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Office of the NASA Chief Engineer

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NOT MEASUREMENT SENSITIVE

STANDARD FOR MODELS AND SIMULATIONS

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.
Change		1	2016-12-07	Administrative/Editorial Changes—Editorial corrections in section 4.2.6, and requirements M&S 25, 32, and 38.
Revision	B		2024-03-05	Significant changes were made to this NASA Technical Standard. It is recommended that it be reviewed in its entirety before implementation. Key changes were: combining some requirements for clarity; promoting recommendations to requirements for recording an M&S Life Cycle Plan, data and software used in development, units and vector coordinate frames, guidance on use; adding a requirement for tracking M&S defects or problems; adding a requirement for a risk assessment with specific details; splitting the M&S Results Credibility Assessment into M&S Capability and M&S Results Assessments.

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 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 identified in the Columbia Accident Investigation Board (CAIB) Report.

This 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.

Submit requests for information via "Email Feedback" at https://standards.nasa.gov. Submit requests for changes to this Standard via Marshall Space Flight Center (MSFC) Form 4657, Change Request for a NASA Engineering Standard, or "Email Feedback" at https://standards.nasa.gov.

Original Signed By:

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Joseph W. Pellicciotti
NASA Chief Engineer

March 5th, 2024

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Approval Date

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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 delegated NASA Technical Authority.

This Standard provides an approved set of requirements, recommendations, and criteria with which 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 NASA-STD-7009B includes important structural changes from NASA-STD-7009A regarding application within the M&S life-cycle, specifically in assessments of credibility products within the development and use phases. The discipline-specific data and process definitions for analyses of a particular M&S should be obtained from relevant recommended practices.

1.1 Purpose

The primary purpose of this Standard is to reduce the risks associated with M&S-influenced decisions by establishing a basic set of best practices applicable to any M&S and a generic, flexible M&S life-cycle process that includes several formal assessments to support the communication of M&S-based results credibility. This Standard achieves this with a minimum set of requirements and recommendations encompassing development, maintenance, operation, results analysis, training, assessments, and reporting. This 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

1.2.1 This Standard:

a. Is generally applicable (relevant and appropriate) to all M&S used by NASA, its contractors, and its partners. However, it is acknowledged that the primary motivation during the development of the Standard was to cover M&S used to support the design, development, manufacturing, ground operations, and flight operations of NASA systems.

b. Is highly recommended for M&S used to support critical decisions or functions in the categories listed above.

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

The use of this Standard, with or without tailoring, to cover M&S uses in categories and applications not listed above is encouraged.

1.2.2 This Standard is approved for use by NASA Headquarters and NASA Centers and Facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. This language applies to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center), other contractors, recipients of grants, cooperative agreements, or other agreements only to the extent specified or referenced in the applicable contracts, grants, or agreements.

1.2.3 References to "this Standard" refer to this NASA-STD-7009B; references to other documents state the specific document information.

1.2.4 Verifiable requirement statements are designated by the acronym "M&S" (Models and Simulations), numbered, and indicated by the word "shall." This Standard contains 43 requirements. To facilitate requirements selection by NASA programs and projects, a Requirements Identification Matrix is provided in Appendix A.

1.2.5 Explanatory or guidance text is indicated in italics beginning in section 4. The terms "may" or "can" denote discretionary privilege or permission, "should" denotes a good practice and is recommended but not required, "will" denotes expected outcome, and "is/are" denotes descriptive material or a statement of fact.

1.3 Tailoring

Tailoring of the requirements in this Standard for application to a specific program, project, organization, or office is acceptable when formally approved by the delegated NASA Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements, and documented in program, project, organization, or office requirements.

2. APPLICABLE DOCUMENTS

2.1 General

2.1.1 The document listed in this section contains provisions coingstitute requirements of this Standard as cited in the text. Latest issuances of cited documents apply unless specific versions are designated. Obtain approval from the delegated NASA Technical Authority to use a version other than as designated.

2.1.2 Access the applicable document at https://standards.nasa.gov.

Note: References are provided in Appendix C.

2.2 Government Documents

NASA

NPR 7120.5, NASA Space Flight Program and Project Management Requirements

2.3 Non-Government Documents

None.

2.4 Order of Precedence

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

2.4.2 Conflicts between this Standard and other requirements documents will be resolved by the delegated NASA Technical Authority. When conflicts exist between this Standard and voluntary consensus standards (VCS), this Standard takes precedence, except in those cases where the VCS is invoked by applicable Government regulation.

3. ACRONYMS, ABBREVIATIONS, 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
DoE	Design of Experiments
EIA	Electronic Industries Alliance
FS	Factor of Safety
GOTS	Government-Off-The-Shelf
HDBK	Handbook
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
JANNAF	Joint Army-Navy-NASA-Air Force
M&S	Models and Simulations
M&SCO	Modeling and Simulation Coordination Office
MIL	military
MOTS	Modified-Off-The-Shelf
MSFC	Marshall Space Flight Center
MUF	Model Uncertainty Factor
NASA	National Aeronautics and Space Administration

NESC	NASA Engineering and Safety Center
NPR	NASA Procedural Requirements
NTRS	NASA Technical Reports Server
OMB	Office of Management and Budget
RPG	Recommended Practices Guide
RWS	Real-World System
SME	Subject Matter Expert
SP	Special Publication
STD	Standard
V&V	Verification and Validation
VCS	Voluntary Consensus Standard
VV&A	Verification, Validation, and Accreditation

3.2 Definitions

The definitions listed below are those used in this Standard. Wherever possible, these definitions have been taken from official NASA documents. In some cases, after reviewing definitions of interest in International Organization for Standardization (ISO) and the Department of Defense (DoD) Modeling and Simulation Coordination Office (M&SCO) documentation, 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 of this Standard. Some definitions may have alternate meanings in other documents and disciplines.

Abstraction: The process of simplifying, focusing, or transforming aspects of a real-world system (RWS), or referent system, represented in M&S. **Note:** Simplifying includes selecting aspects of the RWS to reduce in complexity or discard when formulating the M&S (this includes the concept of aggregation, which is the grouping of several aspects of an RWS and treating them as a single M&S construct). Focusing includes either emphasizing or deemphasizing select aspects of the RWS when formulating the M&S. Transforming includes any change in the appearance, character, composition, configuration, expression, or structure of aspects of the RWS when formulating the M&S (e.g., rotation, translation, mapping, scaling, mathematics). 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 sufficient for a Proposed Use.

Accuracy: The closeness of a parameter or variable (or a set of parameters or variables) within an M&S or experiment to the true value or the assumed true value.

Actual Use: The specific purpose and domain of application for which M&S are being, or were, 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 to understand the item in question and make appropriate recommendations. **Note:** Analysis spans the whole extent of the M&S process from the study of the RWS or its referents, the gathering and reduction of data from the RWS or accepted referents for incorporation into an M&S, 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 product produced by the project team, e.g., requirements, documents, help systems, code, executables, test documentation, test results, records, and diagrams.

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

Calibration: The process of adjusting numerical or modeling parameters in the M&S to improve agreement with a referent. **Note:** Calibration can also be known as "tuning."

Caveat: An explanation to prevent misinterpretation, or a modifying or cautionary detail to be considered when evaluating, interpreting, or doing something. (Source: 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, M&S construction, and M&S verification. It may consist of flow charts, schematic drawings, written descriptions, math models, empirical models, etc., that explain the RWS and its interaction with the surrounding/interfacing environment. The conceptual model should be independent of any specific M&S implementation.

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

Configuration Management: A technical and management discipline applied over the M&S life cycle to provide visibility into and control changes to an M&S. (Adapted from NPR 7120.5F, NASA Space Flight Program and Project Management Requirements)

Correlated (as in an M&S correlated with an 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. **Note:** Use of this term in NASA-

STD-7009 is in respect to M&S results credibility.

Criterion: A standard on which to base a judgment or decision.

Critical Decision: The selection of a course-of-action related to design, development, manufacturing, or operations of a system (ground, flight, or surface) that may significantly impact human safety or mission success.

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. **Note:** 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 (DoE) 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. **Note:** DoE is applicable to both physical processes and simulation models (computer-based, computational, or otherwise).

Deterministic: A term describing a system whose state can be predicted exactly. **Note:** For comparison, see definition of "Probabilistic." The state of a system is a set of variables describing the condition or stage of something.

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

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

Empirical Validation: The process of determining the degree to which an operating M&S exhibits an accurate representation of the real world from the perspective of the intended uses of the M&S.

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

Environment of the System (or RWS): The set of elements, and their associated properties, external to a system. **Note:** The RWS and its environment may interact through the exchange of properties.

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

Factor of Safety: A multiplicative factor applied to the parameters of an M&S (that is, in an M&S, in the input to an M&S, or in the output of an M&S) 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, Agency Risk Management Procedural Requirements, 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 M&S with high relevance to the analysis.

M&S Assessment Thresholds: Minimum acceptable achievement levels for M&S capability and M&S results assessment factors. **Note:** M&S criticality informs M&S Assessment factor thresholds.

M&S Capability: The potential or ability (of an M&S) to represent an RWS, entity, phenomenon, or process.

M&S Limits: The bounding set of parameters or variables for an M&S, based on design and implementation. **Note:** M&S limits are the broadest bounds for potential M&S use that produce results. The M&S limits include any internal or external variables that have limits beyond which the M&S does (or will) not function (correctly). M&S can be used to extrapolate outside the domains of verification and validation (V&V), but within the M&S limits.

M&S Risk: The potential for shortfalls with respect to sufficiently representing an RWS.

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

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

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-2016-6105, 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*)

Metadata: Information about an entity required for access, understanding, and use. **Note:** Metadata is not the 'entity' itself. The 'Entity" may be anything, e.g., data, an M&S, an object, a computer file, a book.

Metrics: Data (numbers, statistics, qualitative facts/levels) used to measure or track performance.

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 go into a model are considered part of the model.

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.

Modeling: (a) The act of creating a system representation (i.e., the act of creating a model); (b) The act of utilizing a system representation (i.e., utilizing a model) as an approach for analyses.

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, properties, processes, or outcomes, which are described by a measure of likelihood. (Adapted from NASA/SP-2009-569, Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis)

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

Real-World System (RWS): The reality of interest an M&S 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 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 M&S types, and NASA handbooks and guidebooks.

Referent: Data, information, knowledge, or theory against which simulation results can be compared. (Adapted from ASME V&V 10) **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 M&S.

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 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. **Note:** The results from an M&S are robust if they are relatively stable (do not change in a meaningful way) with respect to as-designed changes in the control 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 potential for shortfalls with respect to achieving explicitly established and stated objectives. (Source: NPR 8000.4, Agency Risk Management Procedural Requirements)

Scenario: The description or definition of the relevant system and environmental assumptions, conditions, parameters, and timeline used to drive the course of events during the run of an M&S. **Note:** The scenario 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 M&S itself. 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 M&S 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.

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

Stochastic: Involving or containing a random variable or variables. Pertaining to chance or

probability. (Source: 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 seek relief from a prescribed requirement to accommodate the needs of a specific task or activity (e.g., program or project). The tailoring process results in the generation of deviations and waivers depending on the timing of the request. (Source: NPR 7120.5)

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; and (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 and describing their relevant qualities (qualitatively or quantitatively) in all M&S and experiments (inputs and outputs).

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.

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, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, as revised January 27, 2016, at Federal Register Vol. 81, No. 17, page 4673)

Waiver: An official authorization intentionally releasing a program or project from meeting a requirement. (Adapted from NPR 7120.5) **Note:** Deviations and exceptions are considered special cases of waivers.

4. REQUIREMENTS

This 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 inherent in these decisions must be anticipated and correctly estimated throughout the development and use of an M&S, including an adequate assessment of uncertainities. This Standard establishes practices to help reduce, assess, and communicate risk by making the factors supporting M&S credibility more apparent. As such, this Standard contains a number of assessments that occur during the life cycle of an M&S. This 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 the establishment, recording, and maintenance of M&S processes and products to enforce transparency, repeatability, and traceability. The language that follows in many requirements is of the form "shall maintain a record of…" the appropriate outcome, or product, of the relevant activity, to avoid multiple (three) requirements associated with the activity (one for "establishing", one for "recording", one for "maintaining"). However, to maintain a record of an outcome or product implies that the outcome or product be established (created). Furthermore, maintenance of the record implies that the outcome or product is re-established as a result of any changes to either the RWS or the M&S. These requirements and recommendations also encourage the appropriate training and experience base for key M&S personnel.

The requirements and recommendations in this 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 NPR 7150.2, NASA Software Engineering Requirements.

The following organizational structure is employed in this Standard:

4.1 M&S Programmatics, including:

- *M&S Criticality Assessment.*
- *Establishment of the M&S Intended Use.*
- *M&S Development and Use Plans.*
- *Recommended Practices Identification and Use.*
- *Training.*

4.2 M&S Development, including:

- *M&S Design.*
- *M&S Conceptual (Design) Validation.*
- *M&S Verification.*

- *M&S Validation.*
- *M&S Uncertainty Characterization.*
- *M&S Capability Assessment.*
- *M&S Release.*

4.3 M&S Use (Operations), including:

- *M&S Use Assessment.*
- *M&S Setup and Execution.*
- *M&S Results Uncertainty Characterization.*
- *M&S Sensitivity Analyses.*
- *M&S Results Assessment.*
- *M&S Risk Assessment.*
- *M&S Results Reporting 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 Standard is inclusive of all these possibilities.

Program and project management is responsible for identifying and recording the parties responsible for complying with the requirements in this 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 M&S development, operation, analysis, and/or reporting of results to decision makers. Additionally, program and project management, in collaboration with the delegated NASA Technical Authority, is responsible for establishing the extent and level of formality of processes (including any assessments) and products needed to meet the requirements in this Standard. Furthermore, the delegated NASA Technical Authority has the particular responsibility to assure appropriate outcomes of [M&S 40], [M&S 42], [M&S 43], [M&S 44], [M&S 23], [M&S 31], and [M&S 48].

The requirements that include the recording of an activity or data do not imply that either the activity in question is required or that a new record for the model, simulation, or analysis is needed. The intent is to record whether or not the activity was accomplished and the data/information resulting from its accomplishment. Also, if some evidence or artifact of the relevant activity is available, a reference to that evidence (e.g., a journal article, a technical report, an M&S development/test document or computer file, a record, an M&S user/operator guide, or a program/project document) may suffice, provided the required details are contained therein and specific locations of the required information are given. The responsible party is to incorporate M&S products, evidence, and artifacts into the project or program plans for the configuration management or technical data management processes as appropriate (see NPR 7123.1, NASA Systems Engineering Processes and Requirements).

The responsible party is to provide a rationale why any requirement (or recommendation, if imposed by tailoring or direction) is not met. (See Appendices A and B.)

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 "permissible use" at the end of development (see section 4.2) and "proposed use" at the beginning of M&S use (see section 4.3) in this Standard.

Program and project management, in collaboration with the delegated NASA Technical Authority, has the responsibility to identify and record 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.

4.1.1 General M&S Programmatics

4.1.1.1 [M&S 40] A record of the intended use of M&S **shall** be maintained.

[Rationale: The intended use is a general statement of the aspects of an RWS included in the M&S, what the M&S does, the intended domain of validation, and a description of results expected from the M&S, and a description of the decision(s) the M&S results will inform.]

4.1.1.2 [M&S 6] A record of the assessed criticality associated with M&S use **shall** be maintained.

[Rationale: The criticality assessment ensures communication of the amount of influence an M&S has on the intended use 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, is to be recorded.

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

4.1.1.3 [M&S 41] A plan for the acquisition, development, operation, maintenance, and retirement of the M&S (including identifying the responsible organizations) **shall** be maintained.

[Rationale: The M&S development and use plans are proactive bases for proceeding through the life cycle of the M&S, including when compliance with the requirements for developing and using the M&S are accomplished.]

4.1.1.4 [M&S 42] A record of the programmatic and technical metrics for the M&S **shall** be maintained.

[Rationale: Defined metrics for M&S products inform developers and users as to the required data/information to collect during M&S development and use to support process improvements, assessments, or other purposes.]

Some metrics may become the basis for M&S acceptance criteria (see [M&S 43], including the associated rationale and explanatory text). Some metrics may be collected for other purposes, for example, to support M&S process improvement.

Examples of programmatic metrics include, but are not limited to:

a. Schedule progress.
b. Cost incurred.
c. Configuration items managed.
d. Products delivered.

Examples of M&S technical metrics include, but are not limited to, data from/about:

a. Verification.
b. Validation.
c. Uncertainty.
d. Sensitivity analysis activities.

4.1.1.5 [M&S 43] A record of acceptance criteria for the M&S **shall** be maintained, including:

a. Criteria for Verification.
b. Criteria for Validation.
c. Criteria for Uncertainty.
d. Criteria for Sensitivity.
e. M&S assessment level thresholds (for the M&S capability assessment and M&S results assessment).

[Rationale: Defined M&S acceptance criteria provide qualitative or quantitative information with which to judge that the M&S or related products satisfy the intended use.]

M&S acceptance criteria are the bases to judge that an M&S meets its intended use (and other detailed objectives), including, but not limited to, criteria for verification, validation, uncertainty, sensitivity analysis, and assessment level thresholds. Solution accuracy and precision are part of V&V criteria. The M&S capability and M&S results assessments together establish the bases for ascertaining the credibility of the M&S results.

Refer to Appendix E for definitions regarding the M&S capability assessment and M&S results assessment, as pertains to criteria relevant to [M&S 43e].

4.1.1.6 [M&S 44] A record of information unique to the M&S necessary when (relevant to) reporting results from the M&S **shall** be maintained (in addition to [M&S 32-39]).

[Rationale: This requirement asks for information unique to this M&S be reported in addition to the reporting requirements of section 4.3.8 in this Standard.]

4.1.1.7 [M&S 9] A record of results of technical reviews accomplished during the life cycle of the M&S **shall** be maintained.

[Rationale: Technical reviews show 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. This Standard does not require technical reviews; if they occur, the results are to be recorded and made available.]

The results from technical reviews are to include all products, as well as specific rationale, tests, and other insights attributable to the review that support traceability of the findings. Refer to NASA-HDBK-7009, NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009, for more on this topic.

4.1.1.8 [M&S 51] A record of M&S defects or problems from discovery through closure **shall** be maintained.

[Rationale: A record of existing defects of problems with the M&S provides necessary cautions to M&S users and recipients of M&S-based results, as well as areas for future M&S improvement.]

Defects in, or problems with, the M&S may be found during M&S development or use. This does not necessarily preclude use of the M&S, but the M&S users and recipients of M&S-based results are to be made aware of their existence and impacts on M&S risk (as part of [M&S 39]).

4.1.2 General M&S Programmatic Recommendations

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

a. Record the M&S waiver processes.

b. Record 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 configuration management (CM) and M&S support and maintenance.

4.1.3 M&S Best Practices Recommendations

This 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, other best practices documented for specific simulation codes, and NASA handbooks and guidebooks.

Recommendations for the identification of recommended practices by responsible parties are as follows:

a. Identify and record the recommended practices that apply to M&S for the program/project.

b. At a minimum, consider the recommended practices for the following areas:

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

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

(3) V&V 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 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

Recommendations for training by responsible parties follow:

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

b. Record 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. *The requirements and recommendations for recording information specified in this 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. *V&V.*
I. *How to report simulation results to decision makers.*
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 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 M&S life cycle (see Appendix F) begins by specifying the intended use of the M&S and by establishing an understanding of the existing or envisioned system to be modeled. This is followed by developing the concept for the M&S (including conceptual, mathematical, or computational diagrams or models), continues with choosing application methods and platforms for implementing and testing (both verifying and validating) the M&S, and ends with releasing the M&S 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 M&S use, the constraints of implementation methods used, and the limits of operation based on the completeness and success of both V&V.

4.2.1 General M&S Development

4.2.1.1 [M&S 10] A record of relevant characteristics, including data, of the RWS to be modeled, including its pedigree, **shall** be maintained (see Data Pedigree in Appendix E).

[Rationale: Establishing the relevant characteristics of the RWS is part of analyzing and decomposing the RWS and 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.

4.2.1.2 [M&S 45] The data sets and supporting software used in M&S development **shall** be maintained.

[Rationale: The data sets and supporting software provide bases and support to M&S development, possible technical reviews, and re-creation or reproduction of the M&S, as needed.]

4.2.1.3 [M&S 46] A record of the units and vector coordinate frames for all quantities and input/output variables or parameters in the M&S **shall** be maintained (where applicable).

[Rationale: M&S units and vector coordinate frames are a required part of correlating the M&S's representation of the RWS (and are required as part of M&S V&V).]

4.2.1.4 [M&S 11] A record of the assumptions and abstractions underlying the conceptual and implemented model, including their rationales and consequences with respect to the intended uses of the M&S, **shall** be maintained.

[Rationale: Making abstractions and assumptions are part of the modeling process of analyzing, decomposing, and representing an RWS. Recording the abstractions and assumptions clarifies areas where the M&S differs from the RWS or where limits of implementation mechanisms may cause the M&S' response to differ from that of the RWS. This also provides an understanding needed for verification, validation, uncertainty characterization, the specification of permissible uses, and the acceptance of the M&S for a proposed use. Failure to clearly identify, understand, and communicate assumptions and abstractions introduces risks throughout development and use of the M&S.]

4.2.1.5 [M&S 12] A record of the concepts, structures, and mathematics of the M&S (e.g., techniques, equations solved, behaviors or states characterized, flow of execution, conceptual models) **shall** be maintained.

[Rationale: The act of modeling encompasses making choices as to how best to represent the RWS or elements (components) thereof. These concepts, structures, and mathematics of the M&S provide the basis for the detailed design and specification of the M&S, which provide the basis for verification 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 information from [M&S 11-12] may be available in published user guides; a reference to the user guides may suffice for this part of these records.

4.2.1.6 [M&S 13] A record of the M&S limits (e.g., boundary conditions) **shall** be maintained.

[Rationale: The M&S limits provide the broadest bounds for potential M&S Use that produce results, beyond which the M&S does (or will) not function (correctly).]

The M&S limits are determined by the following:

a. The design choices in modeling (representing) the RWS.
b. The implementation mechanisms chosen.

For comparison, see definitions of "Domain of Verification" and "Domain of Validation."

4.2.1.7 [M&S 14] A record of the permissible uses of the M&S **shall** be maintained.

[Rationale: Recording 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 and abstractions, and V&V limits. 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 40]; the model's assumptions and abstractions [M&S 11]; the M&S limits [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].

4.2.1.8 [M&S 48] A record of the assessed M&S capability **shall** be maintained according to each of the following factors:

a. M&S Data Pedigree.
b. M&S Verification.
c. M&S Validation.
d. M&S Development Technical Review.
e. M&S Development Process/Product Management.

[Rationale: The assessment of each M&S capability factor ensures a discussion of the achievements and shortcomings of the M&S as developed with respect to the intended use and provides rationale for either acceptance or rejection of the M&S for release and use.]

See Appendix E for more on this topic.

4.2.1.9 [M&S 47] Guidance on how to use the M&S **shall** be maintained, including:

a. Appropriate practices for:

   (1) Setup.

   (2) Execution.

   (3) Interfaces with other models when the M&S is used as part of either a linked or coupled model.

   (4) Analysis of results.

b. Obsolescence criteria.

c. Parameter calibrations.

d. Computational requirements (e.g., required hardware/software versions, main memory, disk capacities, processor, and compilation options).

[Rationale: A user's guide provides information on the appropriate application of an M&S, including M&S functions and limitations, descriptions of appropriate practices for set-up, execution, interfaces with other models when the M&S is used as part of either a linked or coupled model, and analysis of results.]

An M&S User's Guide Outline is included as an appendix in NASA-HDBK-7009. Obsolescence refers to situations where changes to the real system invalidate the M&S. The computational requirements are for both M&S Development and M&S Use (if they are different). These requirements may be either the minimum computational requirements (operating system, hardware configuration, etc.) for the M&S or the computational configuration(s) used throughout M&S development.

4.2.2 General M&S Development Recommendations

Recommendations for general M&S development are that responsible parties should:

a. Record the methods of uncertainty characterization and the uncertainty in any data used to develop the M&S or incorporated into the M&S.

b. Proceed with development activities in a manner that reduces risk to the project and application of the M&S by limiting the definition of the modeled RWS and its environment to only include interactions relevant to the intended use of the M&S.

c. Design and construct the M&S 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.

d. Record updates of the M&S (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.

e. Include test cases in the CM records that span the M&S limits defined by the program or project. "Test cases" are defined as benchmark input/output sets used to verify proper execution of the M&S.

f. Provide a feedback mechanism for users to report unusual results to M&S developers or maintainers.

g. Maintain (conceptual, mathematical, and computational) models, simulations, and associated records in a controlled CM system.

h. Maintain the data sets and supporting software referenced in [M&S 45] and the associated records in a controlled CM system.

i. 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 an M&S takes two distinct forms: V&V. While both these activities test the M&S, they do so for different reasons. Verification is testing with respect to model specification and design. V&V often occur in a cyclical or mixed manner depending on many factors in the overall M&S development process and the success or failure in the testing process.

4.2.3.1 [M&S 15] The M&S **shall** be verified.

4.2.3.2 [M&S 16] A record of the domain of verification of the verified M&S **shall** be maintained.

[Rationale: Verifying the M&S ensures it is implemented in accordance with its design. The domain of verification for the M&S provides operational criterion for which it is known to produce results within the capabilities for which it was constructed.]

There are two distinct aspects of verification:

a. Implementation (code) verification determines the degree to which the implemented M&S contains everything in the M&S Design (and nothing more). In the M&S life cycle, this is the first activity in the M&S Testing phase.

b. Solution verification determines the M&S is working without errors and achieving accuracy goals. In the M&S life cycle, this takes place each time the M&S is used, either in the M&S Testing phase or M&S Use phase.

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 should:

a. Record verification techniques used. NASA-HDBK-7009 has further information regarding specific verification techniques, including the order of precedence of verification prior to validation to reduce technical and programmatic risk.

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

c. Record the verification status of conceptual, mathematical, and computational models.

d. Record aspects of M&S not verified.

4.2.5 M&S Validation

M&S validation is testing a model or simulation and comparing its responses or results to the system the M&S is representing or an acceptable alternative (e.g., a testbed, prototype, or similar representative system). (See discussion of verification in section 4.2.3.)

4.2.5.1 [M&S 17] The M&S **shall** be validated.

4.2.5.2 [M&S 18] A record of the domain of validation of the validated M&S **shall** be maintained.

[Rationale: Validating the M&S ensures it produces results acceptably similar to the RWS it represents. The domain of validation for the M&S provides operational criterion for which it is known to produce results acceptably similar to the RWS it represents.]

The two distinct aspects of validation are:

a. Conceptual (design) validation determines the degree to which a conceptual model or M&S design adequately represents the real world from the perspective of the intended uses of the M&S. In the M&S life cycle, this takes place at the end of an M&S design phase.

b. Empirical validation determines the degree to which an operating M&S is, or provides an accurate representation of, the real world from the perspective of the intended uses of the M&S. In the M&S life cycle, this takes place during the M&S testing phase.

For each M&S validation, the source(s) of empirical data, the methods and processes used to acquire these data, and the methods and processes to manipulate these data as needed for M&S validation are to be assessed with the same level of rigor as the validation of the respective M&S. Furthermore, assessments of empirical data acquisition and processing are to include evaluation(s) to assure these data are relevant and are sufficiently accurate representations of the RWS for which the M&S is being used and data produced. Further details about the issue of proper use of empirical data for M&S validation is presented in NASA-HDBK-7009.

See Appendix E for more on M&S validation.

4.2.6 M&S Validation Recommendations

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

a. Record the 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.

b. Record the validation metrics, referents, and data sets used for M&S validation.

c. Record the studies conducted, and the status and results of, M&S validation.

d. Record the aspects of the M&S not 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 M&S is used to study. Characterizing the uncertainty in M&S results is 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 M&S through all aspects of M&S 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.

4.2.7.1 [M&S 19] A record of the processes and rationale for characterizing uncertainty in the referent data **shall** be maintained.

[Rationale: Explaining and recording 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.]

4.2.7.2 [M&S 21] A record of the qualitatively described or quantitative uncertainties incorporated into the M&S **shall** be maintained.

[Rationale: Characterizing and recording the uncertainties in an M&S ensure 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

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

4.3 M&S Use

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 in this Standard) of an M&S begins with a specific use being proposed and the assessment of the proposed use against the M&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

4.3.1.1 [M&S 22] A record of the proposed use(s) of the M&S **shall** be maintained.

[Rationale: A defined and recorded 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].]

4.3.1.2 [M&S 23] A record of the appropriateness of the M&S relative to its proposed use(s) **shall** be maintained.

[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.

NASA-HDBK-7009 has additional information on proposed use assessments with respect to M&S permissible uses.

4.3.1.3 [M&S 24] A record of the Input(s) to the M&S, including their pedigrees (see Input Pedigree in Appendix E of this Standard) **shall** be maintained.

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

The span of inputs used for the M&S delineates the domain of M&S use, which must always be within the M&S limits; and the M&S results are best (e.g., most accurate) when M&S use takes place within the domains of V&V.

4.3.1.4 [M&S 25] A record of the processes and rationales for setting up and utilizing the M&S **shall** be maintained.

[Rationale: Recorded 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.

4.3.1.5 [M&S 26] Either of the following **shall** be performed:

a. Ensure M&S uses are conducted in accordance with the permissible uses and within the domains of V&V for the M&S, or

b. Placard the M&S and analysis results with a warning that the M&S were not used in accordance with the permissible uses or were used outside the domains of V&V and include the type of limit exceeded, the extent that the limit was 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 or domains of V&V, provides a warning to the consumers of that information.]

4.3.1.6 [M&S 27] A record of the observed warning messages, error messages, and explanations for the messages resulting from the use of the M&S **shall** be maintained.

[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 should:

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

b. Record the computational M&S used (including revision numbers) in the simulation/analysis.

c. Record the parameter calibrations and the domain of calibration.

d. Record the data sets and supporting software used in input preparation.

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

f. Record the versions of M&S results.

g. Record the use history of M&S, in the same or similar applications, which are relevant for assessing the capability of the current M&S application and the credibility of the results obtained from its use (see Appendix E.4.3.1 in this Standard).

h. Record 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, 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 recording of uncertainties during M&S use (operations).

4.3.3.1 [M&S 28] A record of any processes and rationale for characterizing uncertainty in the following **shall** be maintained:

a. The input to an M&S.

b. The results from an M&S.

c. The quantities derived from M&S results.

[Rationale: Recording 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).]

4.3.3.2 [M&S 29] A record of any uncertainties (qualitatively described or quantitative) in the following **shall** be maintained:

a. The input to an M&S.

b. The results from an M&S, including MUFs incorporated into the M&S as well as 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 recorded.

c. The quantities derived from M&S results.

[Rationale: Characterizing 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.]

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

Responsible parties should record 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' response to variations in input parameters to determine which parameters are key drivers to the M&S's results. If the response is negligible, 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). 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 M&S 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] A record of the extent and results of any sensitivity analyses performed with the M&S **shall** be maintained.

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

4.3.6 M&S Results Assessment

An established process for assessing M&S-based analysis results helps ensure clear and complete communication of the important aspects of an M&S beyond just the results. Appendix E addresses 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; 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 interpret the M&S capability and M&S results assessments to determine the appropriate level of influence the M&S has on specific decision(s).

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

4.3.6.1 [M&S 31] A record of the assessed M&S results **shall** be maintained according to each of the following factors:

a. M&S Use Assessment.
b. M&S Input Pedigree.
c. M&S Uncertainty Characterization.
d. M&S Results Robustness.
e. M&S Use/Analysis Technical Review.
f. M&S Use Process/Product Management.

[Rationale: The assessment of the M&S results according to each factor ensures a discussion of the achievements and shortcomings of the M&S use beyond just the results and provides a rational basis for the appropriate interpretation/use of the M&S results with repect to the intended use.]

See Appendix E for more on this topic.

4.3.6.2 [M&S 49] A record of the assessed risks associated with the use of the M&S-based analysis **shall** be maintained.

[Rationale: The assessment of the risks associated with the M&S-based analysis ensures the open communication of possible issues with the M&S results, 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. Topics in the risk assessment include, but are not limited to:

a. The M&S criticality assessment [M&S 6].

b. The findings from technical reviews [M&S 9].
c. M&S defects or problems [M&S 51].
d. Caveats [M&S 32].
e. Uncertainty [M&S 29].
f. Processes to obtain uncertainty [M&S 28].
g. The M&S capability assessment [M&S 48].
h. The M&S results assessment [M&S 31].
i. The qualifications of developer, users, operators, or analysts.
j. Significant differences in the M&S and their impacts from previous releases.
k. Significant differences in M&S use and their impacts from previous uses of the same M&S release.

NASA-HDBK-7009 has additional information on risk assessments.

4.3.7 M&S Results Assessment Recommendations

Responsible parties should justify and record the M&S results assessment for each of the factors referenced in [M&S 31].

4.3.8 M&S Results Reporting

Because of the inexact nature of an 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) objective, credibility supporting, assessments of the M&S capabilities and M&S results (Appendix E), (4) explicit caveats accompanying the results (e.g., the use of the M&S in violation of its assumptions or M&S limits), 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.

4.3.8.1 [M&S 32] When reporting M&S results to decision makers, explicit warnings **shall** be included for the following occurrences, accompanied by at least a qualitative estimate of the impact of the occurrence:

a. Unachieved acceptance criteria (as specified in [M&S 43]).

b. Violation of assumptions of the M&S used (as specified in [M&S 11]).

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

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

e. Unfavorable outcomes from the assessed appropriateness of the M&S to the proposed use (described in [M&S 23]).

f. Issues encountered during setup and utilization of the M&S (described in [M&S 25]).

g. Waivers to the requirements in this Standard (or the requirements specific to the M&S).

h. Outstanding M&S defects or problems (described in [M&S 51]).

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

In the absence of substantiating evidence (e.g., data, information, records) for the requirements referenced in [M&S 32 (1)-(6)], a warning is to be provided.

4.3.8.2 [M&S 33] When reporting M&S results to decision makers, an estimate of results uncertainty, as defined in [M&S 29 (1)-(3)], **shall** be included in one of the following ways:

a. A quantitative estimate of the uncertainty in the M&S results, or

b. A qualitative description of the uncertainty in the M&S results, or

c. 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.

4.3.8.3 [M&S 34] A description of the processes used to obtain the estimate of uncertainty as defined in [M&S 28 (1)-(3)] **shall** be included when reporting M&S results to decision makers.

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

4.3.8.4 [M&S 50] The outcome of the M&S capability assessment performed per [M&S 48] **shall** be included in reporting M&S results to decision makers.

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

The "outcome" of the M&S capability assessment is understood to include the assessed levels for each capability factor specified per [M&S 48], as well as the gaps between the assessed levels and the thresholds as established per [M&S 43e]. Refer to Appendix E for additional details on this topic.

4.3.8.5 [M&S 35] The outcome of the M&S results assessment performed per [M&S 31] **shall** be included in reporting M&S results to decision makers.

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

The "outcome" of the M&S results assessment is understood to include the assessed levels for each results factor specified per [M&S 31] as well as the gaps between the assessed levels and the thresholds as established per [M&S 43e]. The assessment of M&S results is also dependent on the M&S capability, assessed in [M&S 48] and reported in [M&S 50]. Refer to Appendix E for more on this topic.

4.3.8.6 [M&S 36] The findings from technical reviews accomplished in regard to the development, management (control), and use of the M&S **shall** be included in reporting M&S results to decision makers.

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

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

4.3.8.7 [M&S 37] The qualifications of the developers of the M&S and the users, operators, or analysts involved in producing the results from the M&S, including, but not limited to, their relevant education, training, and experience, **shall** be included in the report of M&S results to decision makers.

[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.]

4.3.8.8 [M&S 38] The records of M&S development and use as shown in Appendix A **shall** be included in the report of M&S results to decision makers.

[Rationale: Reporting M&S records 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 columns for applicability and rationale if not applicable. The location of applicable/required records is also necessary for compliance.

4.3.8.9 [M&S 39] The assessment of, and rationale for, acceptance of the risks associated with the results from the M&S-based analysis as determined in [M&S 49] **shall** be included in reporting M&S results to decision makers.

[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, 50] 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 should:

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

b. Identify how to access more detailed backup material, including high-level descriptions of the M&S used and key assumptions for limits of validity.

c. Place M&S results in the CM system.

d. Summarize deviations from established recommended practices.

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

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

APPENDIX A: REQUIREMENTS IDENTIFICATION MATRIX

A.1 PURPOSE

Due to the complexity and uniqueness of NASA missions, it is unlikely that all of the requirements in a Standard will apply. The Requirements Identification Matrix below contains this Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement, specify proposed tailoring, or to provide an explanation/justification when not applicable.

Table 1—Requirements Identification Matrix

NASA-STD-7009B				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1.1.1	General M&S Programmatics	[M&S 40] A record of the intended use of M&S **shall** be maintained.		
4.1.1.2	General M&S Programmatics	[M&S 6] A record of the assessed criticality associated with M&S use **shall** be maintained.		
4.1.1.3	General M&S Programmatics	[M&S 41] A plan for the acquisition, development, operation, maintenance, and retirement of the M&S (including identifying the responsible organizations) **shall** be maintained.		
4.1.1.4	General M&S Programmatics	[M&S 42] A record of the programmatic and technical metrics for the M&S **shall** be maintained.		
4.1.1.5	General M&S Programmatics	[M&S 43] A record of acceptance criteria for the M&S **shall** be maintained, including: a. Criteria for Verification. b. Criteria for Validation. c. Criteria for Uncertainty. d. Criteria for Sensitivity. e. M&S assessment level thresholds (for the M&S capability assessment and M&S results assessment).		

Table 1—Requirements Identification Matrix

NASA-STD-7009B				
4.1.1.6	General M&S Programmatics	[M&S 44] A record of information unique to the M&S necessary when (relevant to) reporting results from the M&S **shall** be maintained (in addition to [M&S 32-39]).		
4.1.1.7	General M&S Programmatics	[M&S 9] A record of results of technical reviews accomplished during the life cycle of the M&S **shall** be maintained.		
4.1.1.8	General M&S Programmatics	[M&S 51] A record of M&S defects or problems from discovery through closure **shall** be maintained.		
4.2.1.1	General M&S Development	[M&S 10] A record of relevant characteristics, including data, of the RWS to be modeled, including its pedigree, **shall** be maintained (see Data Pedigree in Appendix E).		
4.2.1.2	General M&S Development	[M&S 45] The data sets and supporting software used in M&S development **shall** be maintained.		
4.2.1.3	General M&S Development	[M&S 46] A record of the units and vector coordinate frames for all quantities and input/output variables or parameters in the M&S **shall** be maintained (where applicable).		
4.2.1.4	General M&S Development	[M&S 11] A record of the assumptions and abstractions underlying the conceptual and implemented model, including their rationales and consequences with respect to the intended uses of the M&S, **shall** be maintained.		

4.2.1.5	General M&S Development	[M&S 12] A record of the concepts, structures, and mathematics of the M&S (e.g., techniques, equations solved, behaviors or states characterized, flow of execution, conceptual models) **shall** be maintained.		
4.2.1.6	General M&S Development	[M&S 13] A record of the M&S limits (e.g., boundary conditions) **shall** be maintained.		
4.2.1.7	General M&S Development	[M&S 14] A record of the permissible uses of the M&S **shall** be maintained.		
4.2.1.8	General M&S Development	[M&S 48] A record of the assessed M&S capability **shall** be maintained according to each of the following factors: a. M&S Data Pedigree. b. M&S Verification. c. M&S Validation. d. M&S Development Technical Review. e. M&S Development Process/Product Management.		
4.2.1.9	General M&S Development	[M&S 47] Guidance on how to use the M&S **shall** be maintained, including: a. Appropriate practices for: (1) Setup (2) Execution (3) Interfaces with other models when the M&S is used as part of either a linked or coupled model. (4) Analysis of results b. Obsolescence criteria. c. Parameter calibrations. d. Computational requirements (e.g., required hardware/software versions, main memory, disk capacities, processor, and compilation options).		
4.2.3.1	M&S Verification	[M&S 15] The M&S **shall** be verified.		
4.2.3.2	M&S Verification	[M&S 16] A record of the domain of verification of the verified M&S **shall** be maintained.		
4.2.5.1	M&S Validation	[M&S 17] The M&S **shall** be validated.		
4.2.5.2	M&S Validation	[M&S 18] A record of the domain of validation of the validated M&S **shall** be maintained.		
4.2.7.1	Uncertainty Characterization in M&S Development	[M&S 19] A record of the processes and rationale for characterizing uncertainty in the referent data **shall** be maintained.		

4.2.7.2	Uncertainty Characterization in M&S Development	[M&S 21] A record of the qualitatively described or quantitative uncertainties incorporated into the M&S **shall** be maintained.		
4.3.1.1	M&S Use Requirements	[M&S 22] A record of the proposed use(s) of the M&S **shall** be maintained.		
4.3.1.2	M&S Use Requirements	[M&S 23] A record of the appropriateness of the M&S relative to its proposed use(s) **shall** be maintained.		
4.3.1.3	M&S Use Requirements	[M&S 24] A record of the Input(s) to the M&S, including their pedigrees (see Input Pedigree in Appendix E of this Standard) **shall** be maintained.		
4.3.1.4	M&S Use Requirements	[M&S 25] A record of the processes and rationales for setting up and utilizing the M&S **shall** be maintained.		

4.3.1.5	M&S Use Requirements	[M&S 26] Either of the following **shall** be performed: a. Ensure M&S uses are conducted in accordance with the permissible uses and within the domains of V&V for the M&S, or b Placard the M&S and analysis results with a warning that the M&S were not used in accordance with the permissible uses or were used outside the domains of V&V and include the type of limit exceeded, the extent that the limit was exceeded, and an assessment of the consequences of this action on the M&S results.		
4.3.1.6	M&S Use Requirements	[M&S 27] A record of observed warning messages, error messages, and explanations for the messages resulting from the use of the M&S **shall** be maintained.		
4.3.3.1	Uncertainty Characterization in M&S Use	[M&S 28] A record of any processes and rationale for characterizing uncertainty in the following **shall** be maintained: a. The input to an M&S. b. The results from an M&S. c. The quantities derived from M&S results.		
4.3.3.2	Uncertainty Characterization in M&S Use	[M&S 29] A record of any uncertainties (qualitatively described or quantitative) in the following **shall** be maintained: a. The input to an M&S. b. The results from an M&S, including any MUFs incorporated into the M&S as well as factors of safety (FS) that are intended to cover uncertainties in the model or simulation. c. The quantities derived from M&S results.		
4.3.5	M&S Sensitivity Analysis	[M&S 30] A record of the extent and results of any sensitivity analyses performed with the M&S **shall** be maintained.		
4.3.6.1	M&S Results Assessment	[M&S 31] A record of the assessed M&S results **shall** be maintained according to each of the following factors: a. M&S Use Assessment. b. M&S Input Pedigree. c. M&S Uncertainty Characterization. d. M&S Results Robustness. e. M&S Use/Analysis Technical Review. f. M&S Use Process/Product Management.		

4.3.6.2	M&S Results Assessment	[M&S 49] A record of assessed risks associated with the use of the M&S-based analysis **shall** be maintained.		
4.3.8.1	M&S Results Reporting	[M&S 32] When reporting M&S results to decision makers, explicit warnings **shall** be included for the following occurrences, accompanied by at least a qualitative estimate of the impact of the occurrence: a. Unachieved acceptance criteria (as specified in [M&S 43]). b. Violation of assumptions of the M&S used (as specified in [M&S 11]). c. Violation of the M&S limits (as specified in [M&S 13]). d. Execution warning and error messages (see [M&S 27]). e. Unfavorable outcomes from the assessed appropriateness of the M&S to the proposed use (described in [M&S 23]). f. Issues encountered during setup and utilization of the M&S (described in [M&S 25]). g. Waivers to the requirements in this Standard (or the requirements specific to the M&S). h. Outstanding M&S defects or problems (described in [M&S 51]).		
4.3.8.2	M&S Results Reporting	[M&S 33] When reporting M&S results to decision makers, an estimate of results uncertainty, as defined in [M&S 29 (1)-(3)], **shall** be included in one of the following ways: a. A quantitative estimate of the uncertainty in the M&S results, or b. A qualitative description of the uncertainty in the M&S results, or c. A clear statement that no quantitative estimate or qualitative description of uncertainty is available.		
4.3.8.3	M&S Results Reporting	[M&S 34] A description of the processes used to obtain the estimate of uncertainty as defined in [M&S 28 (1)-(3)] **shall** be included when reporting M&S results to decision makers.		
4.3.8.4	M&S Results Reporting	[M&S 50] The outcome of the M&S capability assessment performed per [M&S 48] **shall** be included in reporting M&S results to decision makers.		

4.3.8.5	M&S Results Reporting	[M&S 35] The outcome of the M&S results assessment performed per [M&S 31] **shall** be included in reporting M&S results to decision makers.		
4.3.8.6	M&S Results Reporting	[M&S 36] The findings from technical reviews accomplished in regard to the development, management (control), and use of the M&S **shall** be included in reporting M&S results to decision makers.		
4.3.8.7	M&S Results Reporting	[M&S 37] The qualifications of the developers of the M&S and the users, operators, or analysts involved in producing the results from the M&S, including, but not limited to, their relevant education, training, and experience, **shall** be included in the report of M&S results to decision makers.		
4.3.8.8	M&S Results Reporting	[M&S 38] The records of M&S development and use as shown in Appendix A **shall** be included in the report of M&S results to decision makers.		
4.3.8.9	M&S Results Reporting	[M&S 39] The assessment of, and rationale for, acceptance of the risks associated with the results from the M&S-based analysis as determined in [M&S 49] **shall** be included in reporting M&S results to decision makers.		

APPENDIX B: RECOMMENDATIONS ADOPTION MATRIX

B.1 PURPOSE

This Appendix provides a listing of recommendations contained in this 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 "Comments" column.)*

Table 2—Recommendations Adoption Matrix

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1.2a	General M&S Programmatic Recommendations	Should record the M&S waiver processes.		
4.1.2b	General M&S Programmatic Recommendations	Should record 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 configuration management (CM) and M&S support and maintenance.		
4.1.3a	M&S Best Practices Recommendations	Should identify and record the recommended practices that apply to M&S for the program/project.		
4.1.3b	M&S Best Practices Recommendations	Should, at a minimum, consider the recommended practices for the following areas: (1) Data and M&S input verification, validation, and pedigree. (2) An auditing method of tracking adherence to recommended practices. (3) V&V processes for the M&S. (4) Uncertainty characterization methods for the M&S. (5) Sensitivity analysis methods for the M&S.		

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
		(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 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 record 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. The requirements and recommendations for recording information specified in this 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. V&V. I. How to report simulation results to decision makers. 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.		

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.2.2a	General M&S Development Recommendations	Should record the methods of uncertainty characterization and the uncertainty in any data used to develop the M&S or incorporated into the M&S.		
4.2.2b	General M&S Development Recommendations	Should design and construct the M&S 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.		
4.2.2c	General M&S Development Recommendations	Should record updates of the M&S (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.		
4.2.2d	General M&S Development Recommendations	Should include test cases in the CM records that span the M&S limits defined by the program or project. “Test cases” are defined as benchmark input/output sets used to verify proper execution of the M&S.		
4.2.2e	General M&S Development Recommendations	Should provide a feedback mechanism for users to report unusual results to M&S developers or maintainers.		
4.2.2f	General M&S Development Recommendations	Should maintain (conceptual, mathematical, and computational) models, simulations, and associated records in a controlled CM system.		
4.2.2g	General M&S Development Recommendations	Should maintain the data sets and supporting software referenced in [M&S 45] and the associated records in a controlled CM system.		
4.2.2h	General M&S Development Recommendations	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 record verification techniques used. NASA-HDBK-7009 has further information regarding specific verification techniques.		

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.2.4b	M&S Verification Recommendations	Should record 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 record the verification status of conceptual, mathematical, and computational models.		
4.2.4d	M&S Verification Recommendations	Should record aspects of M&S not verified.		
4.2.6a	M&S Validation Recommendations	Should record the 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.		
4.2.6b	M&S Validation Recommendations	Should record validation metrics, referents, and data sets used for M&S validation.		
4.2.6c	M&S Validation Recommendations	Should record the studies conducted, and the status and results of, M&S validation.		
4.2.6d	M&S Validation Recommendations	Should record the aspects of the M&S not validated.		
4.2.8	Uncertainty Characterization in M&S Development Recommendation	Should record significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.		
4.3.2a	M&S Use Recommendations	Should record the relevant characteristics of the system that is the subject of the M&S-based analysis.		
4.3.2b	M&S Use Recommendations	Should record the computational M&S used (including revision numbers) in the simulation/analysis.		
4.3.2c	M&S Use Recommendations	Should record the parameter calibrations and the domain of calibration.		
4.3.2d	M&S Use Recommendations	Should record the data sets and supporting software used in input preparation.		

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.3.2e	M&S Use Recommendations	Should record the processes for conducting simulations and analyses for generating results reported to decision makers.		
4.3.2f	M&S Use Recommendations	Should record the versions of M&S results.		
4.3.2g	M&S Use Recommendations	Should record the use history of M&S, in the same or similar applications, which are relevant for assessing the capability of the current M&S application and the credibility of the results obtained from its use (see Appendix E.4.3.1 in this Standard).		
4.3.2h	M&S Use Recommendations	Should record and explain all failure modes, points of failure, and messages indicating such failures.		
4.3.4	M&S Uncertainty Characterization in M&S Use Recommendation	Should record significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.		
4.3.7	M&S Results Assessment Recommendations	Should justify and record the M&S results assessment for each of the factors referenced in [M&S 31].		
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 M&S 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.		

NASA-STD-7009B				
Section	**Description**	**Recommendation in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.3.9e	M&S Results Reporting Recommendations	Should include dissenting technical opinions regarding the credibility of the results or any recommended actions.		
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.		

APPENDIX C: REFERENCES

C.1 PURPOSE

This Appendix provides guidance in the reference documents that follow. Note: The latest releases of cited documents apply unless specific versions are designated.

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), Defense Modeling and Simulation Office (https://www.cto.mil/sea/vva_rpg/)

Federal

OMB Circular No. A-119	Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities, as revised January 27, 2016, accessible beginning on page 12 at https://www.nist.gov/document/revisedcircularara-119asof01-22-2016pdf

NASA

CAIB Report	Columbia Accident Investigation Board Report. (August 2003). Vols. 1-6
NPR 7123.1	NASA Systems Engineering Processes and Requirements
NPR 7150.2	NASA Software Engineering Requirements
NPR 8000.4	Agency Risk Management Procedural Requirements

NPR 8715.3	NASA General Safety Program Requirements
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-HDBK-7009	NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009
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) (Accessible from NASA Technical Reports Server)
NASA/SP-2009-569	Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis
NASA/SP-2011-3422	NASA Risk Management Handbook
NASA/SP-2011-6105	NASA System Engineering Handbook
NASA/SP-2016-6105-SUPPL	Expanded Guidance for NASA Systems Engineering, Volume 1: Systems Engineering Practices
NESC-PR-006	Technical Assessment Initial Evaluation

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 (1998)	Guide for Verification and Validation of Computational Fluid Dynamics Simulation

American Society of Mechanical Engineers (ASME)

ASME V&V 10	Standard for Verification and Validation in Computational Solid Mechanics (2006)
ASME V&V 20	Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

Institute of Electrical and Electronics Engineers (IEEE)

IEEE 610.12-1990	Standard Glossary of Software Engineering Terminology Superseded by IEEE 24765, Standard Glossary of Software Engineering Terminology

International Organization for Standardization (ISO)

ISO/IEC/IEEE 24764:2010	Information Technology: Generic cabling systems for data centres. Withdrawn ISO/IEC 11801-5, Information Technology – Generic Cabling for Customer Premises

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

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APPENDIX D: M&S CRITICALITY ASSESSMENT

D.1 PURPOSE

This Appendix provides guidance for a method to communicate the criticality of the situation(s) or decision(s) to which the M&S results are applied.

The rigor with which an M&S effort is to follow this 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 M&S criticality assessment matrix to communicate this determination. See Figure 1, M&S Criticality Assessment Matrix. Programs, projects, stakeholders, or customers of M&S may find the need to adjust this matrix. This includes adjustments to M&S consequence levels (Figure 2; e.g., consequence definitions, number of consequence) and M&S influence levels (Figure 3; e.g. supporting influence definitions, number of influence) to their particular situation.

M&S Results Influence	I: Negligible	II: Minor	III: Moderate	IV: Significant	V: Catastrophic
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)
	Decision Consequence				

Figure 1—M&S Criticality Assessment Matrix

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

a. Those M&S that are assessed to fall within the red (R) boxes in Figure 1 are clear candidates for completely adhering to the requirements of this Standard.

b. The M&S that are assessed to fall within the yellow (Y) boxes are at the discretion of program/project management in collaboration with the delegated NASA Technical Authority for adhering to the requirements of this Standard.

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

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 Standard as a guide for best 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 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 NASA/SP-2016-6105, NASA/SP-2011-3422, NASA Risk Management Handbook, and the NASA Engineering and Safety Center (NESC) procedure NESC-PR-006, Technical Assessment Initial Evaluation. The affected personnel, hardware, equipment, or facility is to 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 as determined by the affected program, project, or customer.

The first four rows of Table 3, Decision Consequences, indicate what specifically is impacted, and the subsequent rows indicate what aspect of the program or mission is impacted. For each row, quantitative breakpoints should be established between levels 1-5 in coordination with Program/Project Management and delegated NASA Technical Authority. For example, levels 1-5 for Cost might be assessed using the progression “Negligible” – No cost impact, “Minor” – <5% of Program Budget, “Moderate” – >5% of Program Budget, “Significant” – >10% of Program Budget, “Catastrophic” – >15% of Program Budget. Alternatively, the breakpoints could be expressed as cost in dollars. Similarly, the levels for Schedule could be based on percentage of total schedule or number of months.

Table 3—Decision Consequences

	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.	Irrecoverable total loss of function or destroyed.
Flight or Ground Equipment	Inconsequential.	Minor detriment (minor maintenance).	Minor detriment (maintenance required).	Major damage.	Irrecoverable total loss of function or destroyed.
Flight or Ground Facilities	Inconsequential.	Minor detriment (minor maintenance).	Minor detriment (maintenance required).	Major damage.	Irrecoverable total loss of function or destroyed.
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.

D.3 M&S INFLUENCE

M&S Influence estimates the degree to which M&S results impact the (program/project) decision under consideration (see Table 4, 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.) The M&S Influence levels in Table 4 are described as follows:

5: Controlling – the only decision support information is the M&S.

4: Significant – decision support information is primarily from the M&S but has support from another credible model or empirical similar system information.

3: Moderate – the decision support information is balanced between the M&S and some observational information from the real system, empirical information from a similar system, or information from a similar credible M&S.

2: Minor - The decision support information consists of observations in the real system, empirical information from a similar system, or information from a similar credible M&S, with limited support by the current M&S information.

1: Negligible - The decision support information is primarily from observations of the real system supported by information from a similar system or information from a similar credible M&S, with minimal support provided by the current M&S information.

Table 4—M&S Influence

M&S Influence	Real System in Real Environment		Similar System in Similar Environment		Other M&S
5: Controlling	No available information for the real system in the real environment.	&	No available information for a similar system in similar environment.	&	No other M&S or analysis data are available.
4: Significant	No available information 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 available information for the real system in the real environment.	&	No information is available for a similar system in similar environment.	&	Credible results from another M&S are available.
3: Moderate	Limited flight or test information for the real system in the real environment are available.	&	Ample flight or test information for similar systems in similar environments are available.		No other M&S or analysis data are available.
	--- Or ---				
	No information is available for the real system in the real environment.	&	Ample flight or test information for similar systems in similar environments is available.	&	Credible results from another M&S are available.
2: Minor	Some flight or test information for the real system in the real environment is available.	&	Immaterial if flight or test data for similar systems in similar environments are available.	&	No other M&S or analysis data are available.
	--- Or ---				
	Limited flight or test information for the real system in the real environment is available.	&	Some flight or test information for similar systems in similar environments is available.	&	Credible results from another M&S are available.
1: Negligible	Ample flight or test information for the real system in the real environment is available.	&	Immaterial flight or test data for similar systems in similar environments are available.	&	No other M&S or analysis information is available.
	--- Or ---				

M&S Influence	Real System in Real Environment		Similar System in Similar Environment		Other M&S
	Some flight or test information for the real system in the real environment is available.	&	Flight or test data for similar systems in similar environments are available.	&	Credible results from another M&S are available.

APPENDIX E: M&S CAPABILITY & M&S RESULTS ASSESSMENTS

E.1 PURPOSE

This Appendix provides guidance for methods to separately assess the M&S capability and the M&S results, both of which support the overall understanding of the credibility of the M&S-based results.

E.2 INTRODUCTION

This Appendix is a departure from the previous end-point assessment of the results from M&S use. In previous versions of NASA-STD-7009, the assessment of M&S results included factors from M&S development and M&S use. In this version, the factors of M&S development and the factors of M&S use are assessed separately. The M&S capability assessment addresses only the outcomes of M&S development and occurs no later than the end of that life-cycle phase, which is marked by the release of the M&S. The M&S results assessment addresses the outcomes of M&S use and occurs at or toward the end of that phase when the results are obtained. Both assessments are needed when reporting M&S results to decision makers, per requirements [M&S 50] and [M&S 35].

Performing two assessments rather than one acknowledges that some M&S efforts seek only to develop an M&S for release, while some M&S efforts seek only to use an M&S following its development. The capability assessment is a product of the development phase, and the results assessment is a product of the use phase. Of course, other M&S efforts proceed directly from development to use; the capability assessment is still to be performed at or prior to the release of the M&S, as establishing the M&S capability is a prerequisite for the use assessment [M&S 23] performed at the beginning of the use phase.

Neither the M&S capability nor the M&S results credibility can be assessed directly. However, it is possible to identify and assess key factors that contribute to what is meant by the M&S capability, as well as by the credibility of the M&S results. All the practices or attributes contained in the requirements and recommendations of this Standard lend themselves to either improved M&S capability, improved M&S results credibility, or both. Ultimately, what is considered the minimum set of factors for each of these assessments was selected from a group of many possible ones. The factors defined in the following sections have the following in common: (a) they were individually judged to be among the most important factors; (b) they are nearly orthogonal, i.e., largely independent; and (c) they can be assessed objectively. 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. While it is possible to assess either M&S capability or M&S results using other factors not included in this Appendix, the factors described herein are considered the minimum set with any alteration in these factor level definitions likely to incur additional M&S risk.

Factor level labels are used as a descriptive tool for indexing the relative rank of factor level definitions and as an efficient means of communicating the thresholds and assessments of each factor. Reporting factor level assessment is recommended using a 5-tier labeling system representing levels ranging from "no supporting information" to "gold-standard" evidence and rigor. An ordinal indexing system of assessment labels (e.g., 0-4) is utilized for illustration in the assessment of M&S capability and M&S results. The labeling system can be adjusted to meet the program's, project's, stakeholder's, or customer's needs in communicating the relative rank of each factor level definition. Given that the factors are largely independent, comparison between or combining of factor assessments and thresholds is not intended and should be avoided in all labeling approaches.

A special note regarding M&S implemented using a general-purpose software package is that some 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 use. In this case, when evaluating the evidence provided for each of the factors addressed by the M&S capability assessment and the M&S results assessment, both the tool and the computational model constructed using the tool are to be considered wherever applicable.

Section E.3 addresses the M&S capability assessment, starting with an overview of the factors chosen and the key aspects of the level definitions for each. The overview is followed by explanations of each factor along with the complete level definitions. Section E.4 addresses the M&S results assessment and follows the same organization as the previous section. Finally, section E.5 provides examples of ways by which the results of the two assessments may be presented to satisfy the reporting requirements specified in section 4.3.8 of this Standard.

E.3 M&S CAPABILITY ASSESSMENT

E.3.1 M&S Capability Assessment Overview

For the M&S capability assessment, a set of five factors are identified, all of which are associated with processes that take place during the development phase of the M&S life cycle. The five factors are: M&S Data Pedigree, M&S Verification, M&S Validation, M&S Development Technical Review, and M&S Development Process/Product Management, as depicted in Table 5, M&S Capability Assessment Structure.

Table 5—M&S Capability Assessment Structure

M&S Data Pedigree	M&S Verification	M&S Validation	M&S Development Tech Review	M&S Dev. Process/Product Management

Briefly, the assessment of each of these factors is asking the following questions pertaining to aspects of M&S Development:

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

(2) M&S Verification: Were the M&S implemented correctly, per their requirements/specifications?

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

(4) M&S Development Technical Review: Were any technical reviews of the M&S or M&S development accomplished? What were the scopes of the reviews? How formal were the reviews? How recently did the reviews occur, relative to the development activities? Who conducted the reviews, and how independent were the reviewers from the M&S program/project?

(5) M&S Development Process/Product Management: How well managed were the M&S development processes and products?

A synopsis of the capability assessment factors and level definitions is provided in Table 6, Key Aspects of M&S Capability Assessment Levels. Following the table, explanations and the complete level definitions for the factors associated with the M&S capability assessment are provided.

In many of the level definitions, multiple conditions are stated. For those levels, all of the conditions are to be met to achieve that level unless explicitly stated as 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.

Table 6—Key Aspects of M&S Capability Assessment Levels

Level	M&S Data Pedigree	M&S Verification	M&S Validation	M&S Development Technical Review	M&S Development Process/Product Management
4	All data known and traceable to RWS with acceptable accuracy, precision, and uncertainty.	Reliable practices applied to verify the end-to-end M&S; all M&S errors satisfy requirements.	All M&S outputs compare favorably with data from the RWS over the full range of operation in its real operating environment.	Favorable independent peer review accompanied by *independent factor evaluation*. Scope addresses all other capability-related factors.	Controlled processes are applied; measurements used for process improvement.
3	All data known and traced to sufficient referent. Significant data have acceptable accuracy, precision, and uncertainty.	Rigorous practices applied to verify the end-to-end M&S; all important errors satisfy requirements.	All key M&S outputs compare favorably with data from the RWS operating in a representative environment.	Favorable independent peer review. Scope addresses all other capability-related factors.	Controlled processes are applied; process compliance is measured.
2	Some data known and formally traceable with estimated uncertainties.	Documented practices applied to verify all M&S features; most important errors satisfy requirements.	Key M&S outputs compare favorably with data from a sufficiently similar referent system.	Favorable formal internal peer review. Scope addresses Data Pedigree, Verification, and Validation factors, *at a minimum*.	Formal processes are applied.
1	Some data known and informally traceable.	Informal practices applied to verify some features of the M&S and assess errors.	Conceptual model addresses problem statement and compares favorably with available referents.	Favorable informal internal peer review. Scope addresses Data Pedigree, Verification, and Validation factors, *at a minimum*.	Informal processes are applied.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

E.3.2 M&S Data Pedigree Factor

The concept of pedigree 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 their source through all aspects of their transmission, storage, and processing to their 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 a Level of "1" requires at least informal traceability, while traceability becomes formal at a Level of "2" along with the processes for establishing significant data and an estimate of its uncertainty. Attaining a Level of "3" requires all data to be known and traceable but with only significant or key data to have acceptable accuracy, precision, and uncertainty. Attaining a Level of "4" then requires all data to have acceptable accuracy, precision, and uncertainty. (See Table 7, Level Definitions for the M&S Data Pedigree Factor.

Table 7—Level Definitions for the M&S Data Pedigree Factor

Level	M&S Data Pedigree Evidence
4	All data are known and fully traceable to the RWS. All data are acceptable in terms of accuracy, precision, and uncertainty.
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.
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.
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.
0	Insufficient evidence.

E.3.3 M&S Verification Factor

Verification includes all activities that are performed 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. Regression testing is the process of testing changes to computational models to make sure the older aspects still work with the new changes. It is important to also consider changes to the development environment, which includes the compilers, libraries, operating system, and computer hardware. When the computation model is deployed onto other platforms, e.g., cross-compiling for an embedded real-time simulator, changes to the operational environment also need attention. Unit testing is a procedure used to validate that individual units of computational models are working properly. Ultimately, code verification is best 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 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. Solution Verification is also used to detect human errors, e.g., typographical errors or other incorrect/inadvertent interactions with the software, as well as determine the numerical accuracy of the solution. One common method is the echoing of all input data, including selections made by a mouse or other input devices, to a log file for comparison with the intended inputs.

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. (See Table 8, Level Definitions for the M&S Verification Factor.)

Table 8—Level Definitions for the M&S Verification Factor

Level	M&S Verification Evidence
4	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.
3	The model is correctly implemented as determined by rigorous verification practices, which evaluate all components, features, capabilities, and couplings of the end-to-end model. Rigorous methods are used to assess model errors. All important model errors satisfy program/project-specified requirements.
2	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.
1	Verification is informal, with some documentation or evidence of completeness/success.
0	Insufficient evidence.

E.3.4 M&S Validation Factor

Validation starts with conceptual validation, i.e., providing the requisite assurance that the conceptual and mathematical models are valid. Refer to NASA-HDBK-7009 for more details regarding conceptual model validation. 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 43] b 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 any level above "1" is not permitted unless the conditions for "1" are satisfied, i.e., the model has to be conceptually validated before it is empirically validated. (See Table 9, Level Definitions for the M&S Validation Factor.)

Table 9—Level Definitions for the M&S Validation Factor

Level	M&S Validation Evidence
4	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	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	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	The model is conceptually validated. The problem statement (intended use) is clearly stated and well-understood; and the conceptual model, requirements, and specifications are correct and sufficiently address the problem.
0	Insufficient evidence.

E.3.5 M&S Development Technical Review Factor

While this Standard does not require technical reviews in support of, or in association with, the M&S development, the results of any technical reviews accomplished during the entire life cycle of the M&S are to be recorded per [M&S 9]; and the findings of these reviews are to be reported to decision makers per [M&S 36].

When assessing M&S capability, the evaluation of any technical reviews relevant to the development phase of the M&S life cycle should examine the evidence recorded at or following those reviews. Specifically, the examination of this evidence should address the following:

- Scope/Depth of the Review: What was reviewed? At what level of detail?

- Formality/Independence/Expertise: How formal was the review? Who performed the reviews? What were their associations with the M&S project? What were their qualifications relative to the M&S?

- Timeliness/Currency of Review: How recent were the reviews, relative to the M&S development activities, being assessed?

The assessment of the technical review factor may require considerable judgement. Reviews are generally constituted throughout the life of a program or project, and any one review could potentially address material relevant to one or more of the other factors included in the capability assessment. Similarly, the depth to which a given factor is reviewed may vary from factor to

factor. Also, it would not be uncommon for different subject matter experts to be involved in the various reviews, depending upon their availability at a particular time and their particular areas of expertise. Likewise, the same people may serve as reviewers in different capacities throughout the life of a program or project, again depending on their availability and expertise.

By a "peer review," we mean an assessment that is conducted by one or more persons of equal technical standing to person(s) responsible for the work being reviewed. An "informal peer review" is one that is not conducted pursuant to a process established by the reviewed or reviewing organization, whereas a "formal peer review" is one that is sanctioned by the program/project and conducted in accordance with rules explicitly established by the reviewed or reviewing organization. Peer reviews are classified based on their level of independence from the organization responsible for development or use of the M&S. The required level of independence may be prescribed in a governing document or delegated to the NASA Technical Authority. While internal peer reviews can be of great value, independent peer reviews are more likely to provide unbiased evaluations.

The definition for a Level of "4" includes the italicized term *"Independent Factor Evaluation."* Using M&S validation as an example, this means that validation evidence is independently reviewed and assessed according to the factor levels in Table 10, Level Definitions for the M&S Development Technical Review Factor, and that validation outcomes are independently reproduced by the reviewers or their agents.

Table 10—Level Definitions for the M&S Development Technical Review Factor

Level	M&S Development Technical Review Evidence
4	Favorable independent peer review and *independent factor evaluation*. Scope addresses all other capability-related factors.
3	Favorable independent peer review. Scope addresses all other capability-related factors.
2	Favorable formal internal peer review. Scope addresses Data Pedigree, Verification, and Validation factors, *at a minimum*.
1	Favorable informal internal peer review. Scope addresses Data Pedigree, Verification, and Validation factors, *at a minimum*.
0	Insufficient Evidence.

E.3.6 M&S Development 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, throughout its development phase, are managed and maintained as directed by the NASA report NTRS-PB2005-100968, A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report. Assessments at a Level of "1" and higher require evidence addressing each of these topics.

For the M&S Development Process/Product Management factor, an assessment at a Level of either "3" or "4" requires the conditions for a Level of "2" be satisfied. (See Table 11, Level Definitions for the M&S Development Process/Product Management Factor.)

Table 11—Level Definitions for the M&S Development Process/Product Management Factor

Level	M&S Development Process/Product Management Evidence
4	Measurements, including customer/user feedback, are used to improve both the M&S process and products.
3	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	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	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.

E.4 M&S RESULTS ASSESSMENT

E.4.1 M&S Results Assessment Overview

For the M&S results assessment, a set of six factors are identified, all of which are associated with processes that take place during the use phase of the M&S life cycle. The six factors are: M&S Use Assessment, M&S Input Pedigree, M&S Uncertainty Characterization, M&S Results Robustness, M&S Use/Analysis Technical Review, and M&S Use Process/Product Management, as depicted in Table 12, M&S Results Assessment Structure.

Table 12—M&S Results Assessment Structure

M&S Use Assessment	M&S Input Pedigree	M&S Uncertainty Characterization	M&S Results Robustness	M&S Use Tech Review	M&S Use Process/Product Management

(1) M&S Use Assessment: How well does the proposed M&S use match the permissible use(s) of the M&S? How similar is the proposed use of the M&S to previous successful uses?

(2) M&S Input Pedigree: Is the pedigree (and quality) of the data used to setup and run the model adequate or acceptable?

(3) M&S 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?

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

(5) M&S Use/Analysis Results Technical Review: Were any technical reviews of the M&S use or M&S results accomplished? What were the scopes of the reviews? How formal were the reviews? How recently did the reviews occur relative to the use and analysis activities? Who conducted the reviews, and how independent were the reviewers from the M&S program/project?

(6) M&S Use Process/Product Management: How well managed were the M&S Use processes and products?

A synopsis of the credibility factors and level definitions is provided in Table 13, Key Aspects of M&S Results Assessment Levels. Following the Table, explanations and the complete level definitions for the factors associated with the M&S results assessment are provided. 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.

Table 13—Key Aspects of M&S Results Assessment Levels

Level	M&S Use Assessment	M&S Input Pedigree	M&S Uncertainty Characterization	M&S Results Robustness	M&S Use/Analysis Technical Review	M&S Use Process/Product Management
4	The proposed use is within the domain of M&S validation and nearly identical to previous uses.	All input data known and traceable to RWS with acceptable accuracy, precision, and uncertainty.	Statistical analysis of the output uncertainty after propagation of all known sources of uncertainty.	Sensitivities known for most parameters; most key sensitivities identified.	Favorable independent peer review accompanied by independent factor evaluation. Scope addresses all other capability-related factors.	Controlled processes are applied; measurements used for process improvement.
3	The proposed use is within the domain of M&S verification with at most minor differences to prior M&S use.	All input data known and traced to sufficient referent. Significant input data have acceptable accuracy, precision, and uncertainty.	Uncertainty of results are provided quantitatively through propagation of all known uncertainty.	Sensitivities known for many parameters, including many of the key sensitivities.	Favorable independent peer review. Scope addresses all other results-related factors.	Controlled processes are applied; process compliance is measured.
2	The proposed use is within the M&S limits with at most moderate differences to prior M&S use.	Some input data known and 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.	Favorable formal internal peer review. Scope addresses Input Pedigree, Uncertainty Characterization, and Results Robustness factors, *at a minimum.*	Formal processes are applied.
1	M&S type, application domain, and purpose match the proposed use. The M&S' inclusions, exclusions, abstractions, and assumptions are acceptable for the proposed use. The M&S is able to produce the desired outputs. Major differences to prior M&S use or M&S not used before.	Some input data known and informally traceable.	Sources of uncertainty identified and qualitatively assessed.	Qualitative estimates only for sensitivities in M&S.	Favorable informal internal peer review. Scope addresses Input Pedigree, Uncertainty Characterization, and Results Robustness factors, *at a minimum.*	Informal processes are applied.
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.

E.4.2 M&S Use Assessment Factor

This Standard defines the use assessment as the process of determining if an M&S is accepted for a proposed use. Before or during the preparation for M&S use, the specific use is to be proposed, documented [M&S 22], and assessed [M&S 23] with respect to the permissible uses accepted and documented at the conclusion of M&S development [M&S 14] to determine if the M&S are appropriate and either within or outside the known acceptable uses of the M&S.

The permissible uses are to be defined during the M&S development phase and baselined during M&S release. For M&S developed for broad or general use, even within a specific type of application, the permissible uses are key to correct or appropriate use. Even for M&S developed only for a specific real-world system, the permissible uses provide a clear guideline as to what or how the M&S are appropriately applied. In either case, the elements of a proposed use are to address similar criteria as the permissible uses. Table 14, Considerations for the M&S Use Assessment, depicts these similar elements for comparison in the use assessment. Table 15, Level Definitions for the M&S Use Assessment Factor, provides definitions for M&S use assessment factor.

Table 14—Considerations for the M&S Use Assessment

Permissible Use(s) of Model	✓	**Proposed Use(s) of Model**
Type of Use Intended. • Implies the type of model. • The application domain (discipline, area of study) of the Model. • The Purpose of the Model.		Type of Use Needed. • Implied by the type of RWS. • The application area (discipline, area of study) of the subject RWS. • The purpose of proposed model use with respect to the RWS.
Model's Abstractions and Assumptions. • Inclusions in the M&S. • Exclusions from the M&S. • Assumptions of M&S form, fit, or function.		Inclusions & Fidelity Needed. • Specific expectations of what is in, or expected of, the M&S. • The desired level of accuracy, precision, and uncertainty of the M&S.
Limits of Model Parameters, per • Model design (including any computer hardware or software limitations). • Verification. • Validation.		Desired Domain of Use. • With respect to the RWS. • Parameter values the model is expected to represent.
Types of Outputs (Results) Produced, including: • Accuracy. • Precision. • Uncertainty.		Type of Results Needed, including: • Accuracy. • Precision. • Uncertainty of Results.

Table 15—Level Definitions for the M&S Use Assessment Factor

Level	M&S Use Assessment Evidence
4	The proposed use is within the domain of M&S validation. The proposed use is nearly identical to previous M&S uses.
3	The proposed use is within the domain of M&S verification. The proposed use differs in minor ways from prior M&S uses.
2	The proposed use is within the M&S limits. The proposed use differs in moderate ways from prior M&S uses.
1	M&S type, application domain, and purpose match the proposed use. The M&S' inclusions, exclusions, abstractions, and assumptions are acceptable for the proposed use. The M&S is able to produce the desired outputs. The proposed use departs substantially from prior uses of the M&S, or this is the first use of the M&S.
0	Insufficient evidence.

A clear and comprehensive understanding of previous M&S uses can provide important context to the evaluation of M&S-based results. Prior uses provide a base of knowledge and experience that informs best practices on configuring the M&S and defining scenarios to obtain good results for similar uses. Prior use of M&S also provides a history of the utility of the M&S for decision making and can establish how results are best applied to similar decisions under similar uses. The more a new application deviates from previous ones, the less decision makers can rely on previous successful M&S use to support the current results assessment.

E.4.3 M&S Input Pedigree Factor

The concept of pedigree is loosely defined as a traceable record of lineage or heritage. Input pedigree involves the evaluation of all data used as (run-time) 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 a level of “1” requires at least informal traceability, while traceability becomes formal at a level of “2” along with the processes for establishing significant inputs and an estimate of its uncertainty. Attaining a level of “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. Attaining a level of “4” then requires all input data to have acceptable

accuracy, precision, and uncertainty. Table 16, Level Definitions for the M&S Input Pedigree Factor, provides definitions for the input pedigree factor.

Table 16—Level Definitions for the M&S Input Pedigree Factor

Level	M&S Input Pedigree Evidence
4	All input data known and fully traceable to the RWS. All data are acceptable in terms of accuracy, precision, and uncertainty.
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.
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.
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.
0	Insufficient evidence.

E.4.4 M&S 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 of quality. Also, the results of (c) are directly impacted by both (a) and (b).

At a level of "1," some sources of uncertainty are identified in the M&S with qualitative estimates of their uncertainty; their impact on the output uncertainty and uncertainty propagation are not addressed. At a level of "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 a level of "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) and comprehensive (e.g., Monte Carlo sampling) approach. At a level of "4," a statistical analysis (e.g., ANOVA[1]) 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.

[1] ANOVA is a type of statistical test used to determine if there is a statistically significant difference between two or more categorical groups by testing for differences of means using variance. (https://www.simplypsychology.org/anova.html)

Table 17, Level Definitions for the M&S Uncertainty Characterization Factor, provides definitions for the uncertainty characterization factor.

Table 17—Level Definitions for the M&S Uncertainty Characterization Factor

Level	M&S Uncertainty Characterization Level Evidence
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.
3	Quantitative estimates of uncertainties are reported for most output quantities after a propagation of all known sources of uncertainty.
2	Most sources of uncertainty are identified, expressed quantitatively, and correctly classified based on SME opinions and/or by deduction from experimental data. Propagation of the uncertainty to output quantities are addressed by reduced order (e.g., monotonic or boundary analysis) and/or reduced dimension propagation.
1	Sources of input uncertainty are identified with qualitative estimates of the uncertainty. Their impact on output uncertainties and uncertainty propagation are not addressed.
0	Insufficient evidence.

E.4.5 M&S Results Robustness 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 similar sensitivities). That is, if the RWS is sensitive to certain variables or parameters, the M&S results are expected to be similarly sensitive. The purpose of considering robustness is to understand 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” for levels of “2,” “3,” and “4” cannot be generally specified for all situations. As a guideline, “few” implies that the sensitivity of less than 20 percent of the potential variables and parameters is known; “many” implies that the sensitivity of between 20 and 50 percent is known, and “most” implies the majority (i.e., >50 percent) of all parameters and variables is known, including all of the most sensitive variables and parameters. Table 18, Level Definitions for the M&S Results Robustness Factor, provides definitions for the M&S results robustness factor.

Table 18—Level Definitions for the M&S Results Robustness Factor

Level	M&S Results Robustness Evidence
4	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	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	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	Sensitivity of M&S results for the RWS is estimated by analogy with the quantified sensitivity of similar problems of interest.
0	Insufficient evidence.

E.4.6 M&S Use/Analysis Technical Review Factor

This Standard does not require technical reviews in support of, or in association with, the M&S development. The results of any technical reviews accomplished during the entire life cycle of the M&S are to be recorded per [M&S 9], and the findings of these reviews are to be reported to decision makers per [M&S 36].

When assessing M&S results, the evaluation of any technical reviews relevant to the use/analysis phase of the M&S life cycle should examine the evidence recorded at or following those reviews. Specifically, the examination of this evidence should address the following:

- Scope/Depth of the Review: What was reviewed? At what level of detail?

- Formality/Independence/Expertise: How formal was the review? Who performed the reviews? What were their associations with the M&S project? What were their qualifications relative to the M&S?

- Timeliness/Currency of Review: How recent were the reviews, relative to the M&S development activities being assessed?

The assessment of the technical review factor may require considerable judgement. Reviews are generally constituted throughout the life of a program or project, and any one review could potentially address material relevant to one or more of the other factors included in the capability assessment. Similarly, the depth to which a given factor is reviewed may vary from factor to factor. Also, it would not be uncommon for different subject matter experts to be involved in the various reviews, depending upon their availability at a particular time and their particular areas of expertise. Likewise, the same people may serve as reviewers in different capacities throughout the life of a program or project, again depending on their availability and expertise.

A “peer review” is an assessment that is conducted by one or more persons of equal technical standing to person(s) responsible for the work being reviewed. An “informal peer review” is one that is not conducted pursuant to a process established by the reviewed or reviewing organization, whereas a “formal peer review” is one that is sanctioned by the program/project and conducted in accordance with rules explicitly established by the reviewed or reviewing organization. Peer reviews are classified based on their level of independence from the organization responsible for development or use of the M&S. The required level of independence may be prescribed in a governing document or delegated to the NASA Technical Authority. While internal peer reviews can be of great value, independent peer reviews are more likely to provide unbiased evaluations.

The definition for a Level of “4” includes the italicized term *“Independent Factor Evaluation.”* Using M&S Uncertainty Characterization as an example, this is taken to mean that uncertainty characterization evidence is independently reviewed and assessed according to the factor levels in Table 19, Level Definitions for the M&S Use/Analysis Technical Review Factor, and that uncertainty characterization outcomes are independently reproduced by the reviewers or their agents.

Table 19—Level Definitions for the M&S Use/Analysis Technical Review Factor

Level	M&S Use/Analysis Technical Review Evidence
4	Favorable independent peer review and independent factor evaluation. Scope addresses all other capability-related factors.
3	Favorable independent peer review. Scope addresses all other results-related factors.
2	Favorable formal internal peer review. Scope addresses Input Pedigree, Uncertainty Characterization, and Results Robustness factors, at a minimum.
1	Favorable informal internal peer review. Scope addresses Input Pedigree, Uncertainty Characterization, and Results Robustness factors, at a minimum.
0	Insufficient Evidence.

E.4.7 M&S Use 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, throughout its use phase, are managed and maintained as directed by NASA report NTRS-PB2005-100968. Assessments at a level of “1” and higher require evidence addressing each of these topics.

For the M&S use process/product management factor, an assessment at a level of either “3” or “4” requires the conditions for a level of “2” be satisfied. (See Table 20, Level Definitions for the M&S Use Product/Process Management Factor.)

Table 20—Level Definitions for the M&S Use Product/Process Management Factor

Level	M&S Use Product/Process Management Evidence
4	Measurements, including customer/user feedback, are used to improve both the M&S process and products.
3	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	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	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.

E.5 REPORTING THE OUTCOMES OF THE M&S CAPABILITY AND M&S RESULTS ASSESSMENTS

Requirements [M&S 48], [M&S 31], [M&S 50] and [M&S 35], as well as recommendation 4.3.7(a), specify information relevant to reporting the outcomes of the capability and results assessments. The concept behind the requirements and the recommendation is that program/project management, technical authorities, stakeholders, or customers are encouraged to set goals, or thresholds, for these aspects of the M&S effort to achieve. 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.

This Standard does not prescribe any specific methods for reporting the achieved factor levels and the factor thresholds associated with each of the two assessments. Examples of the many possible ways this could be done are presented in this Appendix, using two familiar graphing methods: bar charts and “spider” (or “radar”) plots. These are shown in the following figures, the first two (Figure 2, Bar Graph of M&S Capability Assessment, and Figure 3, Spider Plot or Radar Plot of M&S Capability Assessment) for the results of a hypothetical M&S capabilty assessment, and the next two (Figure 4, Bar Graph of M&S Results Assessment, and Figure 5, Spider Plot or Radar Plot of M&S Results Assessment) for the results of the corresponding M&S results assessment. Note that, as illustrated by these notional examples, the possibility exists of either not achieving or of exceeding the specified threshold. As these methods readily show both the attained factor assessment levels and thresholds, they provide a simple basis for discussion of the background of each as well as the impact of any deficiencies (gaps).

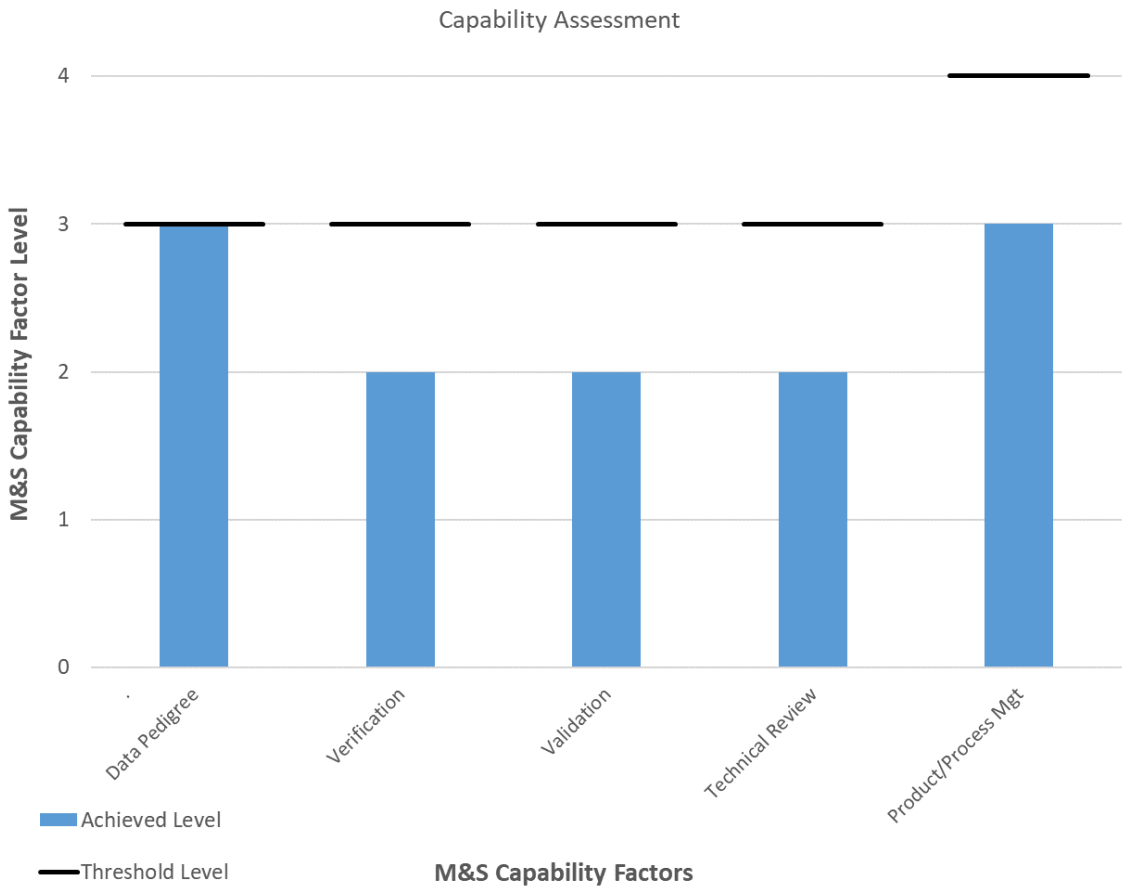

Figure 2—Bar Graph of M&S Capability Assessment

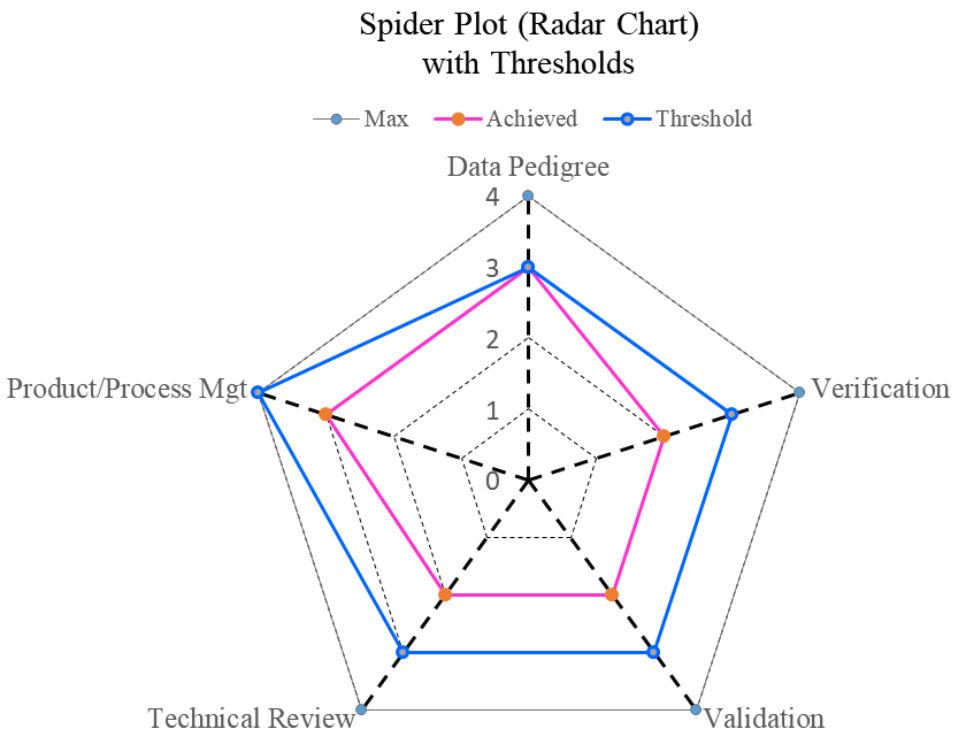

Figure 3—Spider Plot or Radar Plot of M&S Capability Assessment

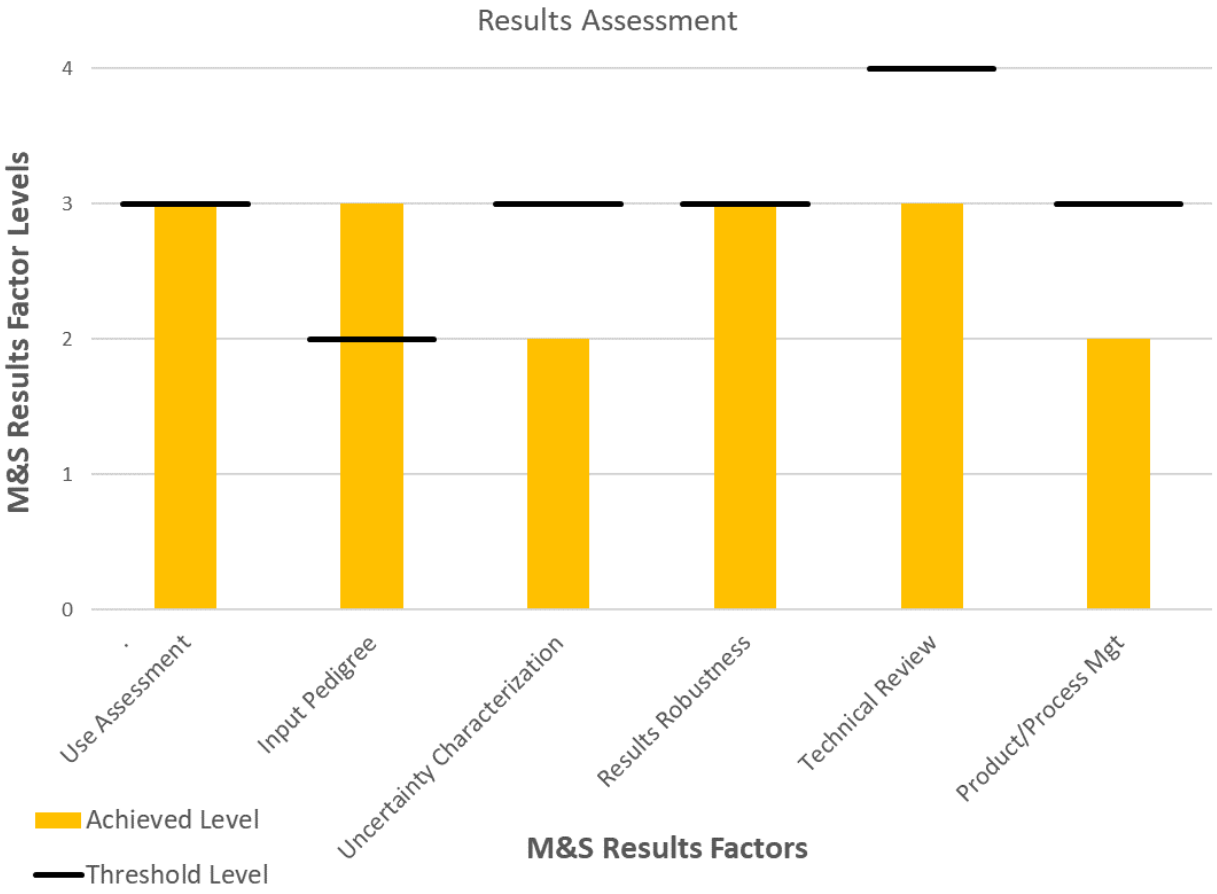

Figure 4—Bar Graph of M&S Results Assessment

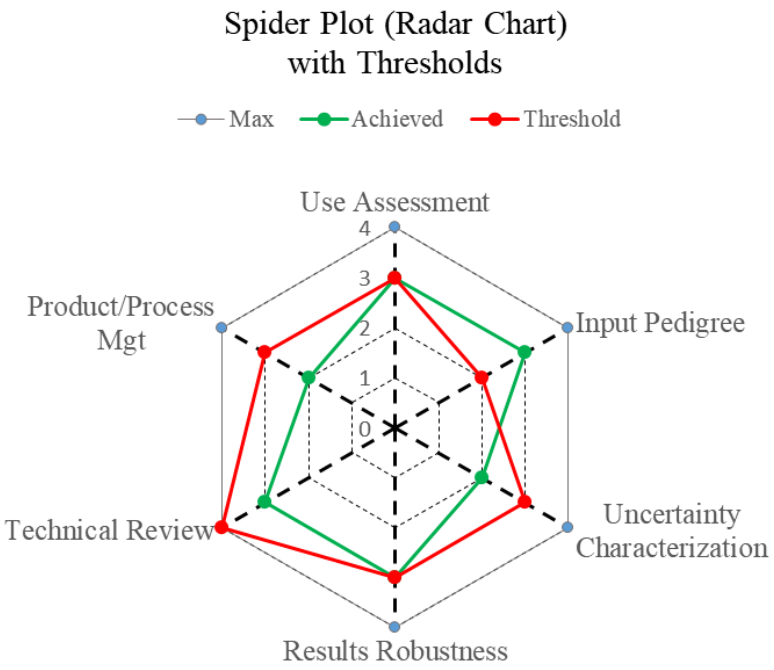

Figure 5—Spider Plot or Radar Plot of M&S Results Assessment

APPENDIX F: M&S LIFE CYCLE

F.1 PURPOSE

This Appendix provides 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 6, M&S Life Cycle.

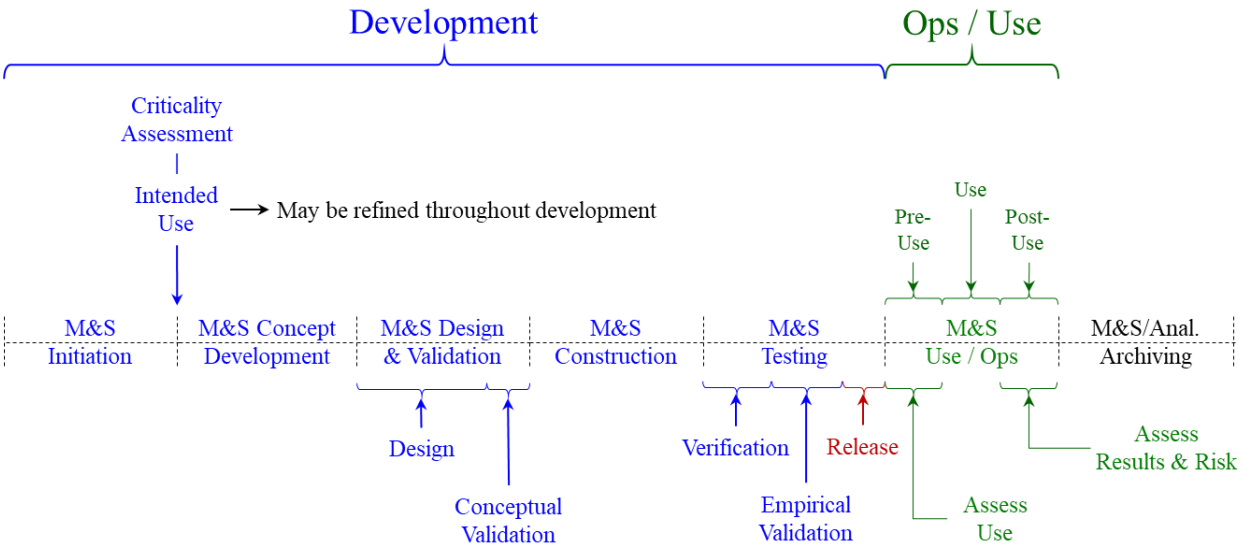

Figure 6—M&S Life Cycle

The need for a model or simulation starts the M&S 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 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. It can be expected that the intended use becomes more refined throughout M&S development, leading to iterations in the M&S development phase to match the evolution in the intended use.

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 behaviors 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 7, M&S Process Relationships (adapted from Sargent, 1979). Additional details about the M&S process are in NASA-HDBK-7009.

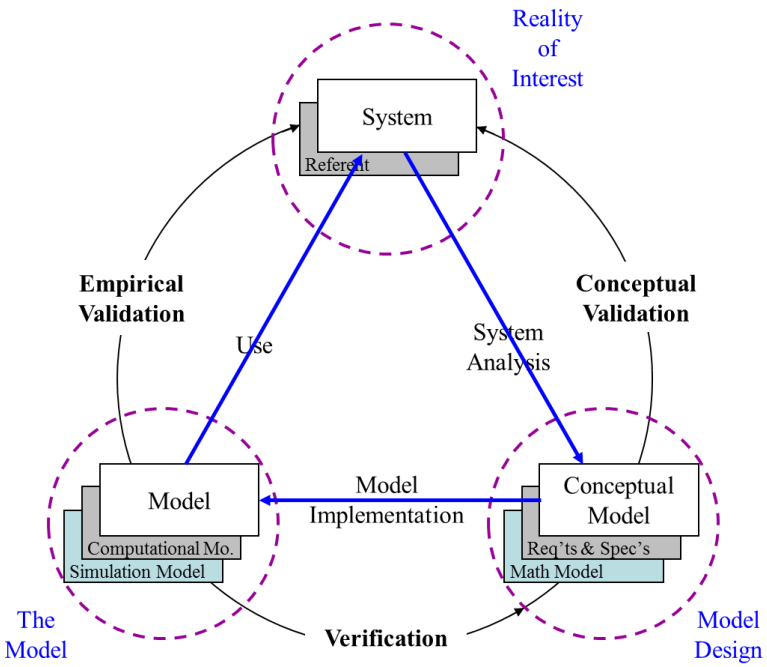

Figure 7—M&S Process Relationships

During M&S testing, verification shows the working M&S adequately represents, and/or behaves like, what is identified in the conceptual model or M&S design. On the other hand, the intent of empirical validation is to show the working M&S adequately represents, or behaves like, the RWS or an alternate referent by a more direct comparison. This testing identifies the M&S' limits of operation, i.e., where the M&S is known to work correctly (i.e., verified and validated). At the end of M&S testing, the M&S' capabilities, assumptions, and limits of operation are recorded and assessed with respect to acceptance criteria [M&S 43] to determine the permissible uses of the M&S. Once M&S testing is successfully completed, the M&S is released, along with guidance of the M&S' capabilities and domain of permissible use, ending M&S development.

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

If the proposed M&S 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 M&S restarts the M&S 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 M&S is assessed using the M&S results assessment requirements of this Standard. The results and other qualifying information 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 M&S used are recorded and archived.

Note: Many other life cycles for M&S projects exist or are possible. The classic waterfall life cycle is idealized as a linear flow, though reverse-flow loops to previous phases are possible (even expected) if problems in M&S development or use occur. Other M&S project life cycles are also acceptable if approved by the delegated NASA Technical Authority. Common alternative life cycles include iterative, spiral, or agile. Whether or not the planned M&S life cycle occurs linearly as a whole or in recurrent increments (e.g., spirals, sprints), they each encompass the basic phases of planning, design, build, and testing.