		

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NASA-STD-7009A				
Section	**Description**	**Requirement in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.3.8b	M&S Results Reporting	[M&S 33] Shall include an estimate of results uncertainty, as defined in [M&S 29 (1)-(3)], in one of the following ways: (1) A quantitative estimate of the uncertainty in the M&S results, or (2) A qualitative description of the uncertainty in the M&S results, or (3) A clear statement that no quantitative estimate or qualitative description of uncertainty is available.		
4.3.8c	M&S Results Reporting	[M&S 34] Shall include a description of any processes used to obtain the estimate of uncertainty as defined in [M&S 28 (1)-(3)].		
4.3.8d	M&S Results Reporting	[M&S 35] Shall include the assessment of credibility for the M&S results for each factor specified in [M&S 31].		
4.3.8e	M&S Results Reporting	[M&S 36] Shall include the findings from any technical reviews accomplished in regard to the development, management (control), and use of the M&S.		
4.3.8f	M&S Results Reporting	[M&S 37] Shall include the qualifications of the developers of the M&S and the users, operators, and/or analysts involved in producing the results from the M&S, including, but not limited to, their relevant education, training, and experience.		
4.3.8g	M&S Results Reporting	[M&S 38] Shall show what aspects of modeling and simulation are documented, as shown in Appendix A.		
4.3.8h	M&S Results Reporting	[M&S 39] Shall include an assessment of and rationale for the risks associated with the use of the M&S-based analysis.		

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APPENDIX B

RECOMMENDATIONS COMPLIANCE MATRIX

B.1 Purpose

This appendix provides a listing of recommendations contained in this NASA Technical Standard for selection and verification if designated by programs, projects, organizations, or offices. *(Note: Enter "Yes" to describe the recommendation's applicability to the program*, projects, organizations, or offices*; or enter "No" if the intent is to tailor, and enter how tailoring is to be applied in the "Rationale" column.)*

NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.1.2a	General M&S Programmatic Recommendations	Should develop a plan (including identifying the responsible organization(s)) for the acquisition, development, operation, maintenance, or retirement of the M&S.		
4.1.2b	General M&S Programmatic Recommendations	Should document M&S waiver processes.		
4.1.2c	General M&S Programmatic Recommendations	Should document the extent to which an M&S effort exhibits the characteristics of work product management, process definition, process measurement, process control, process change, and continuous improvement, including CM and M&S support and maintenance.		
4.1.3a	M&S Best Practices Recommendations	Should identify and document any recommended practices that apply to M&S for the program/project.		
4.1.3b	M&S Best Practices	At a minimum, recommended practices for the following should be considered:		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
	Recommendations	(1) Data and M&S input verification, validation, and pedigree. (2) An auditing method of tracking adherence to recommended practices. (3) Verification and validation processes for the M&S. (4) Uncertainty characterization methods for the M&S. (5) Sensitivity analysis methods for the M&S. (6) Understanding of the disciplines incorporated in the M&S. (7) Analyzing and interpreting the M&S results, including documentation of inference guidelines and statistical processes used. (8) Recognizing and capturing the need for any changes or improvements in the M&S. (9) Reporting procedures for results. (10) Best practices for user interface design to constrain the operation of the M&S to within its limits of operations.		
4.1.4a	M&S Training Recommendations	Should determine the depth of required training or equivalent experience (i.e., qualifications) for developers, operators, and analysts.		
4.1.4b	M&S Training Recommendations	Should document the following: (1) Training topics required for developers, operators, and analysts of M&S, which should include the following: A. The limits of operation for M&S, with implications and rationale. B. CM requirements. C. Documentation requirements and recommendations as specified in this NASA Technical Standard. D. How to recognize unrealistic results from simulations. E. Feedback processes to improve M&S processes and results, including providing feedback for results that are not credible, are unrealistic, or defy explanation. F. Sensitivity analysis. G. Uncertainty characterization. H. Verification and validation. I. How to report simulation results to decision makers.		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
		J. Statistics and probability. K. Discipline-specific recommended practices. Other applicable Agency policy, procedural requirements, and standards. L. Basic modeling structures, mathematics, assumptions, and abstractions. (2) Process and criteria for verifying that training requirements are met.		
4.2.2a	General M&S Development Recommendations	Should document data sets and any supporting software used in model development.		
4.2.2b	General M&S Development Recommendations	Should document units and vector coordinate frames (where applicable) for all input/output variables in the M&S.		
4.2.2c	General M&S Development Recommendations	Should document any methods of uncertainty characterization and the uncertainty in any data used to develop the model or incorporated into the model.		
4.2.2d	General M&S Development Recommendations	M&S should be designed and constructed so that, in the event of a failure, messages detailing the failure mode and point of failure are provided.		
4.2.2e	General M&S Development Recommendations	Should document guidance on proper use of the M&S.		
4.2.2f	General M&S Development Recommendations	Should document any parameter calibrations and the domain of calibration.		
4.2.2g	General M&S Development Recommendations	Should document updates of the model (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.		
4.2.2h	General M&S Development Recommendations	CM records should contain test cases that span the limits of operation for the M&S defined by the program or project.		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.2.2i	General M&S Development Recommendations	Should document obsolescence criteria and obsolescence date of the model.		
4.2.2j	General M&S Development Recommendations	Should provide a feedback mechanism for users to report unusual results to model developers or maintainers.		
4.2.2k	General M&S Development Recommendations	Should maintain (conceptual, mathematical, and computational) models and associated documentation in a controlled CM system.		
4.2.2l	General M&S Development Recommendations	Should maintain the data sets and supporting software referenced in Rec. “a” of this section and the associated documentation in a controlled CM system.		
4.2.2m	General M&S Development Recommendations	Should document any unique computational requirements (e.g., support software, main memory, disk capacities, processor, and compilation options).		
4.2.2n	General M&S Development Recommendations	Developers should convey serious concerns about M&S to project managers (and decision makers, if appropriate) as soon as they are known.		
4.2.4a	M&S Verification Recommendations	Should document any verification techniques used.		
4.2.4b	M&S Verification Recommendations	Should document any numerical error estimates (e.g., numerical approximations, insufficient discretization, insufficient iterative convergence, finite-precision arithmetic) for the results of the computational model.		
4.2.4c	M&S Verification Recommendations	Should document the verification status of (conceptual, mathematical, and computational) models.		
4.2.4d	M&S Verification Recommendations	Should document any aspects of M&S that have not been verified.		
4.2.6a	M&S Validation Recommendations	Should document any techniques used to validate the M&S for its intended use, including the experimental design and analysis.		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.2.6b	M&S Validation Recommendations	Should document any validation metrics and referents, and data sets used for model validation.		
4.2.6c	M&S Validation Recommendations	Should document any studies conducted and results of model validation.		
4.2.6d	M&S Validation Recommendations	Should document any aspects of M&S that have not been validated.		
4.2.8a	Uncertainty Characterization in M&S Development Recommendation	The responsible party should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.		
4.3.2a	M&S Use Recommendations	Should document the relevant characteristics of the system that is the subject of the M&S-based analysis.		
4.3.2b	M&S Use Recommendations	Should document which computational models were used (including revision numbers) in the simulation/analysis.		
4.3.2c	M&S Use Recommendations	Should document any parameter calibrations and the domain of calibration.		
4.3.2d	M&S Use Recommendations	Should document data sets and any supporting software used in input preparation.		
4.3.2e	M&S Use Recommendations	Should document the processes for conducting simulations and analyses for generating results reported to decision makers.		
4.3.2f	M&S Use Recommendations	Should document the versions of M&S results.		
4.3.2g	M&S Use Recommendations	Should document any use history of M&S, in the same or similar applications, which are relevant for establishing the credibility of the current M&S application (see Appendix E.4.3.1, M&S History Factor).		
4.3.2h	M&S Use Recommendations	Should document and explain all failure modes, points of failure, and messages indicating such failures.		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.3.4a	M&S Uncertainty Characterization in M&S Use Recommendation	Responsible parties should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.		
4.3.7a	M&S Results Credibility Assessment Recommendations	Should set credibility sufficiency threshold levels for each factor as described in Appendix E.5.		
4.3.7b	M&S Results Credibility Assessment Recommendations	Should justify and document the credibility assessment for each of the factors referenced in [M&S 31].		
4.3.7c	M&S Results Credibility Assessment Recommendations	Should gain additional insight into the credibility of M&S results by applying the process in Appendix E.5 to determine and report any gaps between the achieved scores and the program/project-defined threshold scores for each of the factors.		
4.3.9a	M&S Results Reporting Recommendations	Should include concluding remarks stating whether the M&S results are credible enough for the actual use.		
4.3.9b	M&S Results Reporting Recommendations	Should identify how to access more detailed backup material, including high-level descriptions of the models used and key assumptions for limits of validity.		
4.3.9c	M&S Results Reporting Recommendations	Should place M&S results in the CM system.		
4.3.9d	M&S Results Reporting Recommendations	Should summarize deviations from established recommended practices.		
4.3.9e	M&S Results Reporting Recommendations	Should include dissenting technical opinions regarding the credibility of the results or any recommended actions.		

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NASA-STD-7009A				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Yes or No)**	**If No, Enter Rationale**
4.3.9f	M&S Results Reporting Recommendations	Should convey serious concerns about M&S or its use to project managers (and decision makers, if appropriate) as soon as they are known.		

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APPENDIX C

REFERENCES

C.1 Purpose

The purpose of this appendix is to provide guidance in the reference documents that follow.

C.2 Reference Documents

C.2.1 Government Documents

Department of Defense (DoD)

DoD Instruction 5000.61	"DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A)" (December 9, 2009).
MIL-STD-3022	Documentation of Verification, Validation, and Accreditation (VV&A) for Models and Simulations (28 January 2008).
Verification, Validation, and Accreditation (VV&A) Recommended Practices Guide (RPG)	*VV&A Recommended Practices Guide (RPG)*, Defense Modeling and Simulation Office. http://www.msco.mil/vva_rpg.html.

National Aeronautics and Space Administration

CAIB	Columbia Accident Investigation Board Report. (August 2003). Vol. 1.
NASA-HDBK-7009	NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009.
NASA/SP-2007-6105	NASA Systems Engineering Handbook.
NASA/SP-2011-3422	NASA Risk Management Handbook.
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware.

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NASA-STD-8719.13	Software Safety Standard.
NESC-PR-006	Technical Assessment Initial Evaluation.
NPR 7123.1	NASA Systems Engineering Processes and Requirements.
NPR 7150.2	NASA Software Engineering Requirements.
NPR 8000.4	Risk Management Procedural Requirements.
NPR 8715.3	NASA General Safety Program Requirements.
NTRS-PB2005-100968	A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report. (January 30, 2004).

C.2.2 Non-Government Documents

American Institute of Aeronautics and Astronautics (AIAA)

AIAA-2005-4524	Lin, J.; West, J.S.; Williams, R.W.; Tucker, P.K. (2005). *CFD Code Validation of Wall Heat Fluxes for a GO_2/GH_2 Single Element Combustor.* Reston, VA: AIAA.
AIAA-2008-2156	Blattnig, S.R.; Green, L.L.; Luckring, J.M.; Morrison, J.H.; Tripathi, R.K.; Zang, T.A. (2008). *Towards a Credibility Assessment of Models and Simulations.* Reston, VA: AIAA.
AIAA G-077	*Guide for Verification and Validation of Computational Fluid Dynamics Simulation.* (1998). Reston, VA: AIAA.

American Society of Mechanical Engineers (ASME)

ASME V&V 10	*Guide for Verification and Validation in Computational Solid Mechanics.* (2006). New York, NY: ASME.
ASME V&V 20	*Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer*

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Institute of Electrical and Electronics Engineers (IEEE)

IEEE 610.12-1990 IEEE Standard Glossary of Software Engineering Terminology.

Sandia National Laboratories

SAND2007-5948 Oberkampf, W.L.; Pilch, M.; Trucano, T.G. (October 2007). *Predictive Capability Maturity Model for Computational Modeling and Simulation.* Sandia National Laboratories. (https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/Oberkampf-Pilch-Trucano-SAND2007-5948.pdf).

SAE International

SAE/EIA 649B Configuration Management Standard

C.2.3 Other Reference Documents

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

Banks, J., ed. (1998). *Handbook of Simulation.* New York: John Wiley & Sons.

Clemen, R.T. (1996). *Making Hard Decisions; an Introduction to Decision Analysis, Second Edition.* Pacific Grove, CA: Brooks/Cole.

Cooke, R.M. (1991). *Experts in Uncertainty: Opinion and Subjective Probability in Science*. New York: Oxford University Press.

Hale, J.P.; Hartway, B.L.; Thomas, D.A. (2007). *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, CPIAC. Columbia, MD: Johns Hopkins University.

Harmon, S.Y.; Youngblood, S.M. (2005). "A Proposed Model for Simulation Validation Process Maturity." J. Defense Modeling & Simulation. Vol. 2, No. 4, pp. 179-190.

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

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Saltelli, A.; Chan, K.; Scott, E.M., eds. (2000). *Sensitivity Analysis.* Chichester, England: John Wiley & Sons.

Sargent, R. G. 1979. *Validation of simulation models.* In Proceedings of the 1979 Winter Simulation Conference, ed. H. J. Highland, M. F. Spiegel, and R. E. Shannon, 497-503. Piscataway, New Jersey: IEEE.

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APPENDIX D

M&S CRITICALITY ASSESSMENT

D.1 Purpose

The purpose of this appendix is to provide a method for communicating the criticality of the situation(s) or decision(s) to which the M&S results are applied.

The determination of how rigorously an M&S effort should follow this NASA Technical Standard is dependent on many influences, with an understanding of the criticality of the decision(s) to which the M&S results are applied being paramount. An M&S criticality assessment considers (1) the consequences to human safety or mission success criteria, and (2) the degree to which M&S results influence a decision. This provides a proactive method to mitigate potential risks as early as possible in the M&S life cycle. This appendix provides a sample M&S criticality assessment matrix to communicate this determination (figure 1, M&S Criticality Assessment Matrix (Sample)). Programs, projects, stakeholders, or customers of M&S may adjust this matrix to their particular situation (e.g., consequence definitions, number of consequence or M&S influence levels) as needed.

M&S Results Influence	5: Controlling	(G)	(Y)	(R)	(R)	(R)
	4: Significant	(G)	(Y)	(Y)	(R)	(R)
	3: Moderate	(G)	(Y)	(Y)	(Y)	(R)
	2: Minor	(G)	(G)	(G)	(Y)	(Y)
	1: Negligible	(G)	(G)	(G)	(G)	(Y)
		I: Negligible	II: Minor	III: Moderate	IV: Significant	V: Catastrophic
		Decision Consequence				

Figure 1—M&S Criticality Assessment Matrix (Sample)

From the perspective of situational criticality, the three possible cases for assessment are:

- Those M&S that are assessed to fall within the red (R) boxes in figure 1 are clear candidates for fully following this NASA Technical Standard.

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- The M&S that are assessed to fall within the yellow (Y) boxes may or may not be candidates for fully following this NASA Technical Standard at the discretion of program/project management in collaboration with the Technical Authority.

- There is not a critical driving force for those falling within the green (G) boxes.

However, any M&S effort within or outside the auspices of a program or project, even without a defined critical use, may choose to use this NASA Technical Standard as a guide for good practices in M&S development, use, and reporting.

D.2 Decision Consequence

Consequence classifications assess the impact of an M&S-influenced decision that may prove detrimental to the RWS. The RWS, of course, may include any personnel, hardware (including software), equipment, or facilities acting with or within it.

The number of Consequence levels is taken from various NASA sources, including the NASA Systems Engineering Handbook (NASA/SP-2007-6105), the NASA Risk Management Handbook (NASA/SP-2011-3422), and the NASA Engineering and Safety Center (NESC) procedure, Technical Assessment Initial Evaluation (NESC-PR-006). The affected personnel, hardware, equipment, or facility should be broadly interpreted as operational (flight or ground) or non-operational (on-site or public). The qualifying terms of few, many, and most are situationally dependent and should be determined by the affected program, project, or customer.

The first four rows of table 1, Decision Consequences, indicate what specifically is impacted, and the subsequent rows indicate what aspect of the program or mission is impacted.

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Table 1—Decision Consequences (Sample)

	I: Negligible	II: Minor	III: Moderate	IV: Significant	V: Catastrophic
Personnel (All, Any)	Inconsequential.	Minor detriment (first aid).	Minor injury or occupational illness.	Severe injury or occupational illness.	Permanent disability or death.
Flight or Ground Hardware	Inconsequential.	Minor detriment (minor maintenance).	Minor detriment (maintenance required).	Major damage.	Destructed.
Flight or Ground Equipment	Inconsequential.	Minor detriment (minor maintenance).	Minor detriment (maintenance required).	Major damage.	Destructed.
Flight or Ground Facilities	Inconsequential.	Minor detriment (minor maintenance).	Minor detriment (maintenance required).	Major damage.	Destructed.
Operational Status	No effect.	At most a temporary effect.	Temporarily off-line for repair.	Permanently degraded until repaired.	Non-operational.
Capabilities (Performance)	No effect; no degradation.	At most a temporary effect; no more than inconsequential degradation.	Temporarily unavailable until restored; some minor degradation.	Significant or permanent degradation until repaired.	Severely degraded to none.
Schedules	No effect.	Minor impact to schedule with no effect on major mission (operations) milestones.	Internal schedule slips with no effect on major mission (operations) milestones.	Impacts to major mission (operations) milestones.	Operational (e.g., mission) windows missed.
Cost	No effect.	Minor cost impact but within nominal margins.	Cost overruns beyond nominal margins, but not detrimental to project execution or completion.	Cost overruns detrimental to program or project execution or full completion.	Cost overruns cause major program or project reductions or cancellation.
Mission Success Criteria	All met.	All met.	A few not met.	Many not met.	Most to all not met.

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D.3 M&S Influence

Influence estimates the degree to which M&S results impact the (program/project) decision under consideration (table 2, M&S Influence). This is predicated on the amount of other information available when making the impending decision. (Engineering decisions include determination of whether design requirements have been verified.)

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Table 2—M&S Influence (Sample)

M&S Influence	Real System in Real Environment		Similar System in Similar Environment		Other M&S
5: Controlling	No data are available for the real system in the real environment.	&	No data are available for a similar system in similar environment.	&	No other M&S or analysis data are available.
4: Significant	No data are available for the real system in the real environment.	&	Ample flight or test data for similar systems in similar environments are available.		No other M&S or analysis data are available.
	--- Or ---				
	No data are available for the real system in the real environment.	&	No data are available for a similar system in similar environment.	&	Credible results from another M&S are available.
3: Moderate	Limited flight or test data for the real system in the real environment are available.	&	Ample flight or test data for similar systems in similar environments are available.		No other M&S or analysis data are available.
	--- Or ---				
	No data are available for the real system in the real environment.		Ample flight or test data for similar systems in similar environments are available.	&	Credible results from another M&S are available.
2: Minor	Some flight or test data for the real system in the real environment are available.		Flight or test data for similar systems in similar environments may or may not be available.		No other M&S or analysis data are available.
	--- Or ---				
1: Negligible	Ample flight or test data for the real system in the real environment are available.		Flight or test data for similar systems in similar environments may or may not be available.		No other M&S or analysis data are available.
	--- Or ---				
	Some flight or test data for the real system in the real environment are available.		Flight or test data for similar systems in similar environments may or may not be available.	&	Credible results from another M&S are available.

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APPENDIX E

M&S CREDIBILITY ASSESSMENT

E.1 Purpose

The purpose of this appendix is to provide a method for assessing the credibility of M&S-based results.

E.2 Introduction

This appendix describes the process and factors for assessing the credibility of M&S-based results. The factors are described in section E.3, along with an overall introduction to the defined credibility levels. Section E.4 gives a detailed description of the credibility levels for each factor of the credibility assessment. Section E.5 describes the concept of program/project-defined sufficiency thresholds recommended in section 4.3 and how they may be used.

E.3 Overview of Credibility Factors and Categories

As mentioned in section 4.3, M&S Use (Operations), the credibility of M&S-based results is not something that can be assessed directly. However, key factors of credibility may be assessed more directly. All of the practices or attributes contained in the requirements and recommendations of this NASA Technical Standard lend themselves to improved credibility of M&S-based results, but the key factors contained in this assessment are considered a minimum set.

The eight factors are Data Pedigree, Verification, Validation, Input Pedigree, Uncertainty Characterization, Results Robustness, M&S History, and M&S Process/Product Management. They are grouped into the three categories of M&S Development (Data Pedigree, Verification, Validation); M&S Use (Input Pedigree, Uncertainty Characterization, Results Robustness); Supporting Evidence (M&S History, M&S Process/Product Management), which may span all aspects of an M&S), as illustrated in figure 2, Credibility Assessment Structure.

Development			Operations			Supporting Evidence	
Data Pedigree	Verification	Validation	Input Pedigree	Uncertainty Characterization	Results Robustness	M&S History	M&S Process/Product Mgt

Figure 2—Credibility Assessment Structure

These eight factors were selected from a long list of factors that potentially contribute to the credibility of M&S results because (a) they were individually judged to be the key factors in this list; (b) they are nearly orthogonal, i.e., largely independent, factors; and (c) they can be assessed objectively. These factors are categorized according to the general phase of the M&S life cycle to which they pertain. The M&S Development category captures those aspects of the M&S that pertain to the general purposes for

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which it was developed; the M&S Use (Operations) category addresses the aspects relevant to the current application of the M&S to generate the particular M&S results under assessment; and the Supporting Evidence category addresses two cross-cutting factors. In short, the key aspects assessed by these eight factors are as follows:

a. M&S Development

(1) *Data Pedigree: Is the pedigree (and quality) of the data used to develop the model adequate or acceptable?*

(2) *Verification: Were the models implemented correctly, per their requirements/specifications?*

(3) *Validation: Did the M&S results compare favorably to the referent data, and how close is the referent to the RWS?*

b. M&S Operations

(1) *Input Pedigree: Is the pedigree (and quality) of the data used to setup and run the model adequate or acceptable?*

(2) *Uncertainty Characterization: Is the uncertainty in the current M&S results appropriately characterized? What are the sources of uncertainty in the results and how are they propagated through to the results of the analysis?*

(3) *Results Robustness: How thoroughly are the sensitivities of the current M&S results known?*

c. Supporting Evidence

(1) *M&S History: How similar is the current version of the M&S to previous versions, and how similar is the current use of the M&S to previous successful uses?*

(2) *M&S Management: How well managed were the M&S processes and products?*

For M&S implemented using a general-purpose software package, some credibility assessment activities are two-fold: (1) those relating to the package itself, and (2) those relating to the implemented M&S. The former is sometimes given insufficient attention in the case of M&S using COTS or other third-party tools, where certain aspects of M&S Development are neither performed nor managed by the parties responsible both for the remainder of M&S Development and for all aspects of M&S Operations. All the verification and validation activities for the tool are evaluated under M&S Development. Additionally, the particular computational model that is constructed using the tool is also evaluated in this category, which necessarily includes the pedigree of the data used in M&S development, as well as verification and validation of the constructed M&S. However, the M&S Operations category deals with the credibility factors for the application of the particular computational model in the generation of the current M&S

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results. This includes the present use of the model (simulation), the analysis, and the reporting of the results. The change and use history of both the tool in general and the particular computational model, and the overall management of the M&S processes and products involved in the development, operation, and analysis of the computational model, are covered in the Supporting Evidence category.

A synopsis of the credibility factors and level definitions is provided in table 3, Key Aspects of Credibility Assessment Levels.

Table 3—Key Aspects of Credibility Assessment Levels

	M&S Development			**M&S Use (Operations)**			**Supporting Evidence**	
Level	**Data Pedigree**	**Verification**	**Validation**	**Input Pedigree**	**Uncertainty Characterization**	**Results Robustness**	**M&S History**	**M&S Process / Product Management**
4	All data known & traceable to RWS with acceptable accuracy, precision, & uncertainty.	Reliable practices applied to verify the end-to-end model; all model errors satisfy requirements.	All M&S outputs agree with data from the RWS over the full range of operation in its real operating environment.	All input data known & traceable to RWS with acceptable accuracy, precision, & uncertainty.	Statistical analysis of the output uncertainty after propagation of all known sources of uncertainty.	Sensitivities known for most parameters; most key sensitivities identified.	Nearly identical model and use.	Controlled processes are applied; measurements used for process improvement.
3	All data known & traced to sufficient referent. Significant data has acceptable accuracy, precision, & uncertainty.	Formal practices applied to verify the end-to-end model; all important errors satisfy requirements.	All key M&S outputs agree with data from the RWS operating in a representative environment.	All input data known & traced to sufficient referent. Significant input data has acceptable accuracy, precision, & uncertainty.	Uncertainty of results are provided quantitatively through propagation of all known uncertainty.	Sensitivities known for many parameters including many of the key sensitivities.	At most minor changes in model and at most minor differences in model use.	Controlled processes are applied; process compliance is measured.
2	Some data known & formally traceable with estimated uncertainties.	Documented practices applied to verify all model features; most important errors satisfy requirements.	Key M&S outputs agree with data from a sufficiently similar referent system.	Some input data known & formally traceable with estimated uncertainties.	Most sources of uncertainty identified, expressed quantitatively, and correctly classified. Propagation of the uncertainties is assessed.	Sensitivities known for a few parameters. Few or no key sensitivities identified.	At most moderate changes in model and at most moderate differences in model use.	Formal processes are applied.
1	Some data known and informally traceable.	Informal practices applied to verify some features of the model and assess errors.	Conceptual model addresses problem statement and agrees with available referents.	Some input data known and informally traceable.	Sources of uncertainty identified and qualitatively assessed.	Qualitative estimates only for sensitivities in M&S.	New model or major changes in model, or major differences in model use; but, model/changes/uses documented.	Informal processes are applied.

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	M&S Development			M&S Use (Operations)			Supporting Evidence	
Level	**Data Pedigree**	**Verification**	**Validation**	**Input Pedigree**	**Uncertainty Characterization**	**Results Robustness**	**M&S History**	**M&S Process / Product Management**
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

E.4 Level Definitions

This subsection includes an explanation for the factor-level definitions in the updated credibility assessment of this revision of this NASA Technical Standard. In many of the level definitions, multiple conditions are stated. In the levels where multiple conditions are stated, all of them are to be met to achieve that level unless they are part of an "or" type listing. The assessment of each factor level is a discrete step function, with no intentions for partial credit at any given level.

Note: The factor assessments are ordinal only, and as such, should not be arithmetically manipulated. Also, as the factors are largely independent, level comparison between factors is not intended except that Level 0 indicates insufficient evidence to claim anything higher and Level 4 indicates the best possible assessment for that factor.

E.4.1 M&S Development Category

The focus of the factors in the M&S Development category is in producing (developing) a good M&S. This starts with having the appropriate data from which design and development may proceed and ends with testing (both verification and validation) from which the adequacy of the M&S is determined. The level definitions for these factors are given in table 4, Level Definitions for Factors in the M&S Development Category.

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Table 4—Level Definitions for Factors in the M&S Development Category

	M&S Development		
Level	**Data Pedigree**	**Verification**	**Validation**
4	All data known and fully traceable to the RWS. All data are acceptable in terms of accuracy, precision, and uncertainty.	The model is correctly implemented as determined by reliable verification practices, which evaluate all components, features, capabilities, and couplings of the end-to-end model. Reliable estimation methods are used to assess model errors. All model errors satisfy program/project specified requirements.	M&S results compare favorably to measurements on the RWS in its operating environment or to results from a higher-fidelity M&S that satisfies the conditions for Level 4. Validation points completely span the domain of operation for the RWS. Favorable comparisons are obtained for all response quantities.
3	All data are known and can be traced to a sufficiently representative referent. All significant data are acceptable in terms of accuracy, precision and uncertainty.	The model is correctly implemented as determined by formal verification practices, which evaluate all components, features, capabilities, and couplings of the end-to-end model. Formal methods are used to assess model errors. All important model errors satisfy program/project-specified requirements.	M&S results compare favorably to measurements on the RWS in a representative environment or to results from a higher-fidelity M&S that satisfies the conditions for Level 3. Validation points significantly span the domain of operation for the RWS. Favorable comparisons are obtained for all important response quantities.
2	Most data are known and traceable to formal documentation. Processes to establish significant data are known. Uncertainties in all data are at least estimated.	The model is correctly implemented as determined by documented verification practices, which evaluate all components, features, capabilities, and couplings of the model. Documented methods are used to assess model errors. Most of the important model errors satisfy program/project-specified requirements.	M&S results compare favorably to measurements from a representative system or to results from a higher-fidelity M&S that satisfies the conditions for Level 2. Validation points are within the domain of operation for the RWS. Favorable comparisons are obtained for at least some of the important response quantities.
1	Some data are known and traceable to informal documentation. Sources of all significant data are known. Uncertainties in data may not even be estimated.	Verification is informal, with some documentation or evidence of completeness/success.	The model is conceptually validated. The problem statement (intended use) is clearly stated & well-understood, and the conceptual model, requirements, & specifications are correct and sufficiently address the problem.

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	M&S Development		
Level	**Data Pedigree**	**Verification**	**Validation**
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

E.4.1.1 Data Pedigree Factor

The concept of pedigree is included in both the data and input factors of the updated credibility assessment and is loosely defined as a traceable record of lineage or heritage. Data Pedigree involves the evaluation of all data used in the development of an M&S, and is formally defined as a record of the traceability of data from its source through all aspects of its transmission, storage, and processing to its final form used in the development of an M&S. Any changes from the (real-world) source data may be of significance to its pedigree. Ideally, this record includes important quality characteristics of the data at every stage of the process.

Assessment of M&S development data at Level 1 requires at least informal traceability, while traceability becomes formal at Level 2 along with the processes for establishing significant data and an estimate of its uncertainty. Attaining Level 3 requires all data to be known and traceable, but with only significant or key data to have acceptable accuracy, precision, and uncertainty. Level 4 then requires all data to have acceptable accuracy, precision, and uncertainty.

E.4.1.2 Verification Factor

Verification, in essence, is what is done to provide assurance that the conceptual and mathematical models are correct, specifications for the computational model are sufficient and accurate, and the computational model is correctly implemented. There are two different aspects with respect to the latter: (a) code verification and (b) solution verification.

Code verification employs standard software development techniques, including regression testing and unit testing. The former is the process of testing changes to computational models to make sure the older aspects still work with the new changes. The latter is a procedure used to validate that individual units of computational models are working properly. Ultimately, code verification should be accomplished via the use of the end-to-end computational model to ensure interactions between the units are not a problem.

Solution verification involves identifying the presence of any numerical and logical errors in the model, assessing their impact upon the accuracy of the results, and taking necessary steps (if any) to ensure that the impact satisfies any requirements or is otherwise minimized to the extent possible. These errors result from inherent characteristics the computer hardware, underlying software, and decisions made by developers/users such as tolerances for iterative convergence or discretization (resolution) of the model. Trade-offs in terms of accuracy and run-time efficiency, in such cases, are often unavoidable.

Other key aspects to consider include: (a) the degrees of rigor and formality of the verification processes, and (b) how well-established and appropriate the processes are in the context of the specific M&S being developed.

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E.4.1.3 Validation Factor

Validation starts with conceptual validation, i.e., providing the requisite assurance that the conceptual and mathematical models are valid. Once the computation model is available, the next step is empirical validation, which is the comparison of M&S results with a referent (generally, data from either the RWS or a "representative system"). In some instances, e.g., for the development of so-called "surrogate models," the referent can be the results obtained from a higher-fidelity (and typically computationally expensive) model.

The Validation factor considers the following aspects when assessing credibility: (a) the similarity between the RWS and the referent, (b) the extent of the *domain of M&S validation* relative to the *domain of RWS operation*, and (c) the extent to which favorable comparison is achieved for all possible model outputs (dependent variables). Compliance with [M&S 8 (4)] ensures specific criteria are defined for what constitutes "favorable comparison."

Favorable comparison, if obtained, occurs at a "validation point," which can be thought of as a unique set of independent variables (i.e., inputs to the model, corresponding to known or controlled conditions for the referent system). The region enclosing all validation points is called the "domain of M&S validation." The region enclosing all points at which the RWS has operated (or is intended to operate) is called the "domain of RWS operation." Each model output may have a unique domain of validation, i.e., favorable comparison may not be obtained for all model outputs at each and every set of model inputs.

The comparison between M&S results and the referent data has to consider: (a) the accuracy of the results – for computational models, the magnitude of the numerical difference between the mean of the M&S result and the mean of the referent data, and (b) the associated uncertainty, i.e., the spread about the means. To achieve favorable comparison between the M&S results and the referent data requires, at a minimum, some overlap between the uncertainty intervals around the means. The comparison may also include sensitivities of the results with respect to corresponding independent variables in both model and experiment.

For the Validation factor, an assessment of Level n ($n \geq 2$), requires all conditions for Level 1 be satisfied, i.e., the model has to be conceptually validated before it is empirically validated.

E.4.2 M&S Use (Operations) Category

The focus of the M&S Use (Operations) category is to assess those factors that most affect the results produced when using an M&S. This starts with having the appropriate data for setup and input to the M&S, and continues through to uncertainty characterization and robustness of the results. The level definitions for these factors are given in table 5, Level Definitions for Factors in the M&S Use (Operations) Category.

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Table 5—Level Definitions for Factors in the M&S Use (Operations) Category

Level	Input Pedigree Evidence	Uncertainty Characterization Evidence	Results Robustness Evidence
4	All input data known and fully traceable to the RWS. All data are acceptable in terms of accuracy, precision, and uncertainty.	A statistical analysis (e.g., ANOVA) of the output uncertainty has been performed for all output quantities after rigorous and validated propagation of all known sources of uncertainty. Reported results may include statistical moments, confidence intervals, sensitivity analysis, etc.	Sensitivity of the M&S results for the RWS is quantitatively known for most of the variables and parameters, including most, if not all, of the most sensitive variables and parameters. Sensitivities of many combinations of these variables and parameters are also quantified.
3	All input data are known and can be traced to a sufficiently representative referent. All significant data are acceptable in terms of accuracy, precision, and uncertainty.	Quantitative estimates of uncertainties have been reported for most output quantities after a propagation of all known sources of uncertainty.	Sensitivity of the M&S results for the RWS is quantitatively known for many variables and parameters, including many of the most sensitive variables and parameters. Sensitivities of some combinations of these variables and parameters are also quantified.
2	Most input data are known and traceable to formal documentation. Processes to establish significant data are known. Uncertainties in all data are at least estimated.	Most sources of uncertainty have been identified, expressed quantitatively and correctly classified based on SME opinions and/or by deduction from experimental data. Propagation of the uncertainty to output quantities has been addressed by reduced order (e.g., monotonic or boundary analysis) and/or reduced dimension propagation.	Sensitivity of the M&S results for the RWS is quantitatively known for a few variables and parameters. Only a few (or none) of the most sensitive variables and parameters are identified. Sensitivities of combinations of variables and parameters are not known.
1	Some input data are known and traceable to informal documentation. Sources of all significant input data are known. Uncertainties in input data may not even be estimated.	Sources of input uncertainty have been identified with qualitative estimates of the uncertainty. Their impact on output uncertainties and uncertainty propagation have not been addressed.	Sensitivity of M&S results for the RWS is estimated by analogy with the quantified sensitivity of similar problems of interest.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

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E.4.2.1 Input Pedigree Evidence Factor

Input Pedigree involves the evaluation of all data used as input to an M&S. It is formally defined as a record of the traceability of data from its source through all aspects of its transmission, storage, and processing to its final form when using an M&S. Any changes from the (real-world) source data may be of significance to its pedigree. Ideally, this record includes important quality characteristics of the data at every stage of the process.

Assessment of M&S input data at Level 1 requires at least informal traceability, while traceability becomes formal at Level 2 along with the processes for establishing significant inputs and an estimate of its uncertainty. Attaining Level 3 requires all input data to be known and traceable, but with only significant or key input data to have acceptable accuracy, precision, and uncertainty. Level 4 then requires all input data to have acceptable accuracy, precision, and uncertainty.

E.4.2.2 Uncertainty Characterization Factor

Uncertainty Characterization includes the identification of uncertainty sources and the qualification or quantification of uncertainty in the current M&S results. The important aspects of Uncertainty Characterization are (a) the sources of uncertainty in the input variables and parameters, (b) the numerical errors incumbent in model implementation mechanisms (e.g., computational/math models), and (c) the propagation of the uncertainty to M&S outputs. These may have variable degrees quality. Also, the results of (c) are directly impacted by both (a) and (b).

At Level 1, some sources of uncertainty are identified in the M&S with qualitative estimates of their uncertainty; however, their impact on the output uncertainty and uncertainty propagation have not been addressed. At Level 2, most sources of uncertainty are identified. These sources are also expressed quantitatively and are correctly classified (e.g., aleatory vs. epistemic) based on either SME opinions and/or by deduction from experimental data. Propagation of the uncertainty to some M&S results are addressed by reduced order analysis (e.g., interval analysis) or reduced dimension propagation based on a sensitivity study. At Level 3, estimates of uncertainties are reported for most output quantities after propagation of all known sources of uncertainty. Propagation at this level is performed by using an appropriate (e.g., probabilistic analysis, evidence theory, fuzzy logic, etc.) and comprehensive (e.g., Monte Carlo sampling) approach. At Level 4, a statistical analysis (e.g., ANOVA) of the output uncertainty is performed for all output quantities after rigorous and validated propagation of all known sources of uncertainty. Reported results may include statistical moments, confidence intervals, sensitivity analysis, etc.

E.4.2.3 Results Robustness Evidence Factor

Results Robustness is the determination of how thoroughly the sensitivities of the current M&S results (to the variables and parameters of the M&S) are known. Simulations aim to imitate the real world or a proposed real world through execution of a (computational) model. Ideally, the imitated system behaves like the RWS (i.e., with acceptable accuracy and precision, and with

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similar sensitivities). That is, if the RWS is sensitive to certain variables or parameters, then the M&S results should be similarly sensitive. The purpose of considering robustness is to garner an understanding of the sensitivity of the RWS to potential fluctuations, either individually or in combinations, in the variables and parameters of the system.

As a matter of clarification:

- Validation Testing yields an understanding of:
    - The accuracy and precision of the M&S with respect to the RWS.
    - How well the sensitivity of the M&S matches that of the RWS, including if M&S sensitivities are similar (in magnitude and direction) to the RWS.
- Sensitivity Analysis determines the stability (robustness) of the scenario(s) under analysis with the knowledge of M&S sensitivities as determined in Validation.

The key sensitivities are defined as parameters and variables shown to produce large changes in results with relatively small perturbations to input.

What constitutes “few,” “many,” and “most” in Levels 2, 3, and 4 cannot be generally specified for all situations. As a guideline, “few” should mean the sensitivity of, say, less than 20 percent of the potential variables and parameters is known; “many” should mean the sensitivity of, say, between 20 and 50 percent is known; at Level 4, “most” implies the majority (i.e., >50 percent) of all parameters and variables is known, including all of the most sensitive variables and parameters.

E.4.3 Supporting Evidence Category

The focus of the Supporting Evidence Category is to assess those factors that cut across both the development and use of an M&S, but still affect, though possibly indirectly, the credibility of the M&S results. The factors include M&S History, including both the change history as well as the use history of the M&S, and M&S Process/Product Management, which assesses the formality of control applied to the M&S’s processes and products. The level definitions for these factors are given in table 6, Level Definitions for Factors in the Supporting Evidence Category.

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Table 6—Level Definitions for Factors in the Supporting Evidence Category

Level	M&S History	M&S Process/Product Management
4	Model changes have stabilized to inconsequential levels and proposed use is within established norms for the model.	Measurements, including customer/user feedback, are used to improve both the M&S process and products.
3	Model has at most (no more than) minor changes from previously used versions, and proposed use is in interpolated regions of validation points.	The formally established process is rigorously controlled and followed. Compliance with the process is formally documented. Measurements of process and product compliance are made and documented. CM of M&S products is rigorously applied.
2	Model has at most (no more than) moderate changes from previously used versions, and proposed use is at most (no more than) moderately different from previous uses.	Roles and responsibilities are defined in the context of an M&S process that is formally documented and approved. Requirements for M&S products are formally documented and approved. CM of M&S products is established and applied using formal methods.
1	Model is new or has major changes from previously used versions, or proposed use has major differences from previous uses; however, the model, changes, and uses are documented.	Roles and responsibilities are defined in the context of an M&S process that is informally documented. Requirements for M&S products are informally documented. CM of M&S products is established and applied using informal methods.
0	Insufficient evidence.	Insufficient evidence.

E.4.3.1 M&S History Factor

The M&S History factor implicitly includes two main elements (or sub-factors): change history and use history. This factor provides an assessment of the "heritage" of the M&S from these two viewpoints.

The change history sub-factor assesses the degree of changes of the current model relative to versions used in previous applications. For the highest level, the model changes are "relatively minor."

The use history sub-factor assesses the degree to which the current proposed or actual use of the M&S is identical to previous uses. For the highest level, the "proposed or actual use is nearly identical" to previous uses.

For the M&S History factor, an assessment of Level n ($n \geq 1$), requires all conditions for Levels 1 through (n-1) be satisfied.

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E.4.3.2 M&S Process/Product Management Factor

The term M&S Process/Product Management is used to describe the extent to which an M&S effort exhibits the characteristics of work product management; process definition; process measurement; process control; process change; continuous improvement, including CM; and M&S support and maintenance. The levels are similar to those for most process maturity models. This factor assesses how rigorously the processes and products of an M&S are managed and maintained as directed by the NASA report "A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report" (NTRS-PB2005-100968). Assessments at Level 1 and higher require evidence addressing each of these topics.

For the M&S Process/Product Management factor, an assessment of Level n ($n \geq 3$) requires the conditions for Level 2 be satisfied.

E.5 Reporting the Credibility Assessment and Sufficiency Thresholds

E.5.1 Reporting the Credibility Assessment

The reporting of the credibility assessment is different from the Baseline version of this NASA Technical Standard in that only individual factor assessments are reported without any attempt at aggregation. Additionally, there is no weighting of sub-factor evaluations required. This simplifies and clarifies reporting, makes it less abstract, and eliminates the problems/limitations associated with non-numerical aggregation.

A few methods were used in the reporting of M&S results credibility since its inception in the Baseline version. Two are provided here as examples, with corresponding examples including Sufficiency Thresholds provided in the following section. The first two methods, the bar graph (figure 3, Bar Graph of Credibility Assessment) and the spider plot or radar plot (figure 4, Spider Plot or Radar Plot of Credibility Assessment), really display the same information, but in graphically different forms.

These methods readily show each factor's assessment and provide a basis for discussion of the background of each.

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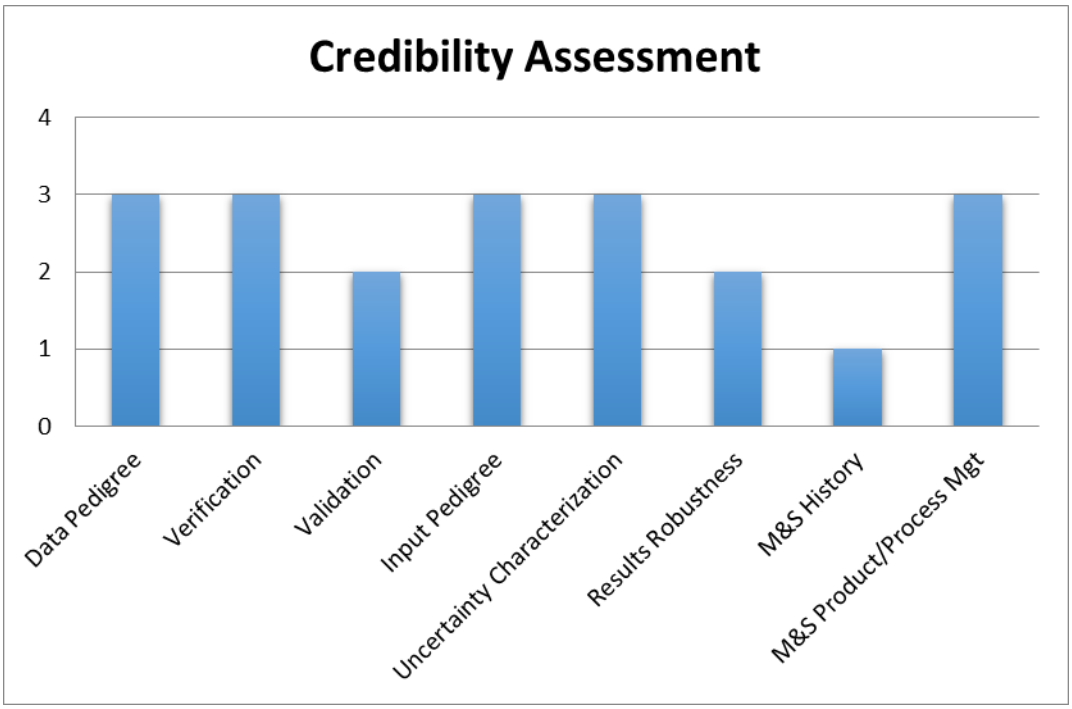

Figure 3—Bar Graph of Credibility Assessment

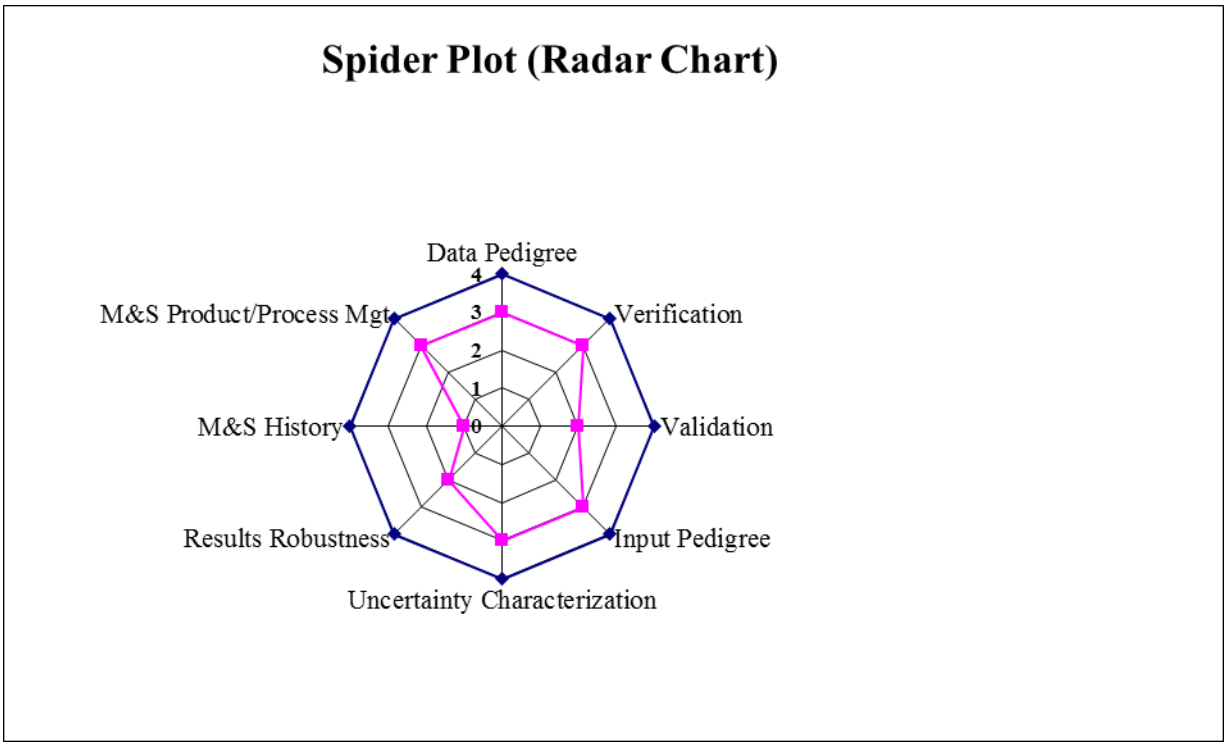

Figure 4—Spider Plot or Radar Plot of Credibility Assessment

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E.5.2 Reporting Sufficiency Thresholds

Recommendations "a" through "c" from section 4.3.7 specify information relevant to credibility sufficiency thresholds.

a. Should set credibility sufficiency threshold levels for each factor as described in Appendix E.

b. Should justify and document the credibility assessment for each of the factors referenced in [M&S 31].

c. Should gain additional insight into the credibility of M&S results by applying the process in this section to determine and report any gaps between the achieved scores and the program/project-defined threshold scores for each of the factors.

The concept behind these recommendations is that program/project management, technical authorities, stakeholders, or customers are encouraged to set credibility goals, or thresholds, for an M&S effort to meet. During the course of M&S planning, development, and use, the developers and users can then allocate the appropriate amount of effort to achieving those thresholds. Reporting the factor assessments with their associated thresholds, as in figure 5, Bar Graph of Credibility Assessment with Thresholds, and figure 6, Spider Plot or Radar Plot of Credibility Assessment with Thresholds, provides an additional basis for credibility discussions. Note, as illustrated in this notional example, the possibility exists of either not reaching (e.g., M&S History and M&S Product/Process Management) or of exceeding (e.g., Input Pedigree) the defined threshold.

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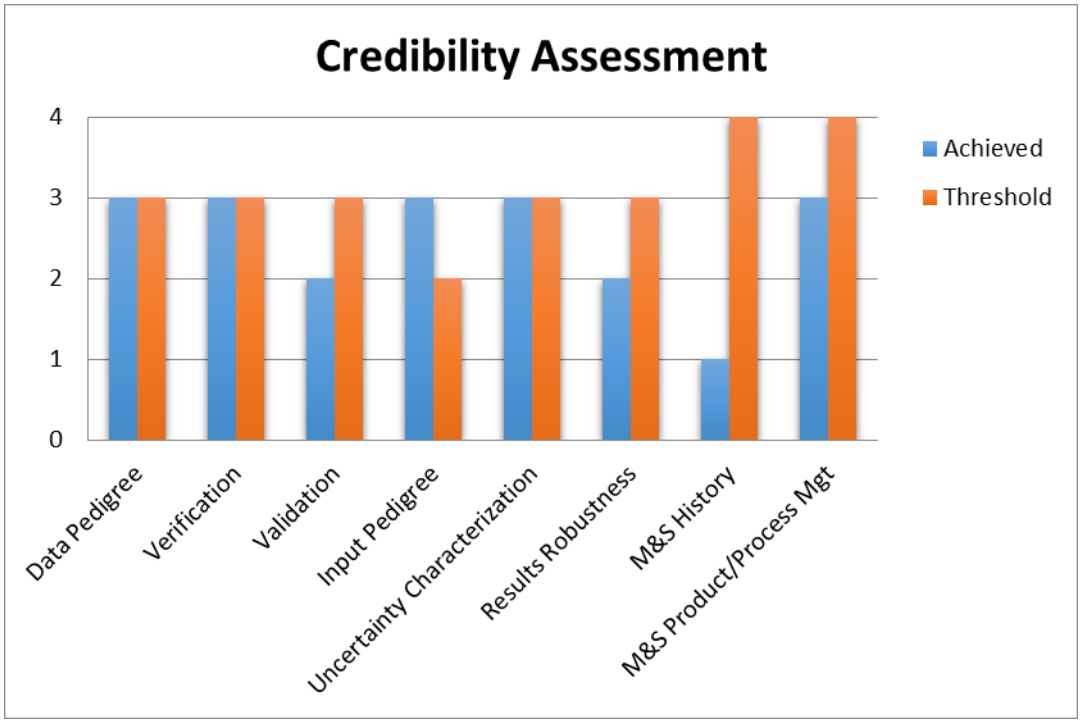

Figure 5—Bar Graph of Credibility Assessment with Thresholds

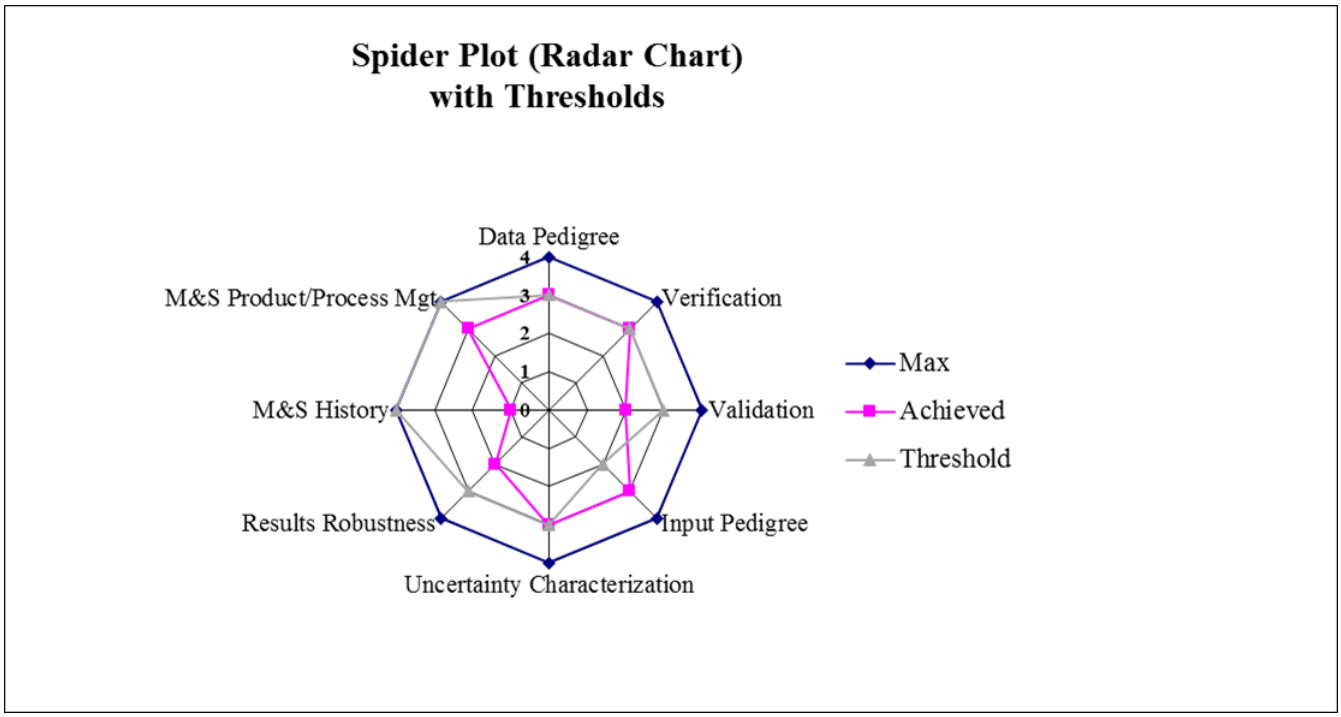

Figure 6—Spider Plot or Radar Plot of Credibility Assessment with Thresholds

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APPENDIX F

M&S Life Cycle

F.1 Purpose

The purpose of this appendix is to provide an explanation of the M&S life cycle.

The life cycle of a model or simulation, like that of any system, has two general parts: M&S development, which includes M&S initiation, concept development, M&S design, M&S construction, and M&S testing; and M&S application, which includes use (or operation) and M&S archiving (including the associated artifacts, products, and analysis performed during a specific use). These phases are summarized in figure 7, M&S Life Cycle.

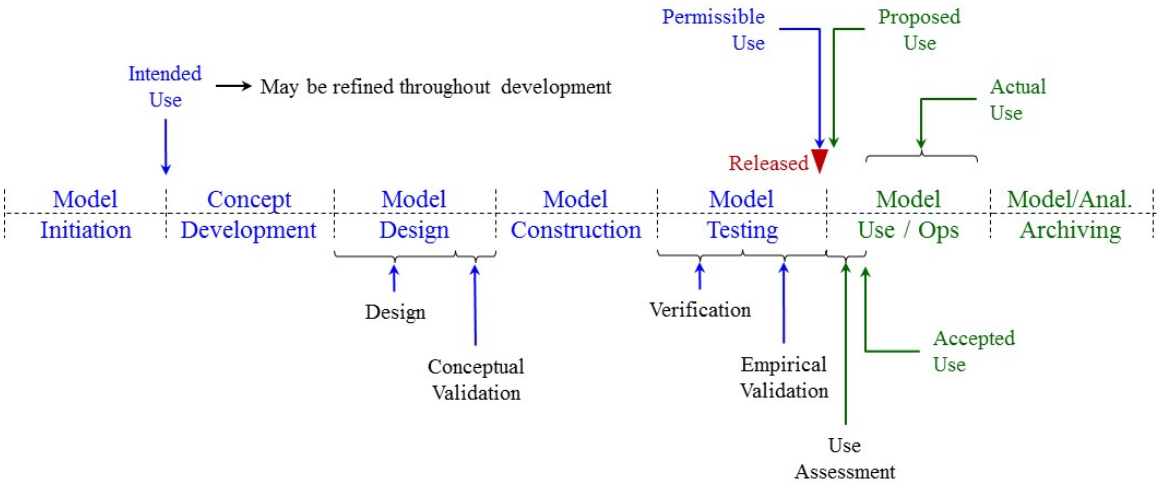

Figure 7—M&S Life Cycle

The need for a model or simulation starts the modeling and simulation life cycle and can occur at any point in a program's or project's life cycle. This need for an M&S starts the M&S initiation phase, where the RWS that needs to be modeled and simulated and the information or results that are required of the M&S are identified, and the intended use of the M&S starts to be defined. The intended use is further defined during the concept development phase, where the aspects of the RWS that need to be included in the M&S and the abstractions and assumptions required to implement the M&S are identified. In addition, the objectives and level of detail required in or from the M&S, and acceptance criteria to determine M&S sufficiency, are identified. The intended use typically becomes more refined throughout M&S development, leading to iterations in the M&S development phase to match the changes in intended use.

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As the M&S moves into the M&S design phase, a conceptual model and other M&S requirements or specifications are developed that describe the physical behavior and interactions of the RWS from which a working M&S can be made. This conceptual model is validated against the aspects and behavior of the RWS within the areas of interest as defined by the intended use during the conceptual validation phase. Once the conceptual model (or M&S design) is validated, the working M&S is constructed. The relationships between the M&S design (conceptual model), the working M&S, and the RWS reality of interest are illustrated in figure 8, M&S Process Relationships (adapted from Sargent, 1979). Additional details about the M&S Process is in NASA-HDBK-7009, section 4.5.2.

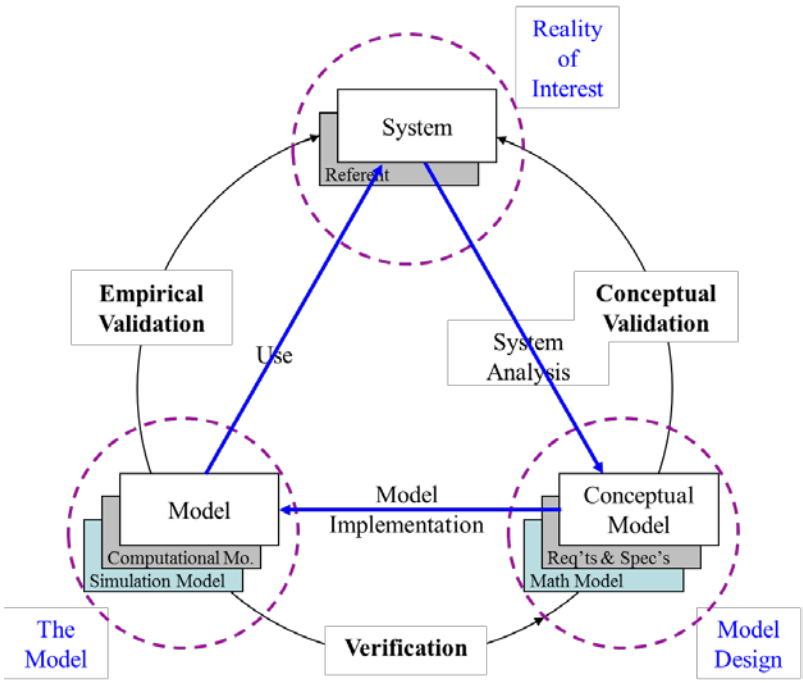

Figure 8—M&S Process Relationships

During model testing, verification shows the working model adequately represents, and/or behaves like, what is identified in the conceptual model or model design. On the other hand, the intent of empirical validation is to show the working model adequately represents, and/or behaves like, the RWS or an alternate referent by a more direct comparison. This testing identifies the model's limits of operation, i.e., where the model is known to work correctly (i.e., verified and validated). At the end of model testing, the model's capabilities, assumptions, and limits of operation are documented and assessed with respect to acceptance criteria to determine the permissible uses of the model. Once model testing is successfully completed, the model is released, along with documentation of the model's capability and domain of permissible use, ending model development.

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During the use (or operations) phase, the model may or may not be used by those who developed it. In both cases, and especially the latter case, the use of a model starts with an assessment of whether or not the proposed use of the model sufficiently matches the permissible use. If the proposed use is acceptable, the model is then used to obtain the results of interest.

If the proposed model use does not meet the defined permissible use, the proposed use will either be rejected or possibly allowed with the appropriate restrictions, caveats, or placarding required. Each application of the model restarts the model use/operation with an assessment of permissible uses against the needs of that specific proposed use.

The credibility of the results from the particular use of the model is assessed using the credibility assessment requirements of this NASA Technical Standard. The results and credibility are reported to the program/project customers for use in their decision-making about the RWS. Information regarding the actual use and the specific version of the model used are documented and archived.