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NASA HANDBOOK FOR MODELS AND SIMULATIONS: AN IMPLEMENTATION GUIDE FOR NASA-STD-7009B

DOCUMENT HISTORY LOG

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Baseline			2013-10-18	Initial Release
Revision	A		2019-05-08	Significant changes were made to this NASA Technical Handbook. It is recommended that it be reviewed in its entirety before implementation. Key changes were: • Alignment with NASA-STD-7009A. • M&S Life Cycle Focused. • M&S Life Cycle Worksheet Revised. • Addresses M&S Risk.
Revision	B		2025-09-24	Significant changes were made to this NASA Technical Handbook. It is recommended that it be reviewed in its entirety before implementation. Key changes were: Key Changes are: • Alignment with NASA-STD-7009B • Updates on the delegated NASA Technical Authority approach to tailoring • Updates to the Life Cycle analogy • Updates to Credibility and other Assessment Processes • Guidance on application of NASA-STD-7009B to Artificial Intelligence Models • Added appendix on use statements. • M&S Life Cycle Worksheet revision • Replaced Table 21

FOREWORD

This NASA Technical Handbook is published by the National Aeronautics and Space Administration (NASA) as a guidance document to provide engineering information; lessons learned; possible options to address technical issues; classification of similar items, materials, or processes; interpretative direction and techniques; and any other type of guidance information that may help the Government or its contractors in the design, construction, selection, management, support, or operation of systems, products, processes, or services.

This Handbook establishes general guidance to assist in complying with the requirements and recommendations of NASA-STD-7009B, Standard for Models and Simulations, including technical information, application instructions, data, recommended practices, procedures, and methods used in support of NASA-STD-7009B. NASA technical standards, by definition and intent, are constrained in their content to include requirements as to what is to be accomplished within the scope of their use. This Handbook includes suggestions as to methods by which to satisfy those requirements. As modeling and simulation span a wide range of technical disciplines, not all methods are similarly applied across all types of models and simulations (M&S).

For additional information on this standard, submit a request via “Email Feedback” at https://standards.nasa.gov.

Original Signed by:
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NASA Technical Standards Program Executive
On Behalf of: *02/03/2026*

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NASA HANDBOOK FOR MODELS AND SIMULATIONS: AN IMPLEMENTATION GUIDE FOR NASA-STD-7009B

1. SCOPE

1.1 Purpose

This NASA Technical Handbook provides technical information, clarification, examples, processes, and techniques to help institute good modeling and simulation (M&S) practices at NASA. As a companion guide to NASA-STD-7009B, Standard for Models and Simulations, this Handbook provides a broader scope of information than is included in a NASA technical standard and promotes good practices in the production, use, and consumption of NASA M&S products. NASA-STD-7009B specifies what a M&S activity shall or should do (in the requirements and recommendations). The standard does not prescribe how they are accomplished. This varies with the specific engineering discipline responsible for accomplishing the M&S activity and the size and type of project. A guidance document, which is not constrained by the requirements of a NASA technical standard, is better suited to address these additional aspects and provide necessary clarification.

This Handbook stems from the Space Shuttle Columbia Accident Investigation (2003), which called for Agency-wide improvements in the "development, documentation, and operation of models and simulations"[1] that subsequently elicited additional guidance from the NASA Office of the Chief Engineer to include "a standard method to assess the credibility of the models and simulations."[2] General methods applicable across the broad spectrum of M&S disciplines were sought to help guide the modeling and simulation processes within NASA and to provide for consistent reporting of M&S activities and analysis results. From this, the life cycle for M&S development and use was developed.

The major contents of this Handbook are the implementation details of the general M&S requirements of NASA-STD-7009B, including explanations, examples, and suggestions for improving M&S credibility throughout the M&S life cycle.

1.2 Applicability

1.2.1 NASA-STD-7009B and this Handbook are intended for use by M&S practitioners, technical reviewers, decision makers, and others in the organization implementing, reviewing, using, or receiving the results from an M&S-based analysis. Further, as NASA-STD-7009B is primarily focused on the results of an M&S-based analysis, which may be used by a variety of people, both internal and external to a given implementing organization, this Handbook may be used by anyone, as in the following examples:

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[1] A Renewed Commitment to Excellence: An Assessment of the NASA Agency-Wide Applicability of the Columbia Accident Investigation Board Report. B2005-100968, January 30, 2004. Retrieved April 22, 2013. http://www.nasa.gov/pdf/55691main_Diaz_020204.pdf.

[2] NASA Office of the Chief Engineer (September 1, 2006). Guidance in the Development of NASA-STD-7009. (Memo)

a. In receiving a presentation of an M&S-based analysis, a decision maker may use the Worksheet (section 6) as a guide to a more complete understanding of the analysis.

b. In substantiating an M&S product or analysis, a peer review team may use the Worksheet and Handbook to structure the results of a technical review.

c. In conducting an analysis with an existing M&S, a user/analyst may use the Worksheet and Handbook as a guide to covering basic M&S topics, which may be addressed during a future technical review or presentation for decision making.

d. During the course of an M&S activity, an M&S development team may use the Handbook to ensure the minimal expectations of a product used for critical analysis are met.

Anyone may use NASA-STD-7009B or this Handbook in the course of their modeling and simulation activities; the use is highly recommended for M&S that meet established risk criteria determined by program/project management in collaboration with the delegated NASA Technical Authority as outlined in Appendix D of NASA-STD-7009B. The application of many different types of M&S is possible in the creation of an analytical tool. While the elucidation of those types may be instructive, it is also most likely to be incomplete. The types of possible M&S are not included here but are discussed briefly in section 4.1 of this Handbook.

NASA-STD-7009B applies to any point in the program/project life cycle to which an M&S-based analysis may be applied. The expectations on the quality of the M&S products and analysis credibility will vary (most likely, improve) as the program/project matures. For example, the results from an M&S-based analysis in predicting the behavior of a Real World System (RWS) will likely be less precise and less accurate in the conceptual phase of a project than after several years of operations. A listing of the NASA program/project management phases is given in section 4.6 of this Handbook.

NASA-STD-7009B also applies to any size M&S activity if the criticality of the analysis, based on the influence of the M&S to the decision and the decision consequence, warrants its application.

1.2.2 This Handbook is approved for use by NASA Headquarters, and NASA Centers and Facilities. 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 their applicable contracts, grants, or agreements.

1.2.3 References to “this Handbook” refer to NASA-HDBK-7009B; references to other documents state the specific document information.

1.2.4 This Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance.

1.2.5 In this Handbook, 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.

2. REFERENCE DOCUMENTS

2.1 General

Documents listed in this section provide references supporting the guidance in this Handbook. Latest issuances of referenced documents apply unless specific versions are designated. Access reference documents at https://standards.nasa.gov or obtain documents directly from the Standards Developing Body or other document distributors, use embedded links or other locators in this document if provided, or by contacting the Office of Primary Responsibility Designee (OPRD) for this Handbook.

2.2 Government Documents

Office of Management and Budget (OMB)

OMB Circular A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities

NASA

NPD 1000.0, NASA Governance and Strategic Management Handbook

NPR 7150.2, NASA Software Engineering Requirements

NPR 7120.5, NASA Space Flight Program and Project Management Requirements

NPR 8000.4, Agency Risk Management Procedural Requirements

NASA-STD-7009B, Standard for Models and Simulations

NASA-HDBK-8739.19-3, Measurement Uncertainty Analysis Principles and Methods NASA Measurement Quality Assurance Handbook – ANNEX 3

NASA/SP-2016-6105, Revision 2, NASA Systems Engineering Handbook

NASA/SP-2010-576, NASA Risk-Informed Decision Making Handbook

NASA/SP-2011-3422, NASA Risk Management Handbook

NASA/SP-2009-569, Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis

NASA/TM-2002-211715, IECEC-2002-20113, "Comparison of ISS Power System Telemetry with Analytically Derived Data for Shadowed Cases", Fincannon, H. James

RP-08-118, NASA Standard for Models and Simulations (M&S): Development Process and Rationale

JWST-PLAN-006165, James Webb Space Telescope (JWST) System Modeling and Analysis and JWST Models Validation, Verification and Calibration Plan (SE-18), D42916 Rev. B

JWST-REF-002290, James Webb Space Telescope Math Models Guidelines Document (SE16), September 19, 2007, D36124 Rev. C

Aerospace Safety Advisory Panel Annual Report for 2008

Aerospace Safety Advisory Panel Annual Report for 2009

Expanded Guidance for NASA Systems Engineering Volume 1: Systems Engineering Practices - March, 2016

Expanded Guidance for NASA Systems Engineering Volume 2: Crosscutting Topics, Special Topics, and Appendices – March 2016

A Renewed Commitment to Excellence: An Assessment of the NASA Agency-Wide Applicability of the Columbia Accident Investigation Board Report. B2005-100968, January 30, 2004. Retrieved April 22, 2013.
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Bolognese, J. (2009). The FEMCI Book. Retrieved February 21, 2018.
http://femci.gsfc.nasa.gov/femcibook.html

Department of Defense (DoD)

MIL-STD-3022, Standard Practice Documentation of Verification, Validation, and Accreditation (VV&A) for Models and Simulations

DoD Modeling and Simulation (M&S) Glossary. Retrieved December 9, 2024.
https://apps.dtic.mil/sti/pdfs/ADA349800.pdf

Conceptual Model Development and Validation, VV&A Recommended Practice Guide special topic, May 18, 2011. Retrieved December 9, 2024.
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Digital Engineering Body of Knowledge (DEBoK). Retrieved February 26, 2025.
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Environmental Protection Agency (EPA)

EPA/100/K-09/003, Guidance on the Development, Evaluation, and Application of Environmental Models

National Institute of Standards and Technology (NIST)

NIST Technical Note 1297, Taylor, B.N.; Kuyatt, C.E. (1994). Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results

Sandia National Laboratories

SAND2005-4302, Oberkampf, W.; Barrone, M. (August 2005). *Measures of Agreement Between Computation and Experiment: Validation Metrics*

SAND2007-0853, Oberkampf, W.; Trucano, T. (February 2007). *Verification and Validation Benchmarks*

SAND2013-8051, Richard G. Hills, Walter R. Witkowski, William J. Rider, Timothy G. Trucano, Angel Urbina (September 2013). *Development of a Fourth Generation Predictive Capability Maturity Model*

SAND2016-6465 TR, How to Phenomenological Identification and Ranking Table (PIRT) (July 2016)

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SAND2002–0341, Trucano, T. G., M. Pilch, and W. L. Oberkampf (2002). General Concepts for Experimental Validation of ASCI Code Applications

United States Nuclear Regulatory Commission

NUREG/CR-5074, Shaw, R. A., Larson, T. K., and Dimenna, R. K. (August 1988). *Development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic Phenomena during a PWR LBLOCA, EG&G, Idaho Falls, ID, Inc.*

2.3 Non-Government Documents

American Institute of Aeronautics and Astronautics (AIAA)

G-045-2003e , AIAA. *AIAA Guide to Assessing Experimental Uncertainty - Supplement to S-071A-1999*

American National Standards Institute (ANSI)/NSCL International

ANSI/NCSL Z540 2-1997 (R2012). (1997). *U.S. Guide to the Expression of Uncertainty in Measurement*

American Society of Mechanical Engineers (ASME)

ASME V&V 10, Guide for Verification and Validation in Computational Solid Mechanics

ASME V&V 20, Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

ASME V&V 40, V&V for Computational. Modeling for Medical Devices

Institute of Electrical and Electronics Engineers (IEEE)

IEEE 1597.1, IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations

IEEE 754, IEEE Standard for Floating-Point Arithmetic

International Organization for Standards (ISO)

ISO/IEC Guide 98-3:2008, Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

ISO/IEC/IEEE 24765:2010 Systems and software engineering—Vocabulary

Los Alamos National Laboratory

LA-14167-MS, Thacker, B.H.; Doebling, S.W.; Hemez, F.M.; Anderson, M.C.; Pepin, J.E.; and Rodriguez, E.A. (October 2004). *Concepts of Model Verification and Validation*

SAE International

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The Aerospace Corporation

TOR-2010(8591)-17, Baxter, Michael J. (2010). Guidance for Space Program Modeling and Simulation

Other

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

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Oberkampf, W.L.; Roy, C.J. (2009). *Verification and Validation in Computational Simulation.* Cambridge, England: Cambridge University Press

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Oberkampf, W.L.; Deland, S.M.; Rutherford, B.M.; Diegert, K.V.; and Alvin, K.F. (March 2002). "Error and Uncertainty in Modeling and Simulation." *Reliability Engineering and System Safety*, Vol. 75, Issue 3, pp. 333-357

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2.4 Order of Precedence

2.4.1 This Handbook provides guidance for promoting good practices in the production, use, and consumption of modeling and simulation products but does not supersede or waive existing guidance found in other Agency documentation.

2.4.2 Conflicts between this Handbook and other documents will be resolved by the delegated NASA Technical Authority.

3. ACRONYMS, ABBREVIATIONS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

%	Percent
®	Registered Trademark
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASAP	Aerospace Safety Advisory Panel
ASCI	Accelerated Strategic Computing Initiative
ASME	American Society of Mechanical Engineers
CA	California

CAD	Computer-Aided Design
CAE	Computer Aided Engineering
CAM	Computer-Aided Manufacturing
CM	Configuration Management
ConOps	Concept of Operations
COTS	Commercial Off the Shelf
CRM	Continuous Risk Management
DEM&S	Digital Engineering, Modeling & Simulation
DoD	Department of Defense
DoE	Design of Experiments
DRM	Design Reference Mission
EPA	Environmental Protection Agency
FEM	Finite Element Model
FEMCI	Finite Element Modeling Continuous Improvement
FFRDC	Federally Funded Research and Development Center
genAI	Generative Artificial Intelligence
GNC	Guidance, Navigation, & Control
GOTS	Government off the Shelf
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
HI	Hawaii
H/W	Hardware
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output
ISO	International Organization for Standardization
ISS	International Space Station
I&T	Integration and Test
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LVC	Live-Virtual-Constructive
MIL	Military
ML	Machine Learning
MOS	Margin of Safety
MOTS	Modified off the Shelf
M&S	Models and Simulations
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory
MUF	Model Uncertainty Factor
NASA	National Aeronautics and Space Administration
NASTRAN	NASA structural analysis system
NCSL	National Conference of Standards Laboratories
NESC	NASA Engineering and Safety Center
NGO	Needs, Goals and Objectives
NIST	National Institute of Standards and Technology
NM	New Mexico

NN	Neural Network
NPD	NASA Policy Directive
NPR	NASA Procedural Requirements
ODE	Ordinary Differential Equation
OMB	Office of Management and Budget
OPRD	Office of Primary Responsibility Designee
PDE	Partial Differential Equation
PDF	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
Req’t	Requirement
RIDM	Risk informed decision making
R/r	Requirements or recommendations
RWS	Real World System
SI	System Internationale
SME	Subject Matter Expert
SP	Special Publication
SPIE	The International Society for Optical Engineering
SRQ	System Response Quantities
STD	Standard
S/W	Software
SWE	Software Engineering
VCS	Voluntary Consensus Standards
V&V	Verification and Validation
VV&A	Verification, Validation, and Accreditation
w.r.t.	With respect to

3.2 Definitions

The definitions listed below are those used in this Handbook and are in the context of M&S unless otherwise stated. Wherever possible, these definitions were taken or adapted from official NASA documents. In some cases, after reviewing definitions of interest in the International Organization for Standardization (ISO), the Department of Defense (DoD) Digital Engineering, Modeling & Simulation (DEM&S), professional society publications (e.g., AIAA, ASME, IEEE), and English language dictionaries, some definitions were taken or adapted from relevant sources to achieve the goal or objectives. Some definitions may have alternate meanings in other documents and disciplines. The definitions have been tagged with where they are defined or if they have been abstracted.

Abstraction: The process of simplifying, focusing, or transforming aspects of an RWS (or referent system) represented in an 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*.

Architecture: The essential elements of any system and their interrelationships, functions, and behaviors, including the influences of the environment and other (interfacing) systems.

Architectural Diagram: Any one of the possible visual (graphical) representations (viewpoints) depicting select aspects (features) of a system. (See definition of Architecture.)

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

Artificial Intelligence: (1) Any artificial system that performs tasks under varying and unpredictable circumstances without significant human oversight, or that can learn from experience and improve performance when exposed to data sets. (2) An artificial system developed in computer software, physical hardware, or other context that solves tasks requiring human-like perception, cognition, planning, learning, communication, or physical action. (3) An artificial system designed to think or act like a human, including cognitive architectures and neural networks. (4) A set of techniques, including machine learning (ML) that is designed to approximate a cognitive task. (5) An artificial system designed to act rationally, including an intelligent software agent or embodied robot that achieves goals using perception, planning, reasoning, learning, communicating, decision-making, and acting. *Note: NASA follows definitions defined in Section 238(g) of the National Defense Authorization Act of 2019* (Source: https://www.congress.gov/115/plaws/publ232/PLAW-115publ232.pdf)

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, 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 Handbook) or M&S design adequately represents the real world from the perspective of the intended uses of the M&S.

Configuration Management (CM): A technical and management discipline applied over the M&S life cycle to provide visibility into and to control changes to an M&S. (Source: 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." (Source: NASA-STD-7009B.)

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

Data Pedigree: A record of traceability from the data's source through all aspects of its transmission, storage, and processing to its final form used in the development of an M&S. *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).[3]

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.

Digital Twin: A set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin. (Source: https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins)

Domain of Operation: The range(s) over which M&S input/output quantities are bounded during expected RWS operations.

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

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

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

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.

Expanded Diagram: An illustration or diagram of a construction showing its parts separately but in positions that indicate their proper relationships to the whole.

Floating-Point Precision: The maximum number p of significant digits that can be represented in a format, or the number of digits to which a result is rounded. (Source: 754-2019 - IEEE Standard for Floating-Point Arithmetic)

Framework: A set of assumptions, concepts, values, and practices constituting a way of viewing reality. *Note: For M&S, this may be a computing environment that integrates multiple*

[3] This definition is largely a direct quote from *A Brief Introduction to Design of Experiments*, by Jacqueline K. Telford. Retrieved December 9, 2024. https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V27-N03/27-03-Telford.pdf.

interacting components on a single computer or across a distributed network.[4]

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. (Source: Adapted from NPR 8000.4 and the NASA Safety Hierarchy.)

Input Pedigree: A record of the 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. *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*.

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

Kriging: An interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location. Weights are based on the distance between the measured points, the prediction locations, and the overall spatial arrangement among the measured points.[5]

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

Live-Virtual-Constructive (LVC): A three-category taxonomy for M&S. Live M&S consists of real actors (usually people) using the RWS in a simulated scenario. An example of Live M&S is automated emergency defibrillator (AED) training using real AEDs in training mode. Virtual M&S consists of real actors using a simulated RWS; a flight simulator is an example of a virtual M&S. A constructive M&S consists of simulated actors using a simulated RWS. Any computation-only M&S is constructive. An M&S use can include a combination of live, virtual, and constructive M&S.

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. Entity refers to any system distinct from the RWS with which the RWS interacts, e.g. a vehicle, ground system, or test fixture.

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*.

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[4] A modification from http://www.answers.com/topic/framework#ixzz1CL7UTZYb. Retrieved April 22, 2013.
[5] http://support.esri.com/en/knowledgebase/GISDictionary/term/kriging. Retrieved April 22, 2013.

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. (Source: 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. (Source: Adapted from ASME V&V 10, Guide for Verification and Validation in Computational Solid Mechanics.)

Metamodel: A model of a model which is intended to give an all-inclusive picture of a process or system by abstracting from more detailed individual models contained within it; metamodeling is the analysis, construction, and development of the frames, rules, constraints, models, and theories applicable and useful for modeling a predefined class of problems.

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, phenomena, or process. *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.* (Source: Adapted from Banks, J., ed. (1998). Handbook of Simulation. New York: John Wiley & Sons.)

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 M&S 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.

Monte Carlo (method): A statistical method of understanding complex physical or mathematical systems by using randomly generated numbers as input into those systems to generate a range of solutions.

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. (Source: Yang, W.Y.; Cao, W.; Chung, T.-S.; and Morris, J. (2005). *Applied Numerical Methods Using MATLAB®.* Hoboken: John Wiley & Sons, Inc.)

Parameter: A value that defines a specific characteristic or attribute of the system being modeled.

Peer Review: A technical assessment conducted by one or more persons of equal technical standing to the person(s) responsible for the work being reviewed.

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

Precision: The consistency and reproducibility of a parameter or variable (or set of parameters or variables) within an M&S or experiment.

Probabilistic: Pertaining to non-deterministic events, the outcome of which is described by a measure of likelihood. (Source: 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 the 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. (Source: Adapted from ASME V&V 10, *Guide for Verification and Validation in Computational Solid Mechanics.*) *Note: A referent may be the RWS to which the analysis is directed, or it could be 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. (Source: Adapted from ISO/IEC/IEEE 24765:2010 Systems and software engineering—Vocabulary.) *Note: This term is in no way related to statistical regression analysis.*

Repeatability: Ability of an M&S to produce similar outputs during repeated simulations of a given scenario with identical inputs (initial conditions, events, boundary conditions, etc.).

Replicability: Obtaining consistent results across studies aimed at answering the same (scientific, technical) question, each of which has obtained its own data. Two studies may be considered to have replicated if they obtain consistent results given the level of uncertainty inherent in the RWS. (Source: tailored from https://www.ncbi.nlm.nih.gov/books/NBK547537/pdf/Bookshelf_NBK547537.pdf)

Reproducibility: Obtaining consistent results using the same input data; computational steps, methods, and code; and conditions of analysis. (Source: tailored from https://www.ncbi.nlm.nih.gov/books/NBK547537/pdf/Bookshelf_NBK547537.pdf)

Responsible Party: The group or individual identified as accountable for complying with requirements in NASA-STD-7009B. *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 in response to 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)

Scalability: The ability of a distributed simulation to maintain time and spatial consistency as the number of entities and accompanying interactions increase.

Scenario: The description or definition of the relevant system and environmental assumptions, conditions, or parameters 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.* (Source: NASA-STD-7009B, adapted from Saltelli, 2005)

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

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

Subject Matter Expert (SME): 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.

Surrogate model: A data-driven model for approximating the relationship between independent and dependent variables. When applied to an M&S, typically the independent variables are repesented by the M&S input variables and the M&S results provide the dependent variables.

Tailoring: The process used to adjust or modify a prescribed requirement to better meet 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; (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).

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

Unit Testing: Any type of software testing conducted on the smallest meaningful, testable fragments of code to ensure the code behaves exactly as intended under various conditions. For procedural programming languages, such code fragments are generally functions or subroutines. (Source: http://www.saravanansubramanian.com/Saravanan/Articles_On_Software/Entries/2010/1/19_Unit_Testing_101_For_Non-Programmers.html)

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

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

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

Voluntary Consensus Standards (VCS): Standards developed or adopted by VCS bodies, both domestic and international, that include provisions requiring that owners of relevant intellectual property have agreed to make that intellectual property available on a non-discriminatory, royalty-free, or reasonable royalty basis to all interested parties. (Source: OMB Circular No. A-119, 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: A documented authorization intentionally releasing a program or project from meeting a requirement. (Source: Adapted from NPR 7120.5F *Note: Deviations and exceptions are considered special cases of waivers*.)

4. INTRODUCTION

The risks associated with the use of M&S to support the development and operation of aerospace systems outside of NASA, e.g., in commercial aviation, can be mitigated by hours of flight test in the operational environment. The nature of NASA's missions often involves one-of-a-kind systems that have a high impact if unsuccessful, such as:

a. Loss of human life.

b. Loss of high-value equipment.

c. Loss of mission products, e.g., unique science.

d. Limited reflight opportunities.

e. Re-design of a previously implemented system.

f. Not meeting stakeholder requirements (e.g., for reliability or affordability).

Because of these impacts, a relatively high-risk profile, long test development and operations time, and overall expense, testing of operational systems in operational environments (e.g., flight tests) is typically limited. NASA's engineering processes depend on models of the system to a higher degree than is typically found in other industries to help mitigate operational risk. Thus, a methodical approach to accepting the results of these models is beneficial. This Handbook provides standardized language, an associated knowledge base, and guidance for users, developers, managers and executive-level personnel to effectively apply M&S to NASA requirements.

4.1 Background

NASA-STD-7009 focuses on the products of models and simulations (M&S). It is uniquely applicable to all types of M&S and all phases of M&S development and use, with its primary focus on the results of an M&S-based analysis, and the reporting thereof. Most M&S standards and recommended practices are either focused on a single type of M&S, e.g., structures, fluids, or electrical controls, or on a particular phase of M&S development, e.g., verification or validation. Considering that program/project management is confronted with numerous types of analyses with which to make critical decisions, a common framework for understanding the results and assessing the analysis credibility is appropriate. This is complicated by the vast differences across engineering systems.

With the formal approval of the Baseline version in July 2008, NASA-STD-7009 was available for the individual program, project, organization, office, or M&S practitioner to adopt. While adoption of NASA-STD-7009 is not required for either development or use of an M&S, unless specified by formal directive, it is highly recommended for those deemed as critical.

Many organizations, both internal and external to NASA, maintain a continuing interest in the accepted revision of NASA-STD-7009, including the NASA Aerospace Safety Advisory Panel (ASAP Reports for 2008 and 2009). The interest and questions regarding the practical implementation of NASA-STD-7009 provided the impetus to develop this Handbook, which was initially sponsored by the NASA Engineering and Safety Center (NESC) in December 2009.

Development of this Handbook included the review of related NASA documentation (software requirements, product data and life cycle management requirements, and NESC procedures); other related U.S. Government documentation, including OMB Circular A-119, VCS, DoD and Department of Energy M&S verification and validation (V&V) and uncertainty quantification guidance; EPA/100/K-09/003, Guidance on the Development, Evaluation, and Application of Environmental Models; and the following external M&S standards and guides:

ASME V&V 10	Verification and Validation in Computational Solid Mechanics

ASME V&V 20	Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer
ASME V&V 40	V&V for Computational Modeling for Medical Devices
IEEE 1597.1	IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations
TOR-2010(8591)-17	Mission Assurance Improvement Workshop, Guidance for Space Program Modeling and Simulation (Baxter, 2010, Aerospace Report)

ASME V&V 40 also adapts several concepts from NASA-STD-7009 for its use.

The development of this Handbook was initiated with several pathfinder evaluations of on-going NASA M&S projects: The Orion Service Module Tank Slosh Model, the Orion Crew Module Water Landing Model, the Ares Thrust Oscillation Model, and the Mars Science Laboratory (MSL) Powered Descent Model. The general findings from these pathfinder studies encourage the following:

a. Have a structured process to follow.

b. Use consistent terminology.

c. Evaluate an M&S-based analysis more broadly (i.e., beyond V&V) to include all credibility assessment factors.

d. Understand the real world system (RWS) project requirements relevant to the M&S.

e. Define accuracy requirements to validate critical analysis models appropriately.

f. Understand how the validation of M&S can be improved.

g. Cross-link credibility assessment factors to NASA-STD-7009B requirements.

h. Address M&S limits of operation.

i. Provide guidance on coupled models.

The questions related to the implementation of the requirements of NASA-STD-7009B by M&S practitioners, the additional emphasis on risk by the ASAP, the details of various aspects of M&S provided by other government and professional organizations, and the findings from NASA pathfinder projects provide the basis for the development of this Handbook. While implementation of NASA-STD-7009B is initially perceived as complex, this is usually a reflection of the complexity of the M&S discipline. Besides the sheer depth of calculation accomplished in many M&S, the variety of M&S types and methods add to the difficulty of uniform application. The following are examples of the varieties of M&S:

a. M&S primarily based on differential equations or difference equations.

b. A relative geometry model of various objects over time.

c. Regression models from empirical data.

d. Various system data relationship models.

e. Stochastic process simulation modeling and analysis.

The uniqueness in implementing the various types of M&S is left to the discipline accomplishing the M&S-based analysis (e.g., finite element analysis, system process analysis, or computational fluid dynamics) and to the relevant professional organizations (e.g., American Institute of Aeronautics and Astronautics [AIAA], ASME, or IEEE). This is not a full elucidation of the M&S disciplines that exist, which becomes even more complex by M&S systems that are combined into larger or distributed analytical platforms. One essential consideration in the development of this Handbook was to provide guidance and explanations about the requirements and recommendations included in NASA-STD-7009B and thus ease and broaden its use. Understanding the development and use phasing of the NASA-STD-7009B requirements and recommendations, along with a worksheet for M&S planning, development, and use, provides context and guidance for a more complete practice of modeling and simulation.

Worksheets and checklists are used in a variety of venues to ensure operations and processes are accomplished in an organized, consistent, and complete manner, which can improve both the safety and quality of the process. "NASA research has led to standardized checklist characteristics in the field of general aviation."[6] Studies were also accomplished in medical/surgical procedures showing that the implementation of checklists had associated "reductions in the rates of death and complications among patients" (Haynes, et al., 2009). As NASA's use of M&S can have safety or critical implications to human life or mission success, the use of a checklist or worksheet to guide the development, use, and discussion of M&S-based results is appropriate. The worksheet resulting from the development of this Handbook combines aspects of both worksheets and checklists.

Note: This Handbook and associated worksheet are not intended to be comprehensive or overly prescriptive. It is not possible to include everything needed for every type and application of M&S. The intent is to provide guidance to a more complete discussion of the details surrounding M&S-based analyses and results.

4.2 Interpreting and Tailoring

[6] http://hwebbjr.typepad.com/openloops/2005/09/how_to_create_a.html. Retrieved April 23, 2013.

Any general standard requires either interpretation or tailoring to a particular application. Both are acceptable, as long as they are justified, approved (as necessary), and documented (see Table 4, Program/Project Management and Delegated NASA Technical Authority Responsibilities as Stated in NASA-STD-7009B, in section 4.8 of this Handbook). Interpretation of the requirements and recommendations are often necessary and depending on the specific type, form, or application of M&S may not be applicable. Tailoring provides the flexibility for these situations. For example, static (e.g., unchanging, deterministic) models may provide no handling for uncertainties that always exist in an RWS, which means the uncertainty characterization requirements might justifiably be eliminated.

In almost all cases, program or project self-tailoring of the standard is the preferred method of balancing the standard and the specific needs of the application. However, some applications may suggest an alternative NASA Standard for M&S credibility be used in place of the NASA-STD-7009B to fulfill the M&S risk reduction intent. The user, program management authority and, ultimately, the designated 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 NASA-STD-7009B including evaluating the equivalency of any tailoring or alternative standards. Evaluating substantial equivalency of alternative processes (i.e. a process is meant to meet the intent of a standard in that it is comparable in testing activities and evidential content but may differ in format or method of delivery) is dependent on the M&S application. Assessing substantial equivalency may include:

a. Judging that the processes address the same or different intents than the standard (i.e. reduction of M&S results risk).

b. Conducting a comparative analysis of processes and Standards.

c. Addressing conflicts or discrepancies between the standard and the processes.

d. Gauging the gaps or overlaps between the standard and the processes.

e. Analyzing the synergy between standards and processes.

In the case of approval of tailoring or alternative standards, the assessment should be documented with information and rationale supporting the designated NASA Technical Authority approval and evaluation of substantial equivalency.

4.3 Applicability to Model and Simulation (M&S) Efforts

The question of the applicability of NASA-STD-7009B often arises in new programs, projects, or M&S efforts. The wording in the current revision of NASA-STD-7009 is clarified from the Baseline version (see NASA-STD-7009, Change 1, section 1.2). The following are noteworthy points:

a. The word “applicable” means relevant and appropriate, i.e., it does not mean required.

b. As a general M&S Standard, it is relevant and appropriate to all M&S regardless of M&S type, discipline, or application (e.g., design, development, manufacturing, ground operations, and flight operations).

c. If an M&S is used in critical decisions or functions, compliance with NASA-STD-7009B is highly recommended.

d. NASA-STD-7009B is required when explicitly cited in a program, project, organization, or office directive.

4.4 Compliance with NASA-STD-7009B

Key aspects of M&S development and use are clarified when the requirements and recommendations of NASA-STD-7009B are followed, such as:

a. Established processes for both M&S development and use.

b. The intended use (the expected purpose and application of an M&S) is documented, which provides the basis for M&S development.

c. Abstractions, Assumptions, and M&S Design are documented.

d. Uncertainties are characterized.

e. The Permissible Uses are documented, as determined during development with an understanding of the abstractions taken in development, the assumptions made during development that impact model use, the constraints of implementation methods used, and the limits of operation based on the completeness and success of V&V.

f. Processes and methods for appropriately using the M&S are documented (e.g., via a user's guide)

g. The results from M&S use are reported with other qualifying information, to include:

(1) Criticality of M&S application (as defined in NASA-STD-7009B, Appendix D).

(2) Uncertainty of the Results.

(3) Caveats to the Results, including:

A. Unachieved Acceptance Criteria.

B. Violation of Assumptions.

C. Violation of Limits of Operation.

D. Execution Warnings & Errors.

E. Unfavorable Use Assessment.

F. Requirement Waivers.

(4) Credibility (as defined in NASA-STD-7009B, Appendix E).

(5) Results from any Technical Reviews.

(6) People Qualifications (e.g., Developers, Users, Analysts).

(7) M&S Documentation (adequacy thereof).

(8) M&S Risk.

Note: The documentation requirements and recommendations of NASA-STD-7009B are intended to convey the need for evidence that the activity was accomplished. It does not expect that a new document is required, but that evidence of the activity, and the results therefrom, are at least cited/referenced. DoD documentation and directives (see MIL-STD-3022, Standard Practice Documentation of Verification, Validation, and Accreditation (VV&A) for Models and Simulations, the online DoD Modeling and Simulation Glossary, and the online Digital Engineering Body of Knowledge) provide excellent process guidelines in documenting M&S activities, and Appendix C of MIL-STD-3022 could be utilized as a tailorable template to incorporate into M&S activities.

For more information, the "rationale" for each requirement is included in NASA-STD-7009B and additional explanations are available in this Handbook (relevant sub-sections of section 5).

4.5 Models – Key Concept

NASA-STD-7009B defines a model as a description or representation of a system, entity, phenomena, or process, including any data going into a model. Models are necessarily imperfect, incomplete, or abstract for a variety of reasons, as follows:

a. An exact representation is not possible because:

(1) Knowledge about the RWS is incomplete and limited by the extent and uncertainty of the subset of RWS factors used to characterize the system.

(2) Details are not sufficiently characterized to be included in the model.

(3) All possible variations of the subject RWS cannot be reasonably included.

(4) The model would exceed the limits of the computational platform.

b. An exact representation is not desirable because:

   (1) Added fidelity (detail) adds cost and complexity.

   (2) Adding unnecessary details detracts from the focus of the analysis.

c. An exact representation is unwieldy because:

   (1) The RWS is extremely small and scaling the model up makes it more readily understood.

   (2) The RWS is extremely large and scaling the model down makes it more readily understood.

As such, models are abstract representations of existing, proposed, or imagined systems; the intent is to include the pertinent representations necessary for the model's intended purpose. The key concept is that M&S are not exact representations, and do not produce exact or perfectly representative results. Both the limitations and imperfections built into the model, i.e., epistemic uncertainty, and the inherent system variability included in the analysis, i.e., aleatory uncertainty, are manifested as uncertainty in the M&S results and need to be clearly understood (additional explanations are found in SAND2003-3769). Considering what is not included in the model can be as important as what is in the model.

4.5.1 Pedigree and Provenance in Models and Simulations (M&S)

A prevalent and important concept in data, information, and computational science, which is also applicable to M&S, is pedigree or provenance. While a variety of definitions exists for both terms, which are somewhat inconsistent, the concepts are overlapping. Both terms embody the concepts of lineage and traceability, and either infer or directly address the quality of the data or information used. For the purposes of this Handbook, pedigree and provenance are synonymous.

NASA-STD-7009B and this Handbook encompass the general concept of data provenance in the form of the Data Pedigree and Input Pedigree factors of Credibility Assessment. The Input Pedigree factor assesses data used as input to a model, which is accomplished when using a model for a specific application. On the other hand, data used during model development, and the subject of Data Pedigree assessments, may be obtained, altered, or included any time from initial model conceptualizations through model construction. In short, whenever data is incorporated in an M&S, that data becomes subject to evaluation in the Data Pedigree factor of the Credibility Assessment (see Appendix D.3).

The concept of provenance may also be applied to a model, as it is influenced by a multitude of data, information, processes, and personalities during its development. Addressing and improving model provenance is essentially one of the cornerstones of NASA-STD-7009B. The ability to reference a specific M&S life cycle and address the processes and products of each phase of that life cycle (see section 5 of this Handbook) is emphasized in both the Standard and this Handbook. A disciplined and documented approach to model development and use directly enhances model provenance.

4.5.2 Models of Models

The definition of a model in NASA-STD-7009B also notes that "a model may be constructed from multiple sub-models; the individual sub-models and the integrated sub-models are all considered models." Other related terms, such as coupled model, linked model, integrated model, surrogate model, and metamodel, are also included as part of the model concept. There are several reasons to construct larger models this way, including taking advantage of already existing models and the benefits of modularity. The interaction between the "component models" may be in a simple one-way (feed-forward) direction, or a complex multipath network of interactions. In either case, the interfaces and interactions between such models should be clearly documented and tested.

An example of a one-way, unidirectional coupling or linking of component models is found in the case of multidisciplinary design-analysis for telescopes and optical instruments, specifically where the analysis considers the impact of temperature changes upon optical image quality. The linked analysis required in this case involves the following:

a. Executing a simulation using a thermal model of the system;

b. Transferring (mapping) the predicted temperatures to a structural model of the system;

c. Executing a simulation of the temperature-induced elastic deformations of the structure using this structural model;

d. Transferring the structural deformations into an optical model;

e. Transferring the predicted temperatures to the optical model to account for temperature-dependent index-of-refraction of lens elements, if any, and;

f. Executing a simulation of the geometric and physical diffraction phenomena using the optical model.

On the other hand, aggregated models with two-way interaction between the elements may mirror the interactions between corresponding parts of the RWS. A typical example is a space vehicle Guidance, Navigation, & Control (GNC) model, where sub-models representing the control system, sensors, actuators, vehicle dynamics, and internal/external environments may interact through complex, multipath feedback loops.

There are also cases in which individual models are developed and possibly used on their own and then integrated into a larger analytical model to address more system-wide issues. In either case, the recommendation is to apply NASA-STD-7009B to the individual M&S and, subsequently, to the linked or wholly integrated M&S. The level definitions for the input pedigree factor in the credibility assessment anticipate exactly this scenario.

Surrogate models are synonymous with emulators and metamodels in some instances, although there are other uses of the latter term that include the integration of sub-models and the linkage of stand-alone models. Within the domain of computational M&S, the term often refers to models constructed in a manner used to construct data-driven models for approximating the relationships between independent and dependent variables. In the computational M&S application simulation data such as the M&S inputs (independent) and simulated outputs (dependent) are used as the source data. This compares to an empirical surrogate model that uses inputs (independent) and observational outputs (dependents). There are many methods for creating empirical and computational surrogate models ranging from statistical to ML-based techniques. Computational surrogate models are usually developed because of their significant performance advantage over more detailed, application- or discipline- specific (e.g., physics-based or phenomenological) M&S implementations. Computational surrogate models also take on all the assumptions and limitations of the computational models on which they are based, as well as incorporate additional limitations from their specific implementation.

Note: Empirical surrogate models may also be developed due to significant advantages over accruing new observational data and subsequently used in an M&S application. When used in conjunction with, or as a part of an M&S decision support application, the assumptions and limitations of the empirical surrogate model should be included in the appropriate M&S credibility evaluation factor evaluation.

Note: When computational or empirical surrogate models are based on ML approaches, they may be considered a sub-set of artificial intelligence (AI) models with respect to M&S use and results credibility. Although a sub-set of AI (as discussed in section 4.5.3 of this Handbook), the ML surrogates used for (M&S supported) critical decisions are subject to the same M&S credibility evaluation and risk evaluations as other non-AI M&S approaches.

4.5.3 NASA's use of Artificial Intelligence (AI) Models

AI has been increasingly used to support, integrate with, and replace discipline- specific (e.g., physics-based or phenomenological) M&S implementations, such as by creating surrogate models as mentioned in section 4.5.2 of this Handbook. Use of AI models in M&S decision making inherently creates additional risks. Simply stated, the use of AI-generated models should be approached with a similar scope and intent as all M&S applications governed by the standard, considering the AI credibility and other risk factors.

Like other data-driven tools, AI can take many forms in the M&S lifecycle. Some examples include instances where AI can be the M&S, AI can produce inputs into the M&S, or AI can automate an M&S activity in the lifecycle. When AI is used in the M&S lifecycle, assessments need to address possible impacts of AI use on credibility. The approaches in the standard should be applicable in most AI applications where AI is the M&S or plays a significant role in the M&S generation of results, i.e. those cases that are intended to predict responses of an RWS. When the AI application in an M&S lifecycle is not associated with predicting the RWS response, the processes in the standard may have less applicability. Such cases may include AI applications, like generative AI (genAI) chatbots, and image, video, and audio generation systems, voice transcribers and notetakers (except in cases where the detailed accuracy of the notes is critical, e.g., during verification/validation testing) used to support the M&S life cycle. In these cases, appropriated AI discipline evaluation criteria should be applied. An AI application used to provide analyses or post-processing of M&S output, just as with other statistical analysis approaches, should also be evaluated for its possible impacts on credibility. Examples of these types of applications may include AI analyses such as those using clustering or decision trees. The risk of using AI within the M&S lifecycle should be appropriately characterized and should be adequately communicated to M&S practitioners, users, technical reviewers and decision maker.

AI model applications make use of extensive data sets to make predictions by combining statistical and computer science techniques (see NASA Software Engineering and Assurance Handbook, See Online Topics 7.25 and 8.25, https://swehb.nasa.gov/). The credibility of the AI model results that are applicable to the standard due to their intended or context of use can often be evaluated in a manner like other statistical models (https://ntrs.nasa.gov/citations/20200002832). Assessing AI model credibility involves understanding and communicating the training data pedigree and assumptions, understanding and communicating the decisions made in constructing and training the AI model, and evaluating the performance of the model against validation data that is independent of the training data. Some important aspects of both capability and results assessments in establishing credibility (i.e. trustworthiness) of the AI model results will pose unique challenges to the M&S practitioner and should be approached with the intent of minimizing the M&S results risk.

The broad application nature of AI models comes with ethical considerations that accompany credibility and trustworthiness, as outlined in the NASA Framework for the Ethical Use of AI (NASA/TM-20210012886). In many ways, these considerations mirror those imposed by web based and COTS M&S tools that exhibit a largely “black box nature.” As in those cases, it may not be possible to examine the AI model in detail, or the training dataset that the model depends on. Even "open" AI models are often only open weights: i.e., the model itself can be inspected and modified, but the training data that was used to create the model is not public. This may make evaluating the AI model difficult or impossible. Additionally, it is important to account for any intellectual property and/or export control concerns associated with web-based or commercial tools. For example, many commercial tools are trained on user inputs and are not suitable for use with any data that is not already publicly available. As of 2024, this warning mostly applies to genAI tools that are outside of the scope of this Handbook, but it should still be kept in mind when developing and deploying future AI/ML systems.

Note: Data curation is perhaps the most significant component of AI use evidence to M&S credibility. In assessing credibility, an M&S practitioner should, as applicable, seek to present evidence as to the appropriateness of the AI data to the M&S application. This may include, but not be limited to, evidence of: (1) having enough training data to fit every parameter of the AI model to a level of confidence necessary for the application, (2) having a comprehensive data set that includes nominal and off-nominal circumstances, (3) performing evaluations to identify and understand coincidental patterns in the data, and (4) evaluations of the training data being “too clean,” leaving the AI unable to address noisy RWS inputs.

Note: In M&S credibility assessments, evidence as to the construction of the AI neural network (NN) is another important aspect. It is recommended that verification evidence include that the AI M&S application be suitably constructed to capture the dimensionality and probability distribution of the RWS responses to the range of M&S inputs. An NN that is too simple cannot match the dimensionality or probability distribution of the RWS and one that is too complex may form biases related to generation of coincidental patterns and low significance interactions.

4.6 The Model and Simulation (M&S) Process/Life Cycle

An M&S life cycle was introduced in Revision A and modified in revision B of NASA-STD-7009 to convey an understanding of when, in the development and use of an M&S, the requirements or recommendations apply. As this life cycle developed, it became even more apparent that some requirements or recommendations be accomplished more specifically than just "in model development" or "in model use." Some things are better accomplished earlier in the development of an M&S than later and there is often the need of a clear distinction of the model development and use phase credibility products. For example, the intended use of an M&S is best determined as early as possible in the life cycle as a standard-bearer for development (even if it is modified at a later time).

The M&S life cycle is adapted from NASA Project Life Cycle (NPR 7120.5F, Fig. 2-5) with its familiar phases and their designations. People who understand, for example, what occurs in Phase B for a program/project, will also understand what occurs in Phase B in an M&S life cycle, simply by thinking of the M&S as the "system" under development. For this reason, the number of life cycle phases are the same, and the names for the phases are correlated to promote a more immediate understanding (see Table 1, Program/Project and M&S Life Cycles).

Table 1—Program/Project and M&S Life Cycles

Phase	**Pre-A**	**A**	**B**	**C**	**D**	**E**	**F**
Prog/Proj Phase Name	Conceptual Studies	Concept & Technology Development	Preliminary Design & Technology Completion	Final Design & Fabrication	System Assembly, Integration, & Test	Operations & Sustainment	Closeout

	↑ Similar Name, Function, Purpose ↓	↑ Similar Name, Function, Purpose ↓	↑ Similar Name, Function, Purpose ↓	↑ Similar Name, Function, Purpose ↓	↑ Similar Name, Function, Purpose ↓	↑ Similar Name, Function, Purpose ↓	
M&S Phase Name	M&S Initiation	M&S Concept Development	M&S Design & (Conceptual) Validation	M&S Construction	M&S Testing	M&S Use	M&S /Analysis Archival

Note: The function/purpose of each phase in both the program/project and M&S life cycles is essentially the same. This does not imply that each M&S life cycle phase occurs in parallel with, or at the same time as, the program/project life cycle phase. Because models can inform decisions in any phase of a program/project, an entire M&S life cycle can exist within one phase or more phases, of the program/project. As one example, Figure 1, M&S Life Cycles in an RWS Life Cycle, depicts multiple M&S life cycles occurring across phases of a program/project life cycle. For M&S developments supporting a specific RWS, care is warranted in specifying M&S versus RWS development phases.

It is understood that actual execution of these M&S life- cycle phases, especially the early phases, is not as discrete in practice as depicted. Pre-phase A and Phase A are often blended, as are Phases A and B. The key point is the activities are best performed and products best developed in the given order as most effective and efficient. Additionally, these activities often occur in reiterative cycles within and between the various phases as development of the end-product matures. This concept is also embodied, at least to some degree, in both spiral and agile development processes. These are not precluded when adopting the life cycle as defined in NASA-STD-7009B. It just means that the series of development and use phases occur multiple times for each round of the spiral or agile sprint for smaller pieces of the model and for the final integrated model.

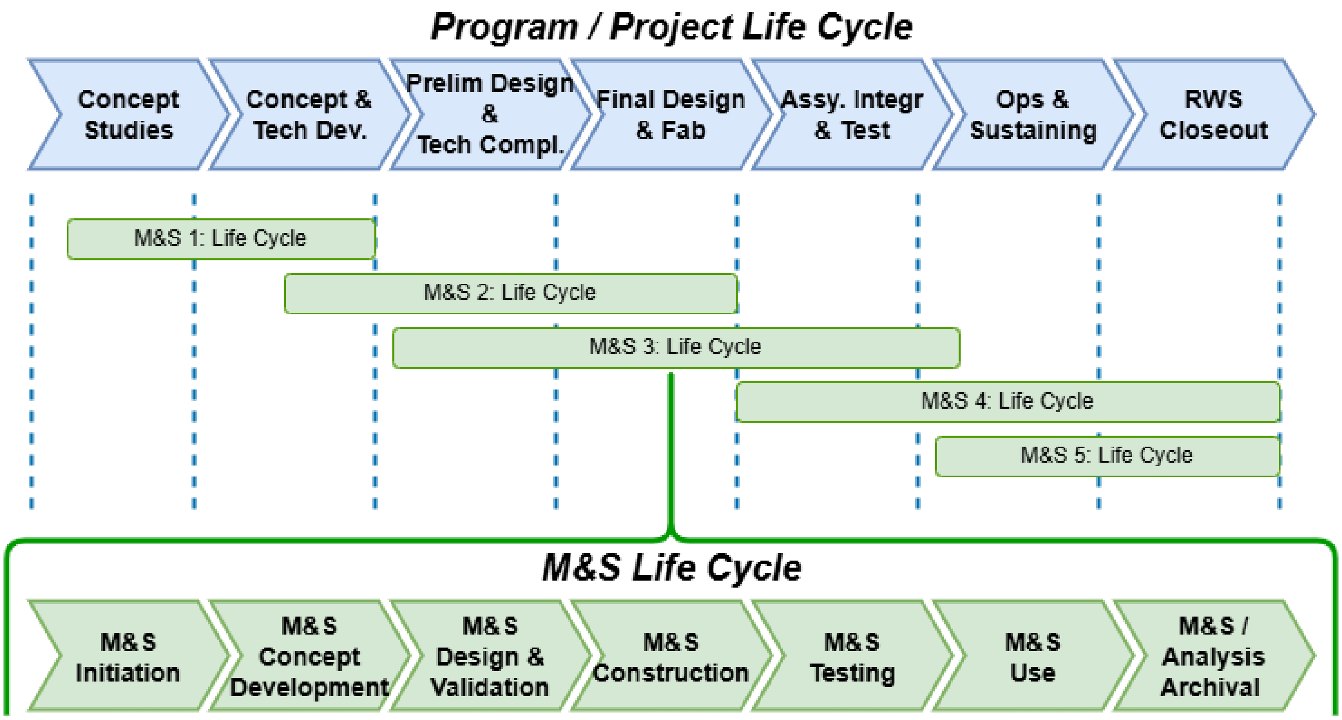


Figure 1—Example M&S Life Cycles in an RWS Life Cycle.

Thoughts about any M&S begin and end with the RWS it is to represent (real, proposed, or imagined). A brief explanation of each M&S life cycle phase is given in Table 2, M&S Life Cycle Phase Descriptions, with a more complete treatment given in the relevant portions in section 5 of this Handbook.

Table 2—M&S Life Cycle Phase Descriptions

Phase	Name	Brief Description
Pre-A	M&S Initiation	The process of determining the scope of the RWS on which to apply an M&S and defining the intended use of the M&S.
A	M&S Concept Development	The process of compiling all relevant information about the scoped RWS and beginning to develop general modeling concepts and requirements for representing the RWS.
B	M&S Design and (Conceptual) Validation	The typically iterative process of creating the detailed, verifiable, and validated specification of an M&S for an intended use, using the relevant information regarding the RWS, the conceptual model, and other defined objectives/criteria. The model design should be conceptually validated prior to commencing with M&S Construction (Phase C).
C	M&S Construction	The process/activity of implementing (generating or building) a usable model, as defined by its requirements, specifications (some of which may be embodied in a conceptual model/diagram), and intended use.
D	M&S Testing	**Verification** is 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. **Validation** is 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. **Model Release** is the process of establishing the baseline and controlled version of the model and associated key documentation for use. *After release, changes to the baseline are to be evaluated, justified, and authorized with traceability prior to implementing and releasing the revision.*
E	M&S Use	The application of an M&S to the purpose for which it is intended. *This Phase begins with assessing a proposed use, preparing the model and scenarios for use or otherwise integrating the model into the simulation, using (e.g., running) the model, gathering and post-processing the output, and assessing and reporting the results.*
F	M&S Analysis/ Archival	The process of storing and cataloging all M&S, and designating development and use artifacts for retrieval and use.

Two final points to note about an M&S life cycle:

a. Many of the NASA-STD-7009B requirements and recommendations can be, or need to be, accomplished in several of the life cycle phases. It is advantageous to initially accomplish the requirements or recommendations in the earliest practical phase (see Appendix A of this Handbook) and then update the information as needed throughout subsequent phases. On the other hand, if a requirement or recommendation is not accomplished in a particular recommended phase, it becomes incumbent on the subsequent phases to make up that shortfall.

b. The Model and Analysis Archiving Phase (Phase F) is placed as if the entire M&S life cycle occurs, from development to use, before archiving any of the artifacts. An M&S may not necessarily get closed out once development or a particular use is completed but may simply be "put on the shelf" until needed. The M&S and associated key products are expected to be archived at key points throughout development and use (e.g., at the end of each life cycle phase), as well as at the end of an M&S's life cycle. This phase is retained here for a few reasons:

(1) To retain commonality with the program/project life cycle phases.

(2) To emphasize that each development or use cycle of an M&S is to conclude with archival of the M&S revision and its requisite by-products from development and use.

The structure of section 5 of this Handbook follows these life cycle phases.

4.7 Relation to NPR 7150.2, NASA Software Engineering Requirements

Models, particularly analytical models, are usually implemented in software. Section 4 of NASA-STD-7009B notes that "*Specific requirements applicable to M&S implemented in software are found in the NASA Software Engineering Requirements (NPR 7150.2).*" The requirements contained within NPR 7150.2 "cover all software created, acquired, or maintained by or for NASA and apply to all of the Agency's investment areas containing software systems and subsystems." NPR 7150.2 classifies NASA's software systems as follows (refer to Table 3, Classes of NASA Software):

Table 3—Classes of NASA Software

Class	Software Description
A	Human-Rated Space Software Systems
B	Non-Human-Rated Space Software Systems or Large-Scale Aeronautics Vehicles
C	Mission Support Software or Aeronautic Vehicles, or Major Engineering/Research Facility Software
D	Basic Science/Engineering Design, and Research and Technology Software
E	Design Concept, Research, Technology, and General Purpose Software
F	General Purpose Computing, Business, and IT Software

NPR 7150.2, Appendix D, defines each class in detail; NPR 7150.2, Appendix C, provides a detailed compliance matrix that defines which requirements are applicable to each software class. Classes A-E are of primary interest here, noting that models may be embedded in flight and ground software (Class A/B/C) systems, and are routinely used within engineering design software (Class D/E) systems. The M&S practitioner is to note that Agency software engineering requirements (and Center implementations thereof) cover, among other things, modeling tools and parametric models. Specifically, NPR 7150.2 states that:

a. Examples of Class D software include, but are not limited to… engineering design and modeling tools (e.g., computer-aided design and computer-aided manufacturing (CAD/CAM), thermal/structural analysis tools); project assurance databases (e.g., problem reporting, analysis, and corrective action system, requirements management databases); propulsion integrated design tools; integrated build management systems; inventory management tools; probabilistic engineering analysis *tools; test stand data analysis tools; test stand engineering support tools; experimental flight displays evaluated in a flight simulator; and tools used to develop design reference missions to support early mission planning.*

b. Examples of Class E software include, but are not limited to, parametric models to estimate performance or other attributes of design concepts; software to explore correlations between data sets; line of code counters; file format converters; and document template builders.

A significant percentage of the requirements in NPR 7150.2 are applicable to Class D software, while far fewer requirements are applicable to Class E software (refer to Appendix C of NPR 7150.2). Compliance with all requirements in NASA-STD-7009B does not ensure compliance with all requirements in NPR 7150.2 spanning Classes A-E. Conversely, compliance with all requirements in NPR 7150.2 does not ensure compliance with all requirements in NASA-STD-7009B. In particular, and of significant importance, NPR 7150.2 does not address M&S-based analysis, the M&S credibility assessment, or reporting of M&S results and M&S risk.

Furthermore, and likely unknown to M&S practitioners, NPR 7150.2 states:

> *In this directive, "software" is defined as (1) the computer programs, procedures, rules, and associated documentation and data pertaining to the development and operation of a computer system… (2) all or a part of the programs, procedures, rules, and associated documentation of an information processing system… (3) program or set of programs used to run a computer… (4) all or part of the programs which process or support the processing of digital information… (5) part of a product that is the computer program or the set of computer programs. This definition applies to software developed by NASA, software developed for NASA, software maintained by or for NASA, COTS [commercial off-the-shelf], GOTS [government off-the-shelf], MOTS [modified off-the-shelf], OSS [open source software], reused software components, auto-generated code, embedded software, the software executed on processors embedded in programmable logic devices…, legacy, heritage, applications, freeware, shareware, trial or demonstration software, and open-source software components.*

This means that NPR 7150.2 requirements can apply to commercial tools [e.g., Mathworks Simulink®] or other reused tools when those tools are integrated into a NASA system or an engineering workflow.

Finally, note that NASA-STD-7009B is referenced in the NPR (in section 4.5.6 of NPR 7150.2), stating that "The project shall verify, validate, and accredit software models, simulations, and analysis tools required to perform qualification of flight software or flight equipment. [SWE-070]. *Note: Information regarding specific V&V techniques and the analysis of M&S can be found in NASA-STD-7009B and this Handbook.*" In NPR 7150.2, a software engineering (SWE) number designates a requirement.

Neither NASA-STD-7009B nor this Handbook provide *specific V&V techniques* (other than a few simple examples contained in this Handbook) but leave such details to discipline-specific recommended practices. Also note, while the definitions of V&V in NASA-STD-7009B and NPR 7150.2 are similar, they differ in context. NPR 7150.2 defines software verification and validation; NASA-STD-7009B defines M&S V&V. Software V&V primarily targets the correctness and usefulness of the software's functionality. Software V&V also assesses non-functional aspects of the software such as quality attributes (e.g., reusability, maintainability, testability, interoperability). M&S V&V primarily targets the correctness and credibility of an M&S to produce results acceptably similar to an RWS for an intended use. As an example, for an M&S to be valid, its results must meet the documented acceptance criteria defining what is considered a favorable comparison with appropriate referent (or RWS) data (per [M&S 43]). Software V&V and M&S V&V do overlap when the M&S is implemented in software since M&S correctness and credibility depends upon the functional correctness and the functional fitness for intended use of the software implementation.

4.8 Program/Project Management and Delegated NASA Technical Authority Responsibilities

Throughout NASA-STD-7009B, there are a number of explicit and implicit responsibilities on either program/project management or the delegated NASA Technical Authority, which addresses the check-and-balance structure in the NASA organization (see NPD 1000.0, NASA Governance and Strategic Management Handbook, and NPR 7120.5). These are consolidated in Table 4, Program/Project Management and Delegated NASA Technical Authority Responsibilities as Stated in NASA-STD-7009B, for easy reference. On the other hand, the requirements in NASA-STD-7009B are addressed to "the responsible party," since it is likely different for each M&S. Table 4 includes the program/project management responsibility to identify "the responsible party" for each requirement.

As the breadth of application and discipline best practices are applied to NASA M&S applications, delegated NASA Technical Authorities and their delegates face challenges carrying out the approval processes listed in Table 4, especially as it relates to tailoring the standard, evaluating, and approving equivalency of alternative standards or deconflicting requirements. Each of these has the potential to influence the information documenting the M&S credibility and risk components. In all approval steps, technical authorities and their delegates are responsible for ensuring the intent of the standard, i.e. that the credible practices and communications of evidence remains sufficient to reduce the risk associated with M&S influenced decisions. It is recommended that as such needs are evaluated for approval, the delegated NASA Technical Authority and their delegates consider what discrepancies or weakness may arise in the expected reportable evidence and do these influence the eventual credibility or risk in using the M&S results. Similarly, maintaining the implicit risk reduction of the communication emphasized in the standard, such as the communication process leading to the discussion around the cause of gaps between achieved and threshold credibility factors, should also play a role in approval decisions as these promote customer developer understanding and expectations of the eventual M&S risk products. It is recommended that the delegated NASA Technical Authority and program management authority err on the side of deferring to the requirements in the standard should alternative processes be unclear on how they satisfy the intent of the standard to reduce M&S risk.

Table 4—Program/Project Management and Delegated NASA Technical Authority Responsibilities as Stated in NASA-STD-7009B

Topic	Sections	Requirements	Rec. Sections	Program/ Project Management Responsibility	Delegated NASA Technical Authority Responsibility
Acceptance Criteria	1	-	-	Defines	Approves
Required application of NASA-STD-7009	1.2	-	-	Specifies	-
Tailoring	1.3	-	-	Documents	Assures intent of standard risk reporting products are maintained and approves
Non-Use of latest cited Applicable Documents	2.1.1	-	-	-	Approves
Requirement Conflicts; Precedence over VCSs	2.4.2	-	-	-	Resolves conflicts

Topic	Sections	Requirements	Rec. Sections	Program/ Project Management Responsibility	Delegated NASA Technical Authority Responsibility
Responsible Parties	4	-	-	ID's & Document	-
Intended Use/ Criticality / Critical Decisions / M&S In Scope	3.2 (Critical Decision), 4.1	[M&S 40], [M&S 6]	-	ID's & Document	IDs & Document
Level of Formality	4	-	-	ID's & Document	IDs & Document
Objectives & Req'ts for M&S Products (metrics, acceptance criteria, reporting)	-	[M&S 42], [M&S 43], [M&S 44]	-	-	Assure appropriate outcomes
Mission Success Criteria	3.2 (Mission Success Criteria)	-	-	Deem achievement	-
Waivers	3.2 (Waivers)	-	-	Accepts	Concurs / Approves
Use Assessment	4.3.1	[M&S 23]	-	-	Assures appropriate outcomes
Credibility Assessment (Capability and Results)	4.3.6	[M&S 31], [M&S 48]	4.2.1.8-4.3.8.4 (thresholds)	-	Establishes & assures appropriate outcomes
Risk	4.3.8.9	[M&S 39]	-	Is informed by	-

5. MODEL AND SIMULATION (M&S) LIFE CYCLE PROCESSES

As introduced in section 4.6, this Handbook is structured according to the M&S life cycle, as defined in NASA-STD-7009B, Appendix F. This section of the Handbook discusses each of the seven phases and what is best accomplished in each of them. Due to the variety of M&S, the consequences and constraints of implementation and their application, the tasks stated for each phase may be delayed to later phases, spread across multiple phases, or updated in later phases. The tasks in the phases described throughout section 5 and the requirements or recommendations (R/r's) depicted in Appendix A are to take this potential flexibility into account.

Note: It is usually best to accomplish and document a given task, requirement, or recommendation as early as possible/practical in the M&S life cycle and update the products/results as development or use continues to remain current and relevant. This includes the archival of the requisite products at the end of each life cycle phase.

5.1 Model Initiation (Pre-Phase A)

The beginning of any model development effort stems from consideration of the RWS and the possibilities of what an M&S can do for it.

To start the M&S life cycle, the following are needed:

a. Information about the RWS, either as:

(1) Existing.

(2) Proposed Changes to the Existing.

(3) Imagined (but not yet existing).

b. The possibility that an M&S can help (inform) the RWS (situation).

With this information, additional details about the RWS (situation) and how an M&S might benefit the RWS are gathered and formulated.

5.1.1 Accomplishing the Model Initiation Phase

With the available information, this Phase accomplishes the following:

a. Gathering additional RWS information.

b. Establishing an initial statement of Intended Use for the M&S.

c. Performing a Criticality Assessment.

d. Justifying an M&S is needed, preferred, or appropriate.

5.1.1.1 Gathering RWS Information

Information about the RWS is needed to give direction to, and provide a basis for, M&S development. Specific parts of the RWS such as RWS elements/components (or aggregations thereof), subsystems, and aspects/attributes to analyze are identified, along with the possible boundaries between the RWS and its environment. When the RWS is imagined, this information may need to be synthesized from the ConOps (concept of operations), mission NGO's (needs, goals, and objectives), or DRM's (design reference missions).

Note: The concept of Data Pedigree, the first factor of the Capability Assessment, is directly influenced in this early phase of simulation and AI model development. Any data gathered, used, altered, or discarded during the course of model development [i.e., from Model Initiation (Pre-Phase A) through Model Construction (Phase C)] has the potential of positively or negatively influencing Data Pedigree (see Appendix D.3).

5.1.1.2 M&S Statement of Intended Use

Once a basic amount of information about the RWS and the specific problem, issue, or aspect to apply an M&S is known, the initial statement of Intended Use [M&S 40] for the M&S may be documented. The Intended Use is the expected purpose and application of an M&S and is best established early in the M&S development life cycle, even though it will likely be modified as the M&S evolves, to serve as the primary guide to M&S development and use. As such, the statement of Intended Use is general, not detailed, in nature, and is intended to be short and concise. The Intended Use includes:

a. A general statement of what the M&S does, which may include a description of results expected from the M&S.

b. General limits of the M&S due to:

(1) What is modeled (i.e., RWS type/class, aspect(s)/attribute(s), context/environment(s)).

(2) The presumed or chosen modeling methods or mechanisms (if any are prescribed at this point).

c. Generalized functions or results expected from the M&S, including:

(1) Providing information for use in RWS analysis (that is otherwise performed manually or by another M&S).

(2) Depicting (visually or otherwise) the RWS (either statically or dynamically).

(3) Predicting how the RWS will behave or react (generally after application of initial or boundary conditions).

(4) Training personnel to operate, maintain, or repair an RWS.

(5) Repeatability of results or playback of results as applicable.

(6) Start or restart of M&S at arbitrary point in scenario as applicable.

(7) Monte-Carlo or parallelized execution of the M&S as applicable.

(8) Interaction of the M&S with operators. This includes:

A. Human-in-the-loop, e.g., simulators.

B. RWS hardware such as hardware-in-the-loop; e.g., system integration labs.

C. RWS measurements; e.g., digital twins

D. Other live-virtual-constructive (LVC), potentially with execution in real-time.

(9) Whether the M&S is centralized or distributed.

d. Specific portions or aspects of an RWS or set of RWSs, to include, such as:

(1) The application or set/range of applications.

(2) The portion(s) of a larger system or type/class of system of that portion.

(3) The attributes of the system modeled.

(4) The context, environment, or set/range of environments surrounding, interacting with, or influencing the RWS.

e. Specific situations or conditions that define or influence the RWS design or as-built configuration, operation, maintenance, repair, storage, or testing. These include:

(1) Project/program phase(s).

(2) Operational phase(s).

(3) Environmental conditions.

(4) Scenarios, including operational, maintenance, repair, testing, inspection, and storage.

Note: The Intended Use of an M&S communicates this information in an inclusive manner, and provides a reference for possible future use of the M&S. When a project develops a reusable M&S (but may not be a user of the M&S), the Intended Use of the M&S documents the potential and permissible uses of the M&S to guide both its representation of the RWS and the generality of its implementation to the identified uses. For reusable M&S, intended uses may be described more broadly than intended uses distinct to a project.

Clarity of Intended Use may be enhanced by appending specific cases or situations to be avoided when using the M&S.

The Intended Use is established early in M&S development, during the “Model Initiation” Phase, to guide development, and may be substantiated or revised throughout M&S development, depending on specific choices made during design and implementation, or depending on results from the M&S during V&V testing. The Intended Use is also used in establishing the permissible uses of an M&S.

5.1.1.3 Performing the Criticality Assessment

The criticality assessment [M&S 6] ensures communication of the following:

a. The consequences to human safety or RWS success criteria.

b. The degree to which M&S results influence all related decisions.

This initial assessment needs to be accomplished in pre-Phase A of the model's development. In part, the outcome of this assessment drives decisions that span the rest of the M&S life cycle and higher-level program/project planning and resource allocations. Appendix D of NASA-STD-7009B suggests a risk-based approach to the criticality assessment, including a representative risk matrix that may be adopted or tailored to meet the needs of the program/project.

5.1.1.4 Justifying the M&S Approach

Another key part of the "Model Initiation" Phase is determining whether an M&S is the best approach. There are potentially many reasons why an M&S should not be developed or used, such as the following:

a. Not enough is known about the RWS to either build or validate an M&S.

b. Not enough resources (time, labor, or budget) are available for M&S development or use to meet the needs of the RWS.

c. Other methods to achieve the same objective are better, less expensive, easier, or more readily available, such as:

(1) Other existing or competing M&S.

(2) Other analytical methods or tools, such as mathematical or statistical methods, which could be considered models, too.

(3) Physical experiments.

(4) Using the RWS.

Factors to consider for each alternative method are in Table 5, Alternative Method Assessment Factors.

Table 5—Alternative Method Assessment Factors

Criteria	Consideration
Resources	Have sufficient resources (e.g., money, time, people, equipment, computing resources including run-time) been allocated for development and use of each method?
Availability	What is the readiness of each method for use? This depends on the current life cycle phase of each method and the demand on the method in that phase.
Hazards	What are the physical hazards associated with developing or using each method?

Risks	What are the risks associated with developing or using each method?
Uncertainties	What uncertainties are known and manifest in each method?
Practicality	Is it realistic to assume each method can be developed or used when needed?
Validation	Is each method, or can each method be, sufficiently accurate and precise?

The decision to produce or acquire an M&S, and subsequently use an M&S, is made when the M&S advantage exists for any of the needed RWS information.

The outcome of the criticality assessment described in section 5.1.1.3 partially informs these factors for the M&S option. Specifically, understanding the consequences of the decision and the M&S influence over it may drive other potential requirements on the M&S, including but not limited to:

a. The level of effort and rigor to be applied throughout the M&S life cycle.

(1) Which requirements and recommendations from NASA-STD-7009B will be in play and enforced.

(2) The required formality for the M&S processes.

(3) The technical reviews required, as well as the scope/depth of these reviews.

(4) Target M&S credibility scores.

b. The requirements for M&S developers and users, in terms of knowledge, skills, and experience.

Some requirements on the M&S, even if only preliminary, are generally needed at this point to completely address the factors listed above, e.g., the requirements for M&S accuracy and uncertainty, or the requirements for the limits of operation. These requirements will likely drive cost and schedule in all the other M&S life cycle phases, potentially steering the outcome of the trades between the M&S and other potential solutions.

The purpose of the M&S is another key consideration, which is at least partially defined in the statement of Intended Use, but also includes the type of knowledge desired about the RWS, of which there are two basic types, “Scientific Knowledge” and “Technical Knowledge.” “Scientific Knowledge” is acquired to improve human understanding of the universe or a portion or segment thereof. With this type of knowledge, there is no interest in influencing the RWS or applying the acquired knowledge to practical or earthly (real world) applications.

“Technical Knowledge” is acquired to create a new or modified RWS, or to create new or modified processes in operating (or maintaining) the RWS. This type of knowledge is the most common type acquired from M&S results in engineering and applied physical sciences.

(Note: As a matter of current interest, and as a current example, the scientific studies of global warming/climate change and the effects of human activities on this phenomenon could be

classified as either "Scientific Knowledge," "Technical Knowledge," or a combination of both, depending on one's point of view. If the acquired knowledge leads to intentional changes to human activities, these studies could be classified in part as "Technical Knowledge.")

5.1.1.5 Empirical Data Availability/Assessment

After the type of needed knowledge about the RWS of interest is determined (or decided), the ability of physical experiments and their expected empirical results in producing all or part of the needed knowledge needs to be evaluated. Operations data and real-time measurements may also be sources of empirical data for an M&S. These experiments, data, and results may negate the need for M&S completely, be embedded in the M&S, supplement M&S results, be used as M&S input data, validate M&S results, reduce the epistemic uncertainty of the RWS or its environment, or improve characterization of the aleatory uncertainty of the RWS or its environment. The program and project may need to assess plans for activities, procedures, and systems to produce, gather, or process new empirical data for M&S use. This assessment may include trade-offs between physical experimentation (or other measurement activities) and M&S. For example, a combination of wind tunnel experiments (physical experiments) and computational fluid dynamics executions (M&S) are often necessary to create high-fidelity aerodynamic databases for aircraft and launch vehicles.

NATO AVT-297 recently published work on model validation hierarchies to assist in planning of uncertainty reduction activities under constrained budgets. Relevant NASA sources can be found at https://ntrs.nasa.gov/citations/20220014628 and https://ntrs.nasa.gov/citations/20220018336. The methods described in these publications apply to other M&S lifecycle phases also but have utility in early planning.

Note: Data used in the development of the model, embedded in it, or used to validate the model are subject to the Data Pedigree assessment. Data used as (run-time) input to the model are subject to the Input Pedigree assessment.

5.1.2 Products and Expected Outcomes of the Model Initiation Phase

Once an M&S is determined necessary (justified), the Model Initiation Phase concludes with a baseline of the following products/artifacts:

a. Statement of Intended Use.

b. Outcome of the Criticality Assessment.

c. Preliminary RWS information to begin developing the model.

d. Preliminary modeling approaches, including justification of pursuing model development over alternative methods.

e. RWS empirical data for any of the following:

(1) Inclusion in the model.
(2) Use as input to the model.

(3) Use in validating the model.

Initial model development plans include the preliminary identification of activities, procedures, or systems to produce, gather, or process new empirical data for the M&S. All information and data collected or developed in this phase, with knowledge of information and data not yet known or obtained, provide the basis for development plans of the M&S.

5.2 Model Concept Development (Phase A)

The Concept Development Phase matures (and potentially finalizes) existing information about the RWS and defines/refines concepts and methods to include in the proposed M&S. Throughout the course of this phase, questions about what to model are answered, RWS data are gathered to support model development, and trade studies are conducted on modeling methods (approaches), model complexity, fidelity, accuracy, and resources. The phase ends with a chosen direction of modeling method(s), a conceptual design, high-level model (and model testing) requirements, and preliminary model system architecture from which to commence detailed model design.

The Model Concept Development Phase uses the products from the Model Initiation Phase:

a. The Statement of Intended Use.

b. Outcome of the criticality assessment.

c. Initial model development plans.

d. Preliminary RWS information.

e. Preliminary modeling approaches.

f. RWS empirical data identification and production.

These are further developed into concepts, information, or specifications to continue model development and enable detailed model design.

5.2.1 Accomplishing the Model Concept Development Phase

The Model Concept Development Phase uses the products from the Model Initiation Phase to continue model development and enable detailed model design, including:

a. RWS refinement and data collection.

(1) With respect to the RWS or its environment, identify needed activities to obtain new empirical data, reduce epistemic uncertainty, and improve characterization of aleatory uncertainty.

b. Model concept trade studies and selection.

c. Establishment of preliminary model requirements and specifications, including:

(1) RWS elements and behaviors to represent.

(2) Relevant RWS characteristics that are subject to M&S-based analysis [M&S 10].

(3) Specific RWS scenarios for empirical validation.

(4) For software M&S, computational resource constraints and runtime limits.

Note: As development progresses, it is expected that any of the products previously produced (at this point, the products from the previous phase, e.g., the Statement of Intended Use) may need to be refined or updated.

5.2.1.1 Real World System (RWS)/Environment Specification and Data Acquisition

The first task in refining the understanding of the RWS to model is determining the physical and conceptual elements to include. Figure 2, Overall Representative System Expanded Diagram (SLS example), is an expanded diagram of the overall representative system, which is the subject of the model, and helps to clarify these elements in context. Depending on the part or portion of the RWS modeled, providing a series of these diagrams at increasing levels of detail can be helpful in understanding the scope of the model in relation to the overall system. This also includes distinguishing elements of the RWS to model from the relevant aspects of the environment that influence it (Figure 3, Distinguishing the RWS and its Environment), which includes all types of events (e.g. physical, chemical, behavioral, other) and sequences of events considered for inclusion in the model. A conceptual element is one that can influence the system in some physical way or respond to events or activities occurring in the system in a conscious manner, with a goal or purpose in mind (Oberkampf, W. L. and Roy, C. J., 2010). An example of a conceptual element is a human operator, who is modeled as part of a system. A human interacting with or within a system is often referred to as an “actor.”

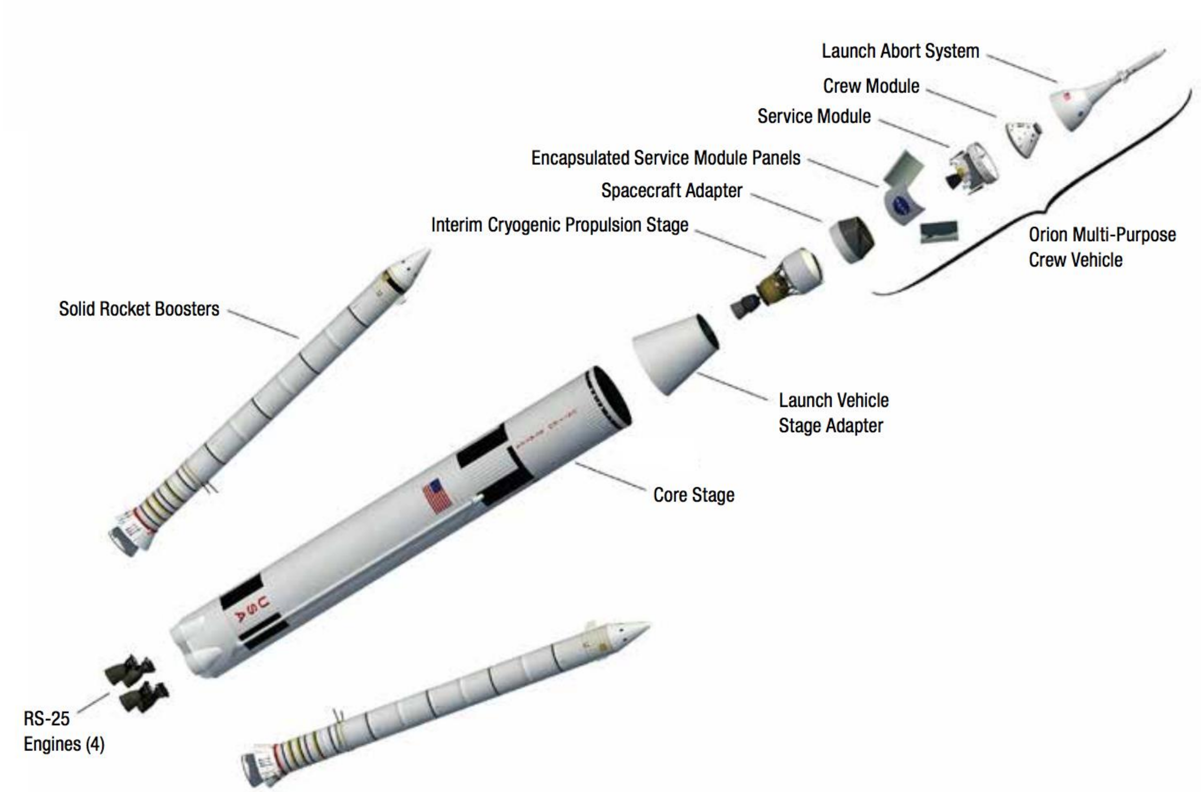
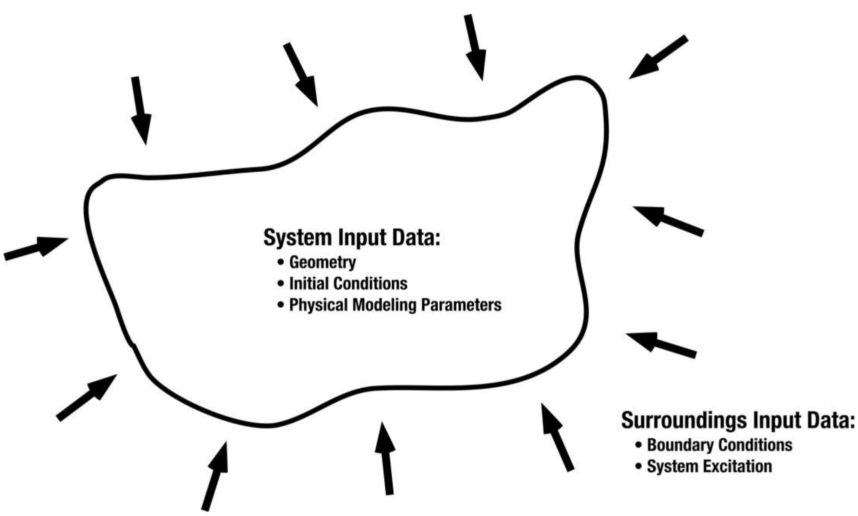


Figure 2—Overall Representative System Expanded Diagram (SLS example)



Types of information in the system and surroundings; from Oberkampf, W. L. and Roy, C. J. (2010)

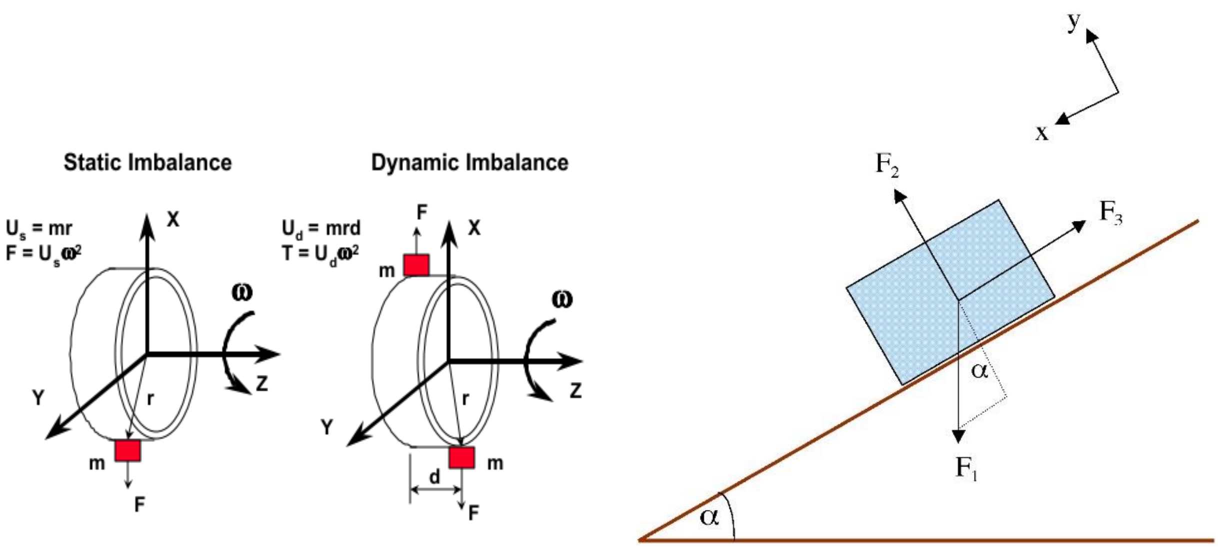
Figure 3—Distinguishing the RWS and its Environment

The Phenomena Identification and Ranking Table (PIRT) is often used in the nuclear industry as a formal and rigorous method to perform this task (Shaw, et al. 1988). In classifying these elements, the following ground-rules apply:

a. The environment may or may not vary with respect to time or spatial location, but it also may or may not be affected by the RWS.

b. The RWS is typically (but may or may not be) influenced by the environment.

One common method for depicting the conceptual elements and the interrelationships to include in an M&S is by drawing a conceptual model (also referred to as a free body diagram in some disciplines), as shown in Figure 4, Conceptual Model Example (Free Body Diagram). A key part of the modeling process is deciding what to include or not include in the model, which is part of the concept of abstraction. This task requires engineering judgment, often the most difficult aspect of this life cycle phase, and is to be justified and documented. The DoD DEM&S provides some background information on conceptual model development (Special Topic: Conceptual Model Development and Validation, VV&A Recommended Practice Guide, https://www.cto.mil/sea/vva_rpg/).



(a) momentum wheels (b) inclined plane

Figure 4—Conceptual Model Example (Free Body Diagram)

Once the physical and conceptual elements designated as part of the RWS to model are identified, information and data for these elements relevant to the planned M&S need to be acquired, including the interactions between each RWS element. Where information and data are absent, the program or project may need to plan activities (e.g., research, physical experiments) to generate the missing information and data. Additionally, the M&S development team needs to work with RWS data acquisition teams (e.g., for ground facilities, flight tests, or mission operations) to define the referent validation data that will be obtained from ground tests, flight tests, or operations. This also likely supports the needs of detailed model design. Data included in the model becomes subject to the Data Pedigree assessment, which will eventually include data design considerations (see section 5.3.2.c of this Handbook).

5.2.1.2 Model Concept Trade Studies and Selection

With a more complete understanding of the RWS to model, concepts are traded with respect to modeling methods (approaches), model complexity, fidelity, accuracy, resources, and, as applicable, runtime. The following overarching concepts may be considered:

a. "Everything should be made as simple as possible, but not simpler." Albert Einstein

b. *"The predictive power of a model depends on its ability to correctly identify the dominant controlling factors and their influences, not upon its completeness."* This is an adaptation of Occam's Razor to modeling by Oberkampf and Roy.

c. "Model building is the art of selecting those aspects of a process that are relevant to the question being asked." – Holland, JH (1995) Hidden Order. Addison-Wesley, New York, USA.

In determining the required level of fidelity and complexity of a planned M&S, as well as the required accuracy or uncertainty bounds in M&S results, the following should be considered and evaluated:

a. Programmatic considerations (constraints):

   (1) Model development-use schedule including derived constraints on M&S computational cost.

   (2) Available versus required hardware, software, and tools.

   (3) Available versus required personnel.

   (4) Available versus required budget.

b. RWS considerations:

   (1) The variety of combinations of RWS environments and scenarios to include.

   (2) Risk that each environment-scenario pair or group poses to the success of the RWS.

   (3) Complexity of each phenomenon covered by the planned M&S.

   (4) Level of coupling between different phenomena.

   (5) Availability of data to support model development.

c. Modeling considerations:

(1) Abstractions (including simplifications) in the model – e.g., physical laws or processes ignored or adjusted.

(2) Basis of empirical or phenomenological model of RWS, as opposed to that of physical law or explanatory model; observed behaviors mimicked vs. detailed processes described.

(3) Complexity of the model, e.g.:

A. Complexity of excitation equations.

B. Mathematical sub-models used to complement sets of equations in the main model – e.g., analytical equations, ordinary differential equations (ODEs) and partial differential equations (PDEs) for constitutive properties of materials and fluids, PDEs for fluid turbulence modeling.

C. Estimated level of temporal and/or spatial discretization needed to achieve defined M&S objectives and requirements. Model testing is required to confirm the adequacy of these initial estimates.

d. Intended use considerations:

(1) Repeatability or determinism of results.

(2) Playback capability (e.g., inject inputs from data recordings of prior flights, human-in-the-loop simulators, or hardware-in-the-loop tests).

(3) Start or restart at arbitrary point in scenario (e.g., vehicle trim, or checkpoint-restart).

(4) Multi-execution automation, scripting, or programming such as for Monte-Carlo analysis or parallelization of scenarios.

(5) The category and role of the M&S in the LVC taxonomy.

(6) Need for real-time execution.

(7) Whether the M&S is centralized or distributed, singular or coupled, and the conditions for component model information exchange.

5.2.1.3 Preliminary Model Requirements and Specifications

With the physical and conceptual elements in section 5.2.1.1 and the modeling trade decisions in section 5.2.1.2, the following activities are performed to develop preliminary model requirements and specifications:

a. System and Scenario Abstraction.

b. Coupled Model Specifications (e.g., coupled physics, chemistry, behaviors, etc.).

c. Nondeterministic Specifications (identifying and specifying which model aspects and results from the above activities are to be nondeterministic).

d. Identifying and specifying the units of measurement and coordinate frames used to define all quantities (e.g., inputs and outputs) of the M&S, especially those quantities exchanged between M&S components.

The resulting information provides the basis for model requirements and specifications.

5.2.1.3.1 System and Scenario Abstraction

System and Scenario Abstraction identifies the events and sequences of events that may have an effect on M&S goals. These events and sequence of events include those that occur, or may occur, under all possible normal and abnormal operating conditions, hostile environments, and human or accidentally caused failure modes. The following are to be considered and may be subject to the Data Pedigree assessment:

a. Definition of what the M&S is to do:

(1) How RWS is to be shown, depicted, or represented in the M&S.

(2) Questions the M&S is designed to answer.

(3) RWS information to be provided by the M&S for its analysis.

(4) Prediction(s) or determination(s) to be made about RWS that is to be modeled, including how it will behave or react (generally after application of initial and boundary conditions and system excitations).

(5) Required uncertainty bounds or accuracies with all model elements, inputs, or responses.

(6) How the M&S will be used (e.g., training for the RWS, analysis or testing of the RWS). This includes the intended-use considerations in section 5.2.1.2 (repeatability, playback, arbitrary start or restart, centralized vs. distributed, real-time execution, etc.)

(7) How personnel will be trained in operating, repairing, or maintaining the model.

(8) RWS applications, sets of applications, or range of applications to be covered by the planned M&S.

(9) RWS aspects or attributes to be covered by the planned M&S.

(10) Context, environment, or sets and ranges thereof surrounding, interacting with, or influencing RWS that are covered by the planned M&S.

(11) RWS life cycle phases applicable to the M&S.

(12) RWS scenarios, including operational, maintenance, repair, testing, inspection, and storage, covered by the planned M&S.

(13) Cases where the planned M&S should not be used, with supporting rationale.

(14) Cases where the planned M&S should only be used with caution and in conjunction with information provided by empirical methods or another M&S.

b. Definition of model application domains, use domains, and expected behavior characteristics:

(1) Anticipated application domains.

(2) Anticipated validation domains.

(3) Customer-defined responses from the M&S (sometimes referred to as System Response Quantities (SRQs)).

(4) Expected prediction accuracy requirements.

(5) Implementation strategies and methods (e.g., Code) and quality assurance activities.

(6) Adequacy of numerical error estimation techniques.

(7) Existing capabilities for model element representation (e.g., capabilities of grid or mesh generation, or other methods to establish configurations and sizes of discrete parts or elements of the RWS), i.e., determining if they are sufficient or will new ones be needed.

(8) Existing, upgraded, or new experimental facilities and test apparatuses for M&S validation.

(9) Existing versus new or upgraded validation metric operators.

(10) Propagation of input uncertainties through the M&S and the expected resulting output uncertainties.

(11) Alternative M&S or contingency plans to revise or supplement M&S or its results if the need arises.

5.2.1.3.2 Coupled Physics Specifications

Coupled Physics includes any connections or interactions between physical (or chemical) processes that are part of the M&S. For each identified coupling, the type and options for the levels of coupling are to be identified for later consideration (i.e., in the Model Design Phase). Even if the coupling, coupling type, or level of coupling is unlikely to be included in the model, it should be identified and documented during the Conceptual Development Phase. The level of coupling is often a trade between M&S efficiency (practicality, affordability, minimum computation time) and M&S accuracy and fidelity.

If and when a coupling phenomenon is identified after completion of the Conceptual Development Phase, M&S development during later phases are to pause and the Conceptual Development updated to include the respective new coupling phenomenon. More often than not, additional branches of connected elements, events, and event series will result.

5.2.1.3.3 Nondeterministic Specifications

Many models include aspects or elements that are nondeterministic in nature, i.e., where a range of values may occur, as opposed to a deterministic (single) value. These are to be identified for further consideration as to how best to present them. These elements may include M&S input data, defined processes in M&S, and output data produced by the M&S. For stochastic situations, some variation of Monte Carlo analysis is accomplished using random numbers (variates) with the M&S.

Examples of possible nondeterministic elements or situations (see Figure 5, General Model Diagram with Nondeterministic Elements) that show the propagation of input uncertainties to obtain output uncertainties (Oberkampf, W. L. and Roy, C. J., 2010) include:

a. Variations in material properties.

b. Variations in manufacturing and assembly processes.

c. Lack of information about hardware storage conditions, damage, or use history.

d. Variations in the latencies of internal information exchanges or physical interactions within the RWS.

e. Uncertainties about the operating environment.

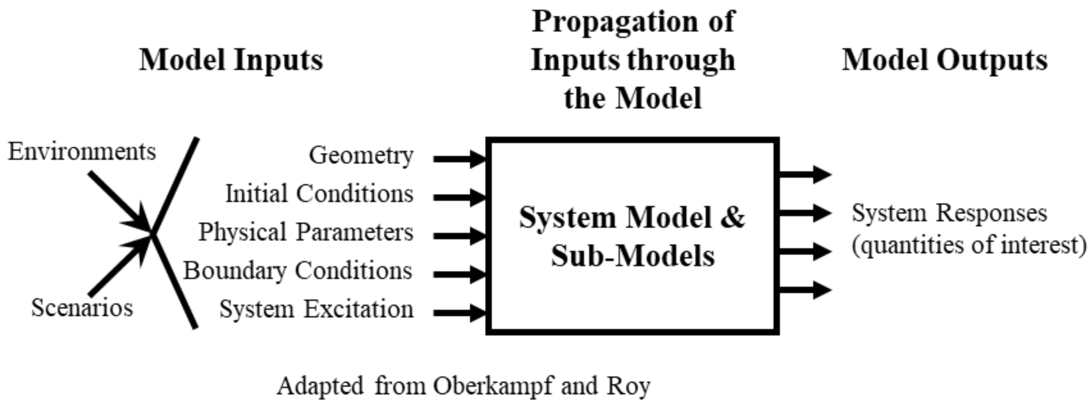


Figure 5—General Model Diagram with Nondeterministic Elements

Nondeterministic solutions/results are often presented as probability distributions or single values with each having an associated error, tolerance, or uncertainty. Consideration should be given to classifying uncertainties (associated with or used to present nondeterministic solutions) as aleatory or epistemic, which are to be presented and later quantified separately.

Mathematical representation and propagation of errors, uncertainties, and probability distributions are not to be performed during Conceptual Development, but deferred to later phases (i.e., in design, testing, or use).

5.2.1.3.4 Units of Measurement and Coordinate Frames

Units of measurement and coordinate frames are essential elements of the definition of quantities in the M&S and help relate those quantities to the RWS. Identifying the units and coordinate frames are, at a minimum, necessary to communicate meaning and magnitude of M&S quantities. However, they are also essential when either the RWS or the M&S uses mixed units or multiple coordinate frames. Operational or engineering conventions of the RWS may introduce mixed units or multiple coordinate frames. For example, there are multiple conventions in aviation for expressing the speed of an aircraft including Mach number, knots (nautical miles per hour), fps (feet per second), or meters per second. Another example is when the RWS is composed of elements from different countries. Elements from the United States may use United States customary units (colloquially referred to as English units) while elements from France may use SI units (Système international d'unités). Likewise, an M&S can introduce mixed units or multiple coordinate frames when reusing models. Reused models may use older conventions for units or coordinate systems or may use the preferred conventions of the original developers. Whenever mixed units or multiple coordinate systems are used, it is important to identify and document any needed conversions or translations between conceptual elements of the M&S.

5.2.2 Products and Expected Outcomes of the Concept Development Phase

The following items should be produced when the Concept Development Phase is complete:

a. Initial Conceptual Model (including all constituent parts, their interconnections, and functions as needed).

b. Model Assumptions.

c. Concept of Operations.

(1) Determination of model users and associated use cases.

(2) Extent of linkage or coupling of this M&S to other M&S (if the M&S is to be part of a coupled system with other M&S's [or will be] or embedded in a larger [representational or analytical] system).

d. High-level model requirements and specifications (as outlined in section 5.2.1.3).

e. Model verification plans, including initial verification requirements.

f. Model validation plans, including:

(1) Initial validation scenarios, including:

A. The RWS or referent used to acquire empirical data.

B. Specific RWS behaviors and scenarios to validate.

(2) Preliminary validation requirements.

(3) Anticipated model applications.

(4) Anticipated validation domain.

5.3 Model Design (Phase B)

M&S Design is the typically iterative process of creating the detailed, verifiable, and validated specification of an M&S for an intended use, using the relevant information regarding the RWS, the conceptual model, and any other defined objectives/criteria.

Note: Any changes to relevant portions of the RWS may invalidate the model design.

The Model Design Phase uses the following products from earlier M&S life cycle phases:

a. Statement of Intended Use (current working version).

b. Outcome of the Criticality Assessment.

c. High-level requirements (needs, goals, objectives, drivers, constraints), such as:

(1) Aspects of the RWS the M&S is to represent.

(2) The problem(s) the M&S is to solve.

(3) The decision(s) the M&S is to support.

d. Concept of Operations.

(1) Determination of model users and associated use cases.

(2) Extent of linkage or coupling of this M&S to other M&S (if the M&S is to be part of a coupled system with other M&S's [or will be] or embedded in a larger [representational or analytical] system).

e. Conceptual/Mathematical Models

(1) May be presented in multiple formats or combinations thereof, typically:

A. Block diagrams.

B. Flow charts.

C. Mathematical equations.

D. Pseudo-code.

(2) May often represent the intended M&S architecture, which usually will be refined throughout the design process.

f. Verification plans and requirements.

g. Validation plans, requirements, scenarios, etc.

Note: Model design may have dependencies to project activities to obtain new empirical data as identified in the Model Initiation Phase (Pre-Phase A) or Model Concept Phase (Phase A). Those activities may be planned and tracked separately from M&S development activities.

5.3.1 Accomplishing Model Design

The design process for an M&S can be the same as, or very similar to, the design process for an RWS, as detailed in relevant NASA requirements documentation, e.g., the Systems or Software Engineering procedural requirements or handbooks. For either the RWS or M&S, the design process begins with the set of high-level requirements and goals, the concept of operations, and the (*intended or initial*) architecture (the *realized* architecture may differ), which may be provided in a variety of formats, e.g., formal "shall" statements, descriptive narratives, block diagrams, flow charts, drawings, or models. The M&S design process then addresses/includes:

a. M&S composition and function:

(1) What the M&S is to include or do to represent the RWS.

(2) How well the M&S is to perform its function.

(3) How, and under what conditions and assumptions, the M&S is to be used.

(4) What the M&S architecture (general form) will be. This may be driven by modularity, scalability, and integration or latency challenges, to name a few examples.

Note: As indicated in section 4.7, specific additional requirements applicable to M&S implemented in software are found in NPR 7150.2, NASA Software Engineering Requirements. These requirements are to be considered part of the high-level requirements (constraints) in effect at the start of the design phase.

b. M&S Requirements and Structure, independent of the tools and methods employed:

(1) The high-level requirements, concept of operations and architecture are logically decomposed into a well-defined collection of lower-level elements (e.g., modules, blocks, and components) and their associated functions, behaviors, and derived requirements/goals. Each element in the resulting hierarchy will interface to one or more of the other elements, and potentially interface to the "M&S environment," which may include, for example, the M&S operator(s), the data sources, other M&S, and the CM system.

(2) The hierarchical structure, internal/external interfaces, functional/logical behaviors, and derived requirements are transformed into a detailed, implementable, and verifiable design specification that enables M&S construction (implementation).

c. M&S Design Considerations:

(1) Per best engineering practices, when a requirement is written, it is essential to document the rationale for the requirement (backwards traceability) and the method by which the requirement will be verified (forward traceability). Capturing the traceability is critical in the event of changes to any higher-level requirement(s) from which the given requirement was derived. In the extreme, the rationale for the requirement may disappear entirely, and the requirement may be deleted. More often, the requirement remains but is modified in some way (as well as, possibly, its verification method).

(2) It is likely, if not intentionally so, that multiple design solutions will emerge at any given level of decomposition, requiring a trade study to decide which solution to pursue. Document the trade spaces (including relevant elements of previous phase trade studies, if any), and document the rationale for the

outcomes, as any of the rejected design solutions may have to be revisited later (e.g., if the M&S is invalidated).

(3) Choices in model design (component representations or constructs) are to be made to minimize model-based uncertainties, as much as practical at this point of the M&S Life Cycle, understanding that model testing is eventually required to fully accomplish this objective.

(4) One key to successful design is determining when the hierarchical decomposition process has reached the point where further decomposition and specification starts to over-constrain the model construction process. Knowing when to stop designing, when enough decomposition and specification is sufficiently complete to confidently proceed to the construction phase, will always be a matter of discretion. A simple and obvious analogy is that no architect or home designer specifies the location of every nail. To attempt to do so would require more effort than could ever be justified, nor is there much chance that every contingency arising during the home construction could be anticipated. Some decisions are simply best left to the carpenter. Similarly, then, for the M&S, some decisions are best left to the model construction phase. It is to be expected that those decisions (and their rationales) will be documented as model construction proceeds.

Note: Once the model design is complete, and before the model is implemented, a review of the model design (i.e., conceptual validation) is to be accomplished with the customer. This is required to meet Level 1 credibility assessment for validation (NASA-STD-7009B, Appendix E). See section 5.3.3.

5.3.2 Considerations in Model Design

Examples of issues/questions often addressed during M&S design include:

a. If not specified in advance, can any existing models, or parts of models, be re-used?

b. When data is required for model development, but no source is specified, what are possible sources for such data?

c. What are the data design considerations for use in the model?

(1) Type (nominal, ordinal, interval, ratio, Boolean, categorical).

(2) Accuracy, Precision, Uncertainty.

(3) Units.

(4) Coordinate system(s): measured in, observed from, represented in and used by interfacing projects or programs.

d. Are unit conversions or coordinate transformations required across model interfaces?

e. What kind of user interface (e.g., command line vs. graphical user interface (GUI)) is needed?

f. What are the relevant CM systems (e.g., for input data, for model elements)?

g. What tools or systems (e.g., computer architectures, COTS software, implementation tools) are to be used/supported during model construction and use? Any system or tool used in model development or use is best evaluated before model construction (Phase C) for their potential influence on the M&S and results credibility.

h. For the case of coupled models, will the implementation be a single executable or multiple executables with appropriate mechanisms for data exchange?

i. For either linked or coupled models implemented as multiple executables, what is the data exchange mechanism?

(1) File exchange.

(2) Inter-process communications on a single workstation.

(3) Network communication between separate workstations.

j. What other user-level functionality (e.g., visualization and plotting, data input/output [I/O] including file formats, error/event logging, saving state of model mid-run, changing parameters mid-run, re-starting from saved or altered state) is either required or desirable?

k. What kind of future scalability is likely? How can the M&S be modularized to facilitate these future changes/upgrades?

l. Are provisions for automation of multiple model runs to be included, e.g., to accommodate Monte-Carlo analysis or structured DoE?

5.3.3 Model Concept (Design) Validation

All of the work performed in the above sections are documented and reviewed prior to the start of model construction. The objectives of this review, which, if favorable, will constitute conceptual validation, are to show that the model design (including the conceptual model) does the following:

a. Acceptably reflects the RWS (including all internal functions, logic, and behaviors), to the extent this can be shown before empirical validation.

b. Satisfies the stated Intended Use of the M&S, as well as all other high-level requirements (needs, goals, objectives, drivers, constraints).

c. Is implementable and verifiable.

d. Is consistent with the available budget and schedule.

5.3.4 Products and Expected Outcomes of the Model Design Phase

The following items should be produced when the Model Design Phase is complete:

a. The validated model design, including all conceptual models depicting, as needed:

(1) The constituent parts.

(2) The interconnection of parts.

(3) The functions of each part.

b. Model architecture.

c. Model requirements and specifications.

d. Model verification requirements.

e. Model validation requirements.

5.4 Model Construction (Phase C)

Model Construction is the process/activity of implementing a model as defined by its requirements, specifications (some of which may be embodied in a conceptual model/diagram) and intended use. The Model Construction Phase uses the following products from earlier M&S life cycle phases:

a. Statement of Intended Use.

b. Outcome of the criticality assessment.

c. The validated model design (including all conceptual models depicting constituent parts, their interconnection, and functions, as needed).

d. M&S architecture, requirements, and specifications.

e. Verification requirements.

f. Validation requirements.

Note: Model construction may have dependencies to project activities to obtain new empirical data as identified in the Model Initiation Phase (Pre-Phase A) or Model Concept Phase (Phase A). Those activities may be planned and tracked separately from M&S development activities.

5.4.1 Accomplishing Model Construction

The M&S Construction Phase begins with a complete and detailed design specification and proceeds, using tools and methods specific to the type of M&S being developed, until the design is implemented and ready to be tested (V&V). In practice, the lines between construction and testing often blur, in the spirit of "build a little, test a little." For example, both agile development (scrum/sprint sequences) and spiral development are approaches to software development, which take different approaches to the "build a little, test a little" approach. The best approach to take is a judgment call, but factors like complexity, customer diversity, team composition, and precision of requirements can strongly influence the choice.

Arguably, such an incremental approach is the best approach to development, as verifying relatively small numbers of requirements at lower levels of assembly of any product is far more tractable than verifying all requirements at once, at the highest level of assembly. For the M&S, the lower levels of assembly are the individual elements, entities, modules, blocks, subroutines, etc., that compose the end-to-end M&S. That said, testing the complete, end-to-end M&S and verifying all requirements is the ultimate objective of the Test Phase.

Independent of the specific tools and methods employed, the M&S construction process necessarily encompasses the following general activities:

The latest NASA Systems Engineering Handbook (SP-2016-6105, Rev 2 – section 3.7, pages 33-34) provides an excellent summary of some key M&S Construction decisions (replacing the word "system" with the phrase "M&S").

a. Detailed planning of construction.

   (1) The sequence of M&S element development and integration.

   (2) The decomposition of M&S elements.

   (3) The assignment of M&S elements to development team.

   (4) Periodic/regular deliveries to interested stakeholders.

b. Pulling together the model construction system (hardware, software, and tools). Multiple instances of the model construction system may be necessary depending on the staff on hand and delegation of component level construction.

c. Building model components (or sections). Specific implementation mechanism choices are made at this point in model development.

d. Incrementally testing lower-level components, so as to find component modeling issues as early as possible, and preclude finding them during the (final, integrated) Test Phase.

e. Assembling and integrating lower-level V&V M&S elements into the desired end product of the higher-level M&S. This includes preparing the M&S integration strategy, performing detailed planning, obtaining M&S elements to integrate, confirming that the lower-level or component M&S elements are ready for integration, preparing the integration environment, and preparing M&S support documentation.

f. Integration of model components (sections), as necessary, to build the overall model.

(1) At least some initial (unofficial) testing of component interfaces should be exercised to ensure they function.

(2) Consider placeholder elements to use as proxies for undeveloped M&S elements.

g. Generating a specific M&S through buying, making, or reusing lower-level components to satisfy the design requirements. This includes building or coding the M&S; reviewing vendor technical information; inspecting delivered, built, or reused M&S elements; and preparing M&S support documentation for integration.

h. Documentation for guiding model use, including user requirements, such as the following:

(1) The architecture required for using the model.

(2) Setting up and using the model.

(3) Limits of model use (as constructed, due to implementation choices or mechanisms).

(4) Required training for model use.

(5)

5.4.2 Considerations in Model Construction

To allow the greatest flexibility in model implementation, the model design (produced in Phase B) should contain conceptual models, or diagrams, and requirements or specifications that are not implementation specific. It is during implementation (construction) that specific choices are made, such as what tools (e.g., COTS packages) or specific implementation methods (e.g., the specific method of numerically integrating differential equations) to use in the final model. All tools used in the construction of the model are to be evaluated (e.g., with respect to their effect on the model, its use, and the results from model use) as part of the V&V credibility factors, as discussed in NASA-STD-7009B, Appendix E.3.
Attention is also to be given to distribution of the model for future purposes (including testing) or to customers (including cost and delivery mechanisms).

Per recommendation 4.2.2.c, an important consideration for model construction is error detection and reporting (and possibly resolution). Depending on the consequences of incorrect results, the M&S should detect errors that adversely impact the validity or credibility of results. M&S response to detected errors may depend on ability to recover without compromising results and whether intended use requires continued operation with best effort. Whether or not the M&S can recover from the error, it should log or report the error for users. Developers implementing M&S in software should also consider adopting defensive programming techniques to assure detection of issues impacting the validity and credibility of results. These techniques include but are not limited to:

a. Performing integrity and quality (e.g., bounds) checks on inputs, resident data, and arguments.

b. Checking pre-conditions on entering units (e.g., functions).

c. Checking post-conditions before returning values.

d. Checking for errors on return of library calls.

e. Capturing signals, exceptions, or other faults (e.g., floating point exceptions).

f. Checking for exceedance of the M&S limits (e.g., exceeding the independent variable range of a lookup table).

g. Checking for domain, pole, and range errors before or after calling math functions.

h. Checking for divide by zero.

i. Checking conditions that increase numerical error or uncertainty of results (e.g., hitting maximum iterations before solution convergence, input values approaching a point of high sensitivity [e.g., approaching $\pi/2$ for tangent function]).

In general, M&S developers should proactively include checks or assertions for any conditions or values that may invalidate or compromise the M&S results. When performance is important to meet constrained runtimes, the M&S developer may implement some or all of these checks as conditionally compiled code (i.e., surrounded by compiler preprocessor conditional statements).

5.4.3 Products and Expected Outcomes of the Model Construction Phase

The following items should be produced when the Model Construction Phase is complete:

a. Model Implementation (Development) System (e.g., specific computers and software).

b. Model (from Model Design).

c. User's Guide (1st Draft).

d. Verification Test Procedures and Test Suites.

e. Validation Test Procedures and Test Suites.

5.5 Model Testing and Release (Phase D)

The Model Testing Phase of the M&S life cycle checks the model (and M&S system) to determine if it meets all requirements and operational intensions, and, if successful, releases the model for use. This phase uses the latest updates to the following products:

a. Statement of Intended Use.

b. Outcome of the Criticality Assessment.

c. M&S architecture, requirements, and specifications.

d. Model (implemented from Model Design Phase).

e. User's Guide (1st Draft).

f. Verification Test Procedures and Test Suites.

g. Validation Test Procedures and Test Suites.

Note: During the course of V&V, include the evaluation of any tools for model construction or use for their potential influence on M&S results credibility.

5.5.1 Activity Precedence for Model Testing and Release

This phase of the M&S life cycle distinctly and separately accomplishes the activities of verification, (empirical) validation, and model release for use.

These activities are shown in the preferred order of occurrence, as the most effective and, arguably, most efficient. While model release is obviously the last activity in the development of an M&S, the accomplishment of verification and (empirical) validation are often reversed or (somewhat) combined. Validating the model without prior verification:

a. Assumes the model is working correctly.

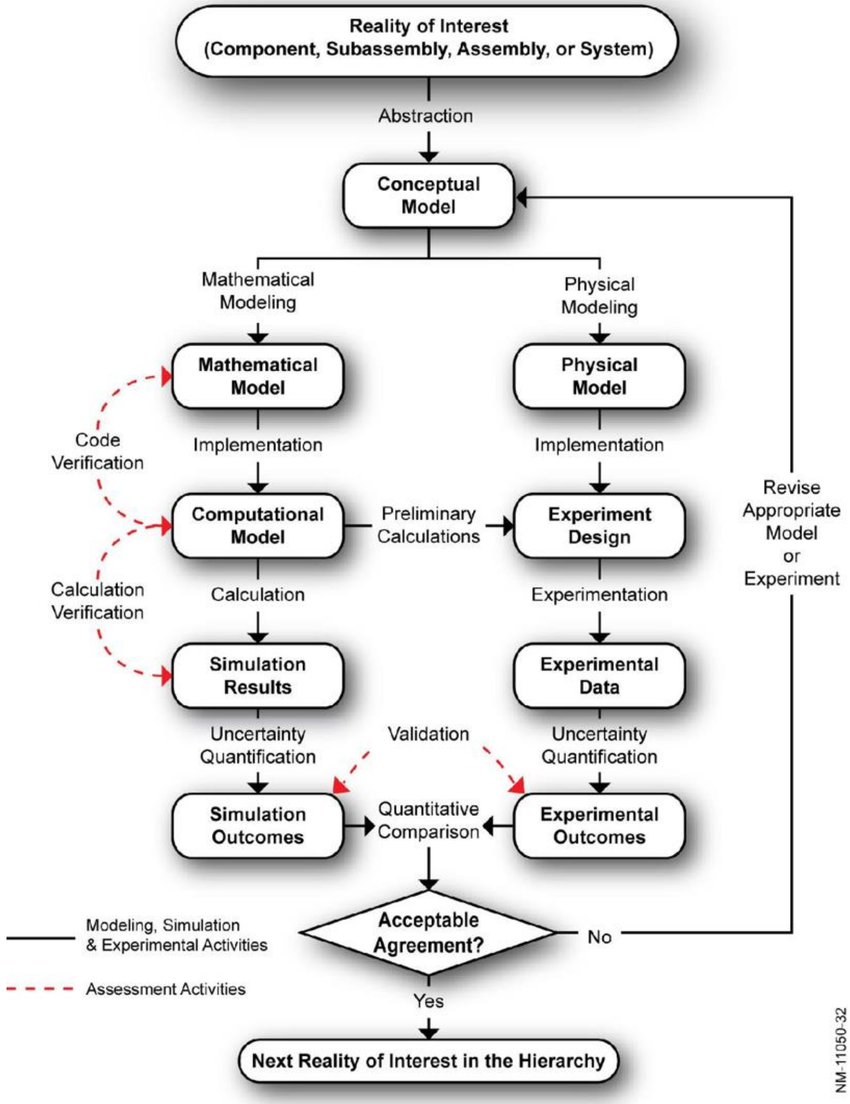
b. Will not establish a reliable basis that the model will work for any scenario other than those used for validation.

c. May lead to an erroneous conclusion regarding the cause of an apparent model-referent mismatch, as determined by validation, specifically that the model design (or concept) is at fault when the mismatch is actually due to errors in model implementation (construction).

d. May result in falsely concluding that the model is valid when, in fact, all model errors have not been identified and accounted for as part of the model-referent comparison.

Attempting empirical validation prior to full model verification is a highly risky practice, should be avoided, and induces inefficiencies requiring repeated V&V cycles. With some types of models, the process of validation includes some parameter calibrations, which are dependent on a fully functional and verified model.

Figure 6, General Flowchart for M&S Development, which is taken from the *ASME Guide for V&V in Computational Solid Mechanics*, depicts the preferred sequence of events, with verification (shown separately as code verification and solution verification) down the left-hand side of the flowchart, preceding empirical validation (simply labeled as validation) at the bottom-center of the flowchart. The activities down the right-hand side of the flowchart are related to conducting physical experiments with the RWS (or an acceptable surrogate) to obtain the referent (data) necessary to accomplish empirical validation. Quantification (or characterization) of uncertainties is a key step in each of the parallel activities (model verification and physical experimentation).



Guide for V&V in computational solid mechanics. American Society of Mechanical Engineers, ASME Standard V&V 10–2006, New York, NY.

Figure 6—General Flowchart for M&S Development

Whenever possible, incremental V&V of models is best accomplished in parallel with the development, integration, and test of the RWS. Waiting until later in the RWS development life cycle, when the RWS is at higher levels of assembly and many complex interactions are present, poses more significant challenges to model testing. Insight regarding behaviors and properties of the RWS, and regarding the corresponding representation in the models, is more readily obtained when model V&V occurs at lower levels of assembly. The trust gained in knowledge of these behaviors and properties allows them to be “locked down” in the model as the model itself grows in size and complexity to match the RWS, generally simplifying subsequent V&V efforts tied to tests performed at larger RWS levels of assembly. The generic model V&V flow illustrated in

Figure 6 will then, in practice, be executed multiple times throughout the RWS life cycle, in parallel with its own Integration and Test (I&T) flow.

5.5.2 Model Verification (What is Verification?)

Model verification is 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. Code (software) and solution (calculation) verification are key aspects of the overall verification process. The M&S can be considered verified when the following three conditions are satisfied:

a. The (computational) model meets its specifications. These (software) specifications start with the conceptual/mathematical model and include additional requirements for functions, e.g., user interfaces and data I/O.

b. All significant sources of numerical errors inherent in the (software) implementation are identified, quantified, and within assigned upper bounds.

c. Evidence is gathered to address the following, or justify why they are not addressed:

(1) The actions demonstrating, and the results showing, the model functions as intended, as specified by the conceptual model or other model requirements document.

(2) The processes used in, and the results obtained from, quantifying numerical errors resulting from the software algorithms.

(3) The processes used to quantify numerical errors resulting from factors such as sampling or quantization, the step size chosen for the numerical integration of differential equations in a time-domain simulation, convergence tolerances or iteration limits for iterative methods, and the methods and intervals used for interpolation of model parameters, and the results.

5.5.2.1 Accomplishing Model Verification (What is Done in Verification?)

The following are needed to begin model verification:

a. The defined objectives and requirements for verification [M&S 43(b)].

b. The model design (specifications, requirements, conceptual models, etc.).

c. The implemented model.

The first task during verification is to establish the official (formal) plans and procedures for verification, which may be provided by the Model Design or Construction phases (Phases B or C). These expound upon what is needed to accomplish verification and what exactly will be accomplished (inspected, demonstrated, or tested) during verification. The actual task of verification then confirms the implemented model includes or addresses the objectives, requirements, and design.

5.5.2.2 Considerations in Model Verification

The term "verification" is generally accepted to refer to two related processes: Implementation (code) verification; and solution (calculation) verification. These processes are designed to demonstrate that the implemented model (software) performs correctly.

a. Implementation (Code) verification is the process by which the structure, flow, and fidelity of the (computational) model are demonstrated to be correct with respect to its specifications. The first step is to ensure, structurally, by inspection that the model contains all the components, or elements, it is supposed to have, and nothing more. Verification of computational model structure or flow is performed first by code tracing and then unit testing, i.e., running the M&S through a series of low-level tests, and comparison of the implemented (coded) model with the conceptual/mathematical models. Some, if not all, of the tests should be re-run any time the model (code) is changed (a process known as regression testing) either to fix errors or to add new functionality to ensure the changes do not introduce new errors. This topic also addresses the issue of model (code) coverage, i.e., the percent of relevant logical branches within a model (code) tested for proper numerical and logical execution, as well as the handling of "hard" errors such as floating-point exceptions. The latter is an example where the code can produce unexpected results, including halting execution, due to misevaluation of conditions (branches, loops) at the boundaries of the condition parameters.

b. Solution (Calculation) verification encompasses efforts to assess (computational) model correctness and numerical accuracy, most importantly when closed-form solutions are unavailable and approximations are required to solve the problem at hand. Independent of whether the solution is closed-form or approximate, finite precision effects such as underflow/overflow, rounding, and loss of precision will contribute to accuracy/uncertainty in the results and needs to be evaluated. For the case of approximate solutions, additional sources of error come into play. The process of identifying and evaluating the contribution of these sources typically involves a systematic sensitivity analysis of parameters and behaviors associated with the design and implementation of the model, as opposed to the parameters and behaviors associated with the RWS itself. Examination of the latter is, instead, the focus of Sensitivity Analysis (section 5.6.3.1.3). Examples of model-specific parameters to be varied during the solution verification process include iterative solver tolerances and sampling intervals (e.g., temporal sampling for integration of differential/difference equations in time-domain models, or spatial sampling for geometric mesh and ray-trace models). Ideally, these parameters are varied until the solution is stable, i.e., it appears to have converged at an asymptotic limit. It is important to understand that stability/convergence of the numerical solution is no guarantee that the model meets accuracy requirements – this cannot be determined until Empirical Validation (section 5.5.3) is complete. The final choice of the model-specific parameters generally involves a trade between accuracy and run-time efficiency, where it is not uncommon for a non-minimal numerical error to be accepted to achieve an acceptable run-time. In such a case, the difference between the apparent stable (asymptotic) solution and the solution obtained using the accepted values of the model-specific parameters is factored into Uncertainty Characterization (section 5.6.3.1.2).

Note: An additional context for solution verification is not associated with M&S development testing (verification), but rather with M&S use (or execution) and is commonly called input verification (section 5.6.2.2).

5.5.2.3 Products and Expected Outcomes of Model Verification

The positive outcome from verification is that the model is implemented according to design, including the following:

a. Everything that is needed is in the model (per the Design) and nothing more.

   (1) Constituent parts (model elements/functions) are included.

   (2) Parts are "interconnected" appropriately (by Design).

   (3) Nothing extra is in the model that is not in the Design.

   (4) Logic paths work per Design.

   (5) Functions work per Design.

b. Verification Scenarios (above) work as expected.

   (1) Results produced correctly for defined (test case) scenarios.

   (2) Numerical errors are identified/quantified/bounded.

   (3) Uncertainties are identified/qualified/quantified within defined expectation.

If deficiencies are found during verification, re-work or even re-design of the model may be needed.

Once verification is successfully completed, the domain of verification is to be documented per [M&S 16] and a suite of plans, procedures, and test cases can be archived for use in future regression testing of the model from the perspective of verification.

5.5.3 Model Empirical Validation

Empirical validation is 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, using pre-defined and accepted requirements as to what constitutes "favorable agreement." Correlation and calibration (tuning) of the model are key aspects of the empirical validation process. Ultimately, and most importantly, validation determines the accuracy, precision, bias, sensitivity, and uncertainty of the model, and ensures these metrics satisfy any and all associated requirements. This is based on comparisons between the simulation (computational) results and some corresponding referent. Validation also addresses uncertainties arising from both experimental and modeling (computational) procedures. The term "uncertainty" is used in a general sense and can comprise a number of related terms, including the concept of error. The M&S is considered validated when the following conditions are satisfied:

a. The (computational) model meets pre-defined criteria for matching RWS behavior (i.e., within accepted bounds of uncertainty).

b. The uncertainties in the model, and propagated into model results, are understood.

5.5.3.1 Accomplishing Model Empirical Validation

To begin model validation, the following are needed:

a. The defined objectives and requirements for validation [M&S 43(c)], including the criteria for RWS similarity (i.e., criteria for achieving "favorable comparison" between model and referent, when performing empirical validation).

b. The implemented model (preferably verified; see section 5.5.2).

c. Test cases (scenarios) from the RWS, or an acceptable referent thereof, with requisite data. The scenarios to be identified, addressed, and taken into account include:

(1) Normal operating environment(s).

(2) Emergency, abnormal, and off-design operating environments.

(3) Testing environment(s).

(4) Expected inputs and excitations to the RWS being modeled.

(5) Possible unintended and unexpected inputs and excitation to the RWS (including human operator inputs and human-in-the-loop influences and effects).

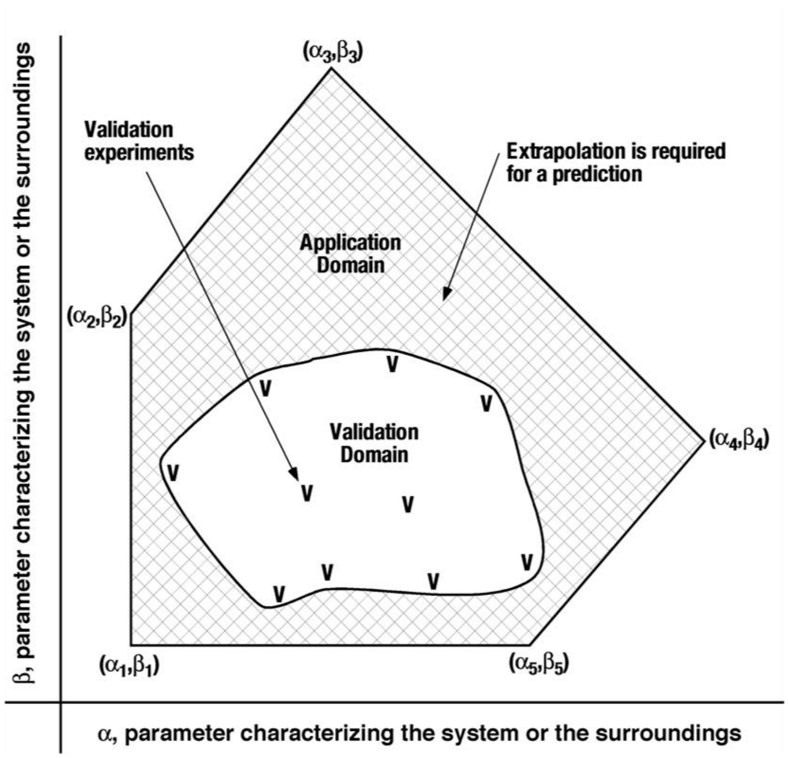
(6) Non-operational environments and processes for the RWS, including inspections, repairs, maintenance, storage, transport, and testing.

(7) Operational processes.

(8) The transitions between the different environments, processes, excitations, and inputs listed above.

Identifying, addressing, and accounting for all scenarios (relevant to the Intended Use) for empirical validation testing are critical because the RWS will almost certainly be exposed to and influenced by a wide variety of environments as well as internal and external excitations and inputs. These environments, inputs, and excitations can be, and often include those that are unexpected, unintended, or are far outside or far more severe than normal operating conditions.

The RWS scenarios established for, and then executed during, empirical validation testing in turn determine and establish the "Domain of Validation," notionally illustrated in Figure 7, Domain of Validation, also known as the "Validation Domain" [M&S 18].



(*Trucano, T. G., M. Pilch, and W. L. Oberkampf (2002). General Concepts for Experimental Validation of ASCI Code Applications. SAND2002–0341, Albuquerque, NM, Sandia National Laboratories)*

Figure 7—Domain of Validation

As previously shown in Figure 6, there are two parallel processes that precede (empirical) validation. One is the verification of the model, or the M&S, and the other is verification of empirical methods and processes to acquire resultant data from the referent, where both include the verification of resultant data and their associated uncertainties or errors. Section 5.5.2 describes the requirements for model (or M&S) verification.

As previously stated, empirical validation includes the correlation and calibration sub-processes. These are depicted in Figure 8, Empirical Validation Process, Including Correlation and Calibration. NASA-STD-7009B provides the following definitions:

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

b. 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.

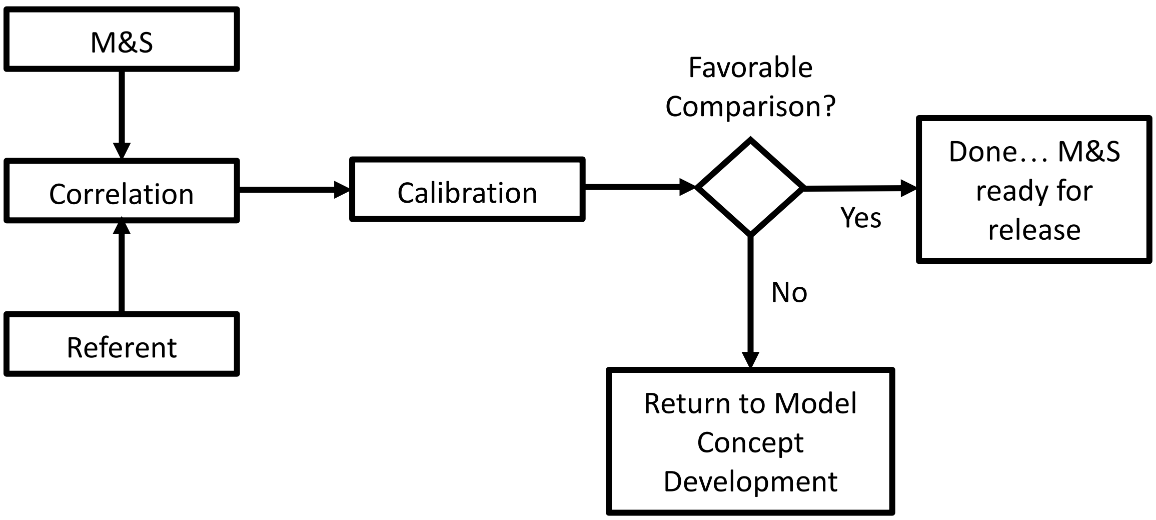


Figure 8—Empirical Validation Process, Including Correlation and Calibration

Assuming the model is verified, if the correlation and calibration efforts cannot achieve the required match between model and referent, then the model form itself is suspect, necessitating that the conceptual model, its assumptions, and design be revisited. Obtaining good correlation between predictions from the M&S and measurements from the RWS (or independent predictions in some cases) over the widest range of parameter space, initial conditions, boundary conditions, and modes of operation is desirable to maximize confidence. This is not always possible or affordable. The pre-defined acceptance criteria for the M&S [M&S 43] identifies the conditions the program/project is to satisfy to achieve a favorable comparison between the M&S and the referent.

Once validation is successfully completed, the Domain of Validation is to be documented per [M&S 18] and a suite of plans, procedures, test cases, and referent data can be archived for use in future regression testing of the model from the perspective of validation.

5.5.3.2 Considerations in Model Empirical Validation

A review of the validation process and results should address the following questions:

a. What was the referent?

b. What are the significant similarities and differences of:

(1) The referent with respect to the RWS?

(2) The M&S with respect to the referent?

(3) The M&S with respect to the RWS?

c. Is the data obtained from the referent compatible with or convertible to data required to correctly validate the M&S?

d. Which uncertainties in the simulation and referent, e.g., numerical error, input data variability, measurement error, were considered when comparing the simulation output to the referent?

e. What model or input data calibration (tuning, adjustment) was performed so that agreement between the referent and the predictions met the requirements for the intended use of the model? Was this justified?

Note: Calibration can be difficult for complex simulations, e.g., those for flight. There could be hundreds of changes needed to tune the model to match the RWS. Conversely, one change could make a good match for one scenario but could cause an issue for other scenarios. For some modeling techniques, such as ML surrogates, it is possible to overfit the validation data such that the model only produces good results within the validation set but poor results for other inputs. One can avoid overfitting by using only a portion of the validation data to tune the model and retain the rest of the validation data to validate the tuning. It is also possible for tuning to result in a model with bias if the validation data itself exhibits bias and is not fully representative of the application domain.

When reviewing the validation activities for a given M&S, identifying known differences between the referent and the RWS is important (see Figure 9, RWS to Referent Similarity). A referent may be the RWS to which the analysis is directed, or it could be a similar or analogous system, whereby the closeness of the referent to the RWS becomes pertinent. The source of referent data obtained empirically from an experiment, a series of experiments, simulated RWS, sections or segments of an RWS, actual RWS in simulated environments, or RWS in the actual environment needs to be verified with the same level of rigor used to verify the M&S. Appendix B of this Handbook provides further details describing the importance of referent similarity to the RWS. For a detailed case study to illustrate the importance of properly verifying the empirically acquired data used for model validation, refer to Oberkampf and Roy (2010), 11.2 through 11.4.

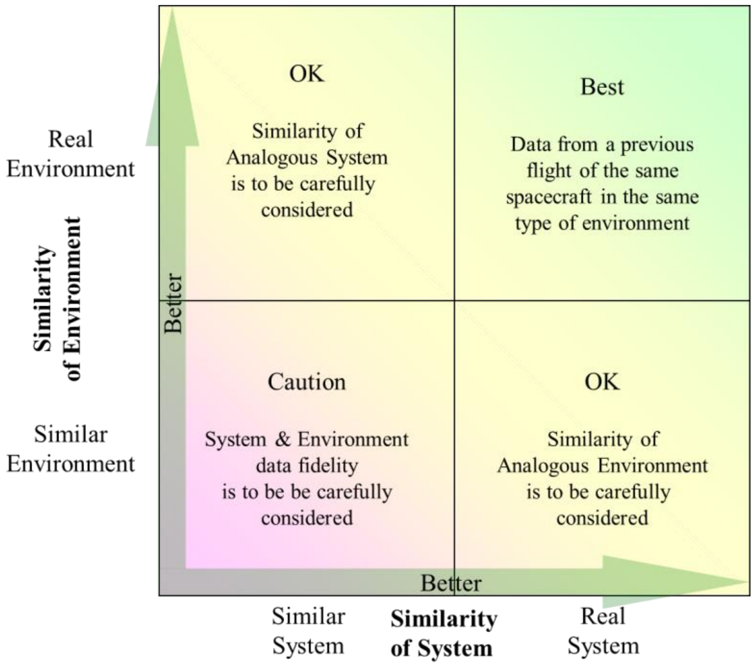


Figure 9—RWS to Referent Similarity

An essential outcome and product of empirical validation is the criteria used to determine and then establish whether or not an M&S is a "good," "good enough," or "value-added" tool for the project or program it is supporting. To be effective, these criteria are to be established at or before the start of empirical validation, so that the actual validation testing processes and resulting data and information do not lead to biases in deciding what is acceptable versus unacceptable, especially for situations where resource constraints can influence key decision makers.

Validation also addresses uncertainties arising from both experimental and computational procedures. The term "uncertainty" is used in a general sense and can comprise a number of related terms, including the concept of error. These uncertainties or errors are also used in establishing the criteria for RWS similarity, as they ultimately provide the quantitative information necessary to determine whether or not the M&S is sufficiently similar to the RWS being modeled. Establishing allowed or acceptable uncertainties is also to be completed before validation testing is started to avoid the decision-making biases mentioned in the preceding paragraph.

5.5.3.2.1 Uncertainty/Error Bounds for Empirical Validation

The uncertainties or errors associated with data and results acquired from both the M&S and referent are necessary for proper and complete empirical validation of an M&S. These provide the quantitative information necessary to determine whether or not the M&S is sufficiently similar to the RWS being modeled. As a first step, visual inspection of the graphically plotted data from an M&S with uncertainty bounds should significantly overlap with the related referent data with uncertainty bounds, for the model to be presumed valid. While this can be acceptable for a quick look when comparing data, statistical tests (e.g., the t-test) provide more reliable and objective indicators of acceptability, especially for plots with limited overlap. This comparison is notionally depicted below for two scenarios.

Figure 10, Simple Comparison of Uncertainty Bounds Between M&S and Referent, shows the simplest case where the uncertainty bounds about a single referent (data) response quantity are compared against the uncertainty bounds about the corresponding M&S response quantity. The M&S would likely be considered valid, certainly by casual inspection. In the case of demanding statistical criteria, e.g., "99 percent confidence that the error is less than 1 percent," then perhaps not.

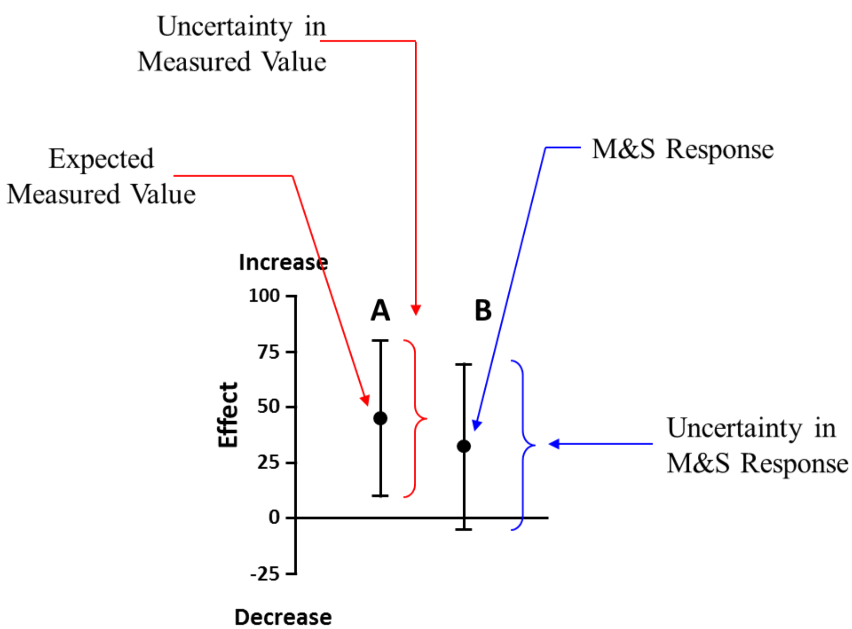


Figure 10—Simple Comparison of Uncertainty Bounds Between M&S and Referent

At best, the outcome of the scenario depicted in Figure 10 is "point validation," as it is simply the favorable comparison between a single model response to a single measurement, for a common set of inputs (conditions). The objective of empirical validation is to establish the Domain of Validation, as discussed in section 5.5.3.1, which is a region in parameter space enclosing all points at which validation is successful. This is accomplished by varying the inputs to both the test and the model, obtaining the corresponding responses for all inputs, and assessing validity of the model at each point. Figure 11, Comparison of Uncertainty Bounds Between M&S and Referent over Range of Input Values, depicts this scenario, for the case of a single model/test input, and illustrates that the overlap between the uncertainty bounds can change as the input varies over its range. Over most of the range in this example, the uncertainty bounds for the M&S lie within the empirical uncertainty bounds. At the far-right end of the data set, the uncertainty bounds for the M&S exceed the upper bound of the data. Over this upper range, the acceptance or use of model results warrants more caution.

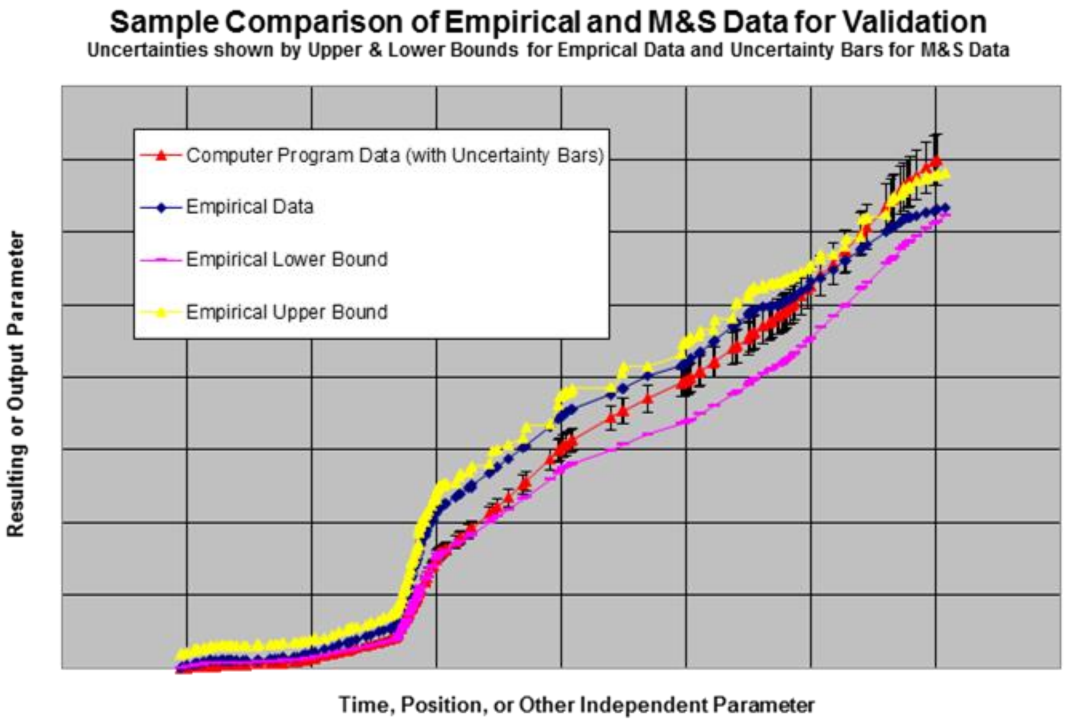


Figure 11—Comparison of Uncertainty Bounds Between M&S and Referent over Range of Input Values

For the M&S, it is absolutely essential for uncertainties (or error bounds) of all input data, the propagation of uncertainties through M&S execution, and uncertainties of intermediate and end-resultant data produced during M&S execution be documented and fully traceable to the governing equations and solution methods incorporated in the model. It is also essential for the governing equations and solution methods, with their derivations, to be documented; these include equations that are derived from governing equations to model the uncertainty propagations.

For empirically acquired data from the referent, it is absolutely essential for uncertainties (or error bounds) of all data obtained from instrument measurements and the propagation of uncertainties through conversion and manipulation of instrument measurement data to usable data for M&S validation be documented or fully traceable to the governing equations and solution methods. As with M&S uncertainties, it is also essential that the governing equations and solution methods, with their derivations, be documented. These include equations that are derived from governing equations to model the uncertainty propagations.

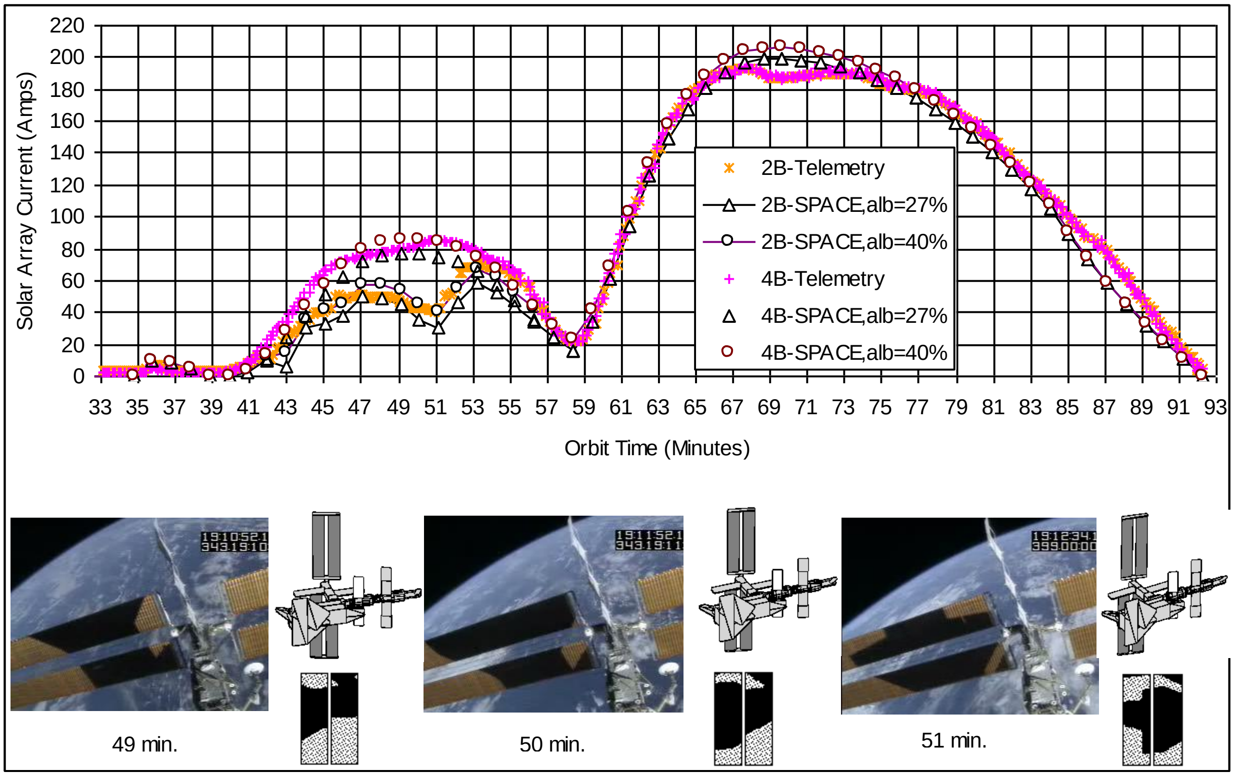
5.5.3.2.2 Limits of Validated Model

The Domain of Validation is the region enclosing all sets of model inputs for which the M&S's responses compare favorably with the referent. Ideally, the limits of model use are to be contained within this domain, but there are many situations, mainly in exploration, and research and development activities/projects/programs, where a model is to be used for an RWS that is, or is operating, outside this domain. When an M&S is used in scenarios outside its Domain of Validation, the model fidelity as governed by the underlying physics, solution methods, all error sources, and performance of the respective model, plus the associated uncertainties of resultant data produced by the M&S, becomes increasingly important. In these situations, expanding the Domain of Validation to the maximum possible extents through further validation testing should be pursued at every opportunity.

The final Domain of Validation, initially described in section 5.5.3.1, shall be established and documented at the completion of empirical validation of the M&S. The scenarios described in this section and selected for validation testing establish this Domain of Validation. The initially prescribed Domain of Validation will likely be revised due to the iterative process associated with empirical validation. The tracking and documentation of these revisions are essential to correct and complete empirical validation of an M&S, which includes a traceable documentation trail or records that others can use effectively for future projects, programs, and activities supported by M&S.

Note: If the use of a model predicts beyond the range of currently existing empirical data and is subsequently proven correct with new 'operational' data, then the domain of validation for that model can be justifiably updated. A model developed for long-term use on an RWS will likely have its domain of validation updated. See the corresponding note in section 5.6.4 regarding retaining the relevant data from M&S Use to accomplish the extended model validation activities.

As an example of empirical validation, accurate prediction of the power available from the solar arrays on the International Space Station (ISS) requires modeling of the location and amount of shadowing on the arrays. Analysis tools are available to predict array shadowing and its impact on the solar array current; these tools include several key assumptions, such as lower fidelity geometry models of the ISS, minimal Sun subtense angle effects, and minimal reflected energy from adjacent hardware. With these differences between the model and the RWS, the model's results were compared with on-orbit flight video stills and flight telemetry, showing the model produces a good representation of the RWS (Figure 12, ISS Power Prediction).



(NASA TM-2002-211715, IECEC-2002-20113, "Comparison of ISS Power System Telemetry with Analytically Derived Data for Shadowed Cases", Fincannon, H. James)

Figure 12—ISS Power Prediction

For this example, the M&S would be assessed to satisfy all requirements to achieve a Level 4 credibility score for the validation factor: (1) M&S results compare favorably to measurements on the RWS in its operating environment; (2) validation points completely span the domain of operation for the RWS; (3) favorable comparisons are obtained for all response quantities.

5.5.3.3 Products and Expected Outcomes of Model (Empirical) Validation

The positive outcomes from validation are:

a. The model behaves similarly to the RWS.

   (1) The operating conditions for which the model is determined acceptable when in use (e.g., domain of validated use).

   (2) Within defined uncertainty/error bounds.

b. The validated uses of the M&S are determined [M&S 18].

If deficiencies are found during validation, re-work or even re-design, and likely re-accomplishment of V&V, of the model may be needed.

5.5.4 Assessing Model and Simulation (M&S) Capability: An Essential Element of the Overall M&S Credibility

Prior to the release of NASA-STD-7009B a comprehensive M&S Credibility Assessment was performed near the end of the M&S Use phase. This assessment evaluated a set of factors relevant to both the M&S Development and M&S Use phases, and the outcome of the assessment was reported to the decision makers along with the M&S Results and other critical supporting information.

Following the release of NASA-STD-7009B, per [M&S 18] a M&S Capability Assessment is to be performed following the activities of the M&S Development phase, prior to Model Release and any Model Use. This assessment only includes factors relevant to the activities and accomplishments of the M&S Development phase. Subsequently, following the activities of the Model Use phase, a M&S Results Assessment is to be performed, per [M&S 31], including only factors associated with the M&S Use phase. Together, the outcomes of the capabilities and results assessments combine to provide the overall assessment of the credibility of the M&S results influencing the critical decisions.

One motivation for this change is that some M&S efforts seek only to develop an M&S for release, e.g. to produce a general-purpose, reusable model, while other M&S efforts start with an available model and proceed to apply the model to a specific RWS. In such cases, the M&S developers and M&S users may not be the same, and it is clearly preferrable for the development team to perform (or be involved with) the evaluation of the factors included in the capability assessment.

In any case, even if the developers and users are the same, an evaluation of the model's capabilities per the factors specified in Appendix E.3.1 of NASA-STD-7009B need to be available at the start of the M&S Use phase, when the M&S users perform (or are involved with) the M&S Use Assessment [M&S 23]. The Use Assessment (refer to Appendix E.4.2 of NASA-STD-7009B) compares the proposed uses of the model against the permissible uses of the model as established during development by the outcomes of M&S Verification and M&S Validation.

Detailed guidance for performing the M&S Capability Assessment appears in Appendix D of this Handbook.

5.5.5 Model Release

Model Release is the process of establishing the baseline and controlled version of the model and associated key documentation for use, including permissible uses for the M&S, guidance for proper use (e.g., User's Guide), and the outcome of the M&S Capability Assessment. All requisite development artifacts are to be archived when the M&S is released for use. After release, changes to the baseline are to be evaluated, justified, and authorized with traceability prior to implementing and releasing the revision.

5.5.5.1 Accomplishing Model Release

Along with the release of the M&S, the M&S requirements, designs, test procedures, test reports, and model correlation reports are baselined as approved, built, or run.

Permissible uses of the M&S are documented per [M&S 14] in NASA-STD-7009B, along with guidance on appropriate ways (methods) in which to use the model and the specifics of model calibrations (NASA-STD-7009B, section 4.2.2d). The criteria for determining permissible uses of an M&S include:

a. Intended use [M&S40].

b. Abstractions [M&S 11].

c. Assumptions [M&S 11].

d. Limits of operation [M&S 13].

e. Domain of verification [M&S 16].

f. Domain of validation [M&S 18].

5.5.5.2 Considerations in Model Release

All final artifacts from model development are to be archived, if not previously accomplished.

Requirement changes are evaluated, justified, and authorized with detailed designs that are implemented with traceability, and versioned iterative tests that contain unique version identifiers.

A user's guide is released along with the model. Refer to Appendix C of this Handbook.

5.5.5.3 Products and Expected Outcomes of Model Release

At the conclusion of model release, all the products and expected outcomes from V&V are to be available, and archived as necessary, along with the following:

a. The formally released model.

b. Documented permissible uses.

c. M&S User's Guide (Final).

d. Procedures for M&S Use.

e. M&S Capability Assessment Results

Note: It is incumbent on the M&S practitioner to include all V&V procedures and test results with each model release. This allows M&S reuse to have proper regression testing should a user modify the M&S for an alternative application not specifically covered by the M&S intended use.

5.6 Model Use (Phase E)

The Model Use Phase of the M&S life cycle is composed of the model pre-use, model use, and model post-use sub-phases. *[Note: Throughout this section – in fact, throughout the entire handbook – "model use" should be generally interpreted to also mean (or include) "model re-use".]* This section discusses each of these sub-phases in the context of the requirements and recommendations provided in NASA-STD-7009B, along with examples to aid the explanations.

The Model Use Phase uses the latest updates to the following products:

a. Formally released model.

b. Statement of Intended Use.

c. Outcome of the Criticality Assessment from model development.

d. Documented Permissible Uses.

e. M&S User's Guide (Final).

f. M&S Capability Assessment Results.

g. Procedures for M&S Use.

h. Proposed Use (obtained at any point prior to commencing with the Model Use Phase).

Note: When developing the statement of Permissible and Proposed Use (as well as statements of Accepted Use and Actual Use), statements should follow the guidance in section 5.1.1.2 regarding considerations for the statement of Intended Use and include additional details regarding "deficiencies" or "exceedances" from the intended use. More information on each use statement is provided in Appendix F.

5.6.1 Model Pre-Use

The model pre-use sub-phase prepares for model (or M&S system) use and is composed of three primary activities:

a. Ensuring readiness for model use.

b. Assessing the proposed use of a model.

c. Preparing input scenario definition and pedigree assessment.

5.6.1.1 Readiness for Use

Aspects of readiness for M&S use focus on the M&S users/analysts, the processes and procedures for M&S use, and the criticality associated with M&S use.

Before using the M&S, the user/analyst should be reasonably familiar with the M&S and the associated disciplines incorporated. While there are occasions when the M&S developer also fulfils the role of M&S user/analyst, this is not always the case; the roles are considered as distinctly separate. Except in the most trivial cases, it is advantageous, even for the M&S developer, to consult recommended practices and the M&S User's Guide when using the M&S.

Ways for the User/Analyst to prepare for using the M&S are:

a. Identification and familiarization with recommended practices for the type of M&S in use (see the potential recommended practices in section 4.1.3 of NASA-STD-7009B).

b. Training associated with specific M&S or, more generally, with the type of M&S (see the potential recommended training areas in section 4.1.4 of NASA-STD-7009B).

c. Training in the operations of the RWS or the scientific background of the RWS phenomena being modeled.

d. Thoroughly understand the user's guide for the specific M&S if one is available (per Recommendation section 4.2.2e of NASA-STD-7009B). Suggested content for the user's guide is in Appendix C of this Handbook. As a minimum, the following information about the M&S is to be well understood:

(1) Assumptions and abstractions underlying the M&S, including their rationales [M&S 11] in NASA-STD-7009B.

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

(3) Limits of operation (e.g., boundary conditions) of models [M&S 13].

(4) Permissible uses of the M&S [M&S 14].

The processes and procedures for using the M&S are best established before concluding M&S development in Model Phase D; if that has not occurred, they can also be established at the beginning of Model Phase E (recommendations are in sections 4.1.2c and 4.3.2e of NASA-STD-7009B).

Reviewing or re-accomplishing the criticality assessment for the M&S during use preparations helps ensure the appropriate level of rigor is attained or maintained in keeping with the criticality.

5.6.1.2 Use Assessment

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 were defined during the M&S Development phase and baselined during the M&S Capability Assessment and M&S release (section 5.5.5) activities. 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 6, M&S Use Assessment, depicts these similar elements for comparison in the use assessment.

Table 6—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, & uncertainty of the M&S.
Limits of Model Parameters, per • Model design (including any computer H/W or S/W limitations). • Verification.		Desired Domain of Use. • With respect to the RWS. • Parameter values the model is expected to represent.

• Validation.		
Types of Outputs (Results) Produced, including: • Accuracy. • Precision. • Uncertainty.		Type of Results Needed, including: • Accuracy. • Precision. • Uncertainty of Results.

An example of the assessment of assumptions, as part of the use assessment, is in computational fluid dynamics, where a gas is modeled as a thermodynamically perfect gas, approximating the behavior of molecules in a gas. This modeling approach is applicable in many subsonic and low-supersonic external flow regimes. Extending this approach to high-temperature flows, such as planetary entry simulations, may not be appropriate as the assumptions of a perfect gas model can be violated due to real gas effects. In such a case, the use of the model is to be limited to subsonic and low supersonic external flow regimes. This limitation, and associated rationale, should be succinctly described.

5.6.1.3 Input Scenario Definition and Pedigree

Configuring a model for a particular use includes defining the scenarios to run and setting up the model to implement those scenarios. The scenarios to employ during use are sequences of events, sets of conditions (e.g., parameter values), or configurations of the modeled RWS or its operating environment. These scenario inputs define or control the function of a model during use and are subject to assessment for the input pedigree credibility factor. The inputs to a model are dependent on the type of model of analysis employed, such as material property data for a structural model, atmospheric data for a trajectory model, or arrival and process times, event probabilities, and resource quantities and schedules for a process model. The credibility of input data typically depends on traceability to an RWS, accuracy of the data, and known uncertainty.

The input pedigree factor strives to address the adequacy or quality of the inputs to the model, including their completeness, breadth, and accuracy for a particular use. Models are generally considered as encapsulations of certain system characteristics (see Figure 5) to which a set of data is applied for a specific analysis. The input to a model broadly refers to the data used to obtain simulation and analysis results. The input does not address the model mathematics or structure, the processing of information within the model, or statements of uncertainty accompanying the results. The data can include specific modifying parameters, with or without uncertainty, to the model or be used to set up and initialize the model.

Even an imperfect input can be used in a critical analysis, but only if the associated uncertainty is identified. The central idea of input pedigree is to clearly communicate the credibility of the input used in the analysis based on various attributes of the data used, including the source, quality, diversity, and quantity of the data, as well as the form of the input used.

5.6.1.3.1 Source of the Input Data

The goal for the input data used in any analysis is that it originates from an authoritative source, which could be:

a. An SME.

b. A credible document, e.g., project documents, journal articles, operators manuals or standard operating procedures for the RWS.

c. Test results or datasheets (from the RWS vendor).

d. Operational data or observations.

e. Another model.

5.6.1.3.2 Quality of the Input Data Source

The quality characteristics of M&S input may span the range between subjective and objective, such as:

a. Notional: An uninformed or hypothetical estimate.

b. Informed: An educated or experienced estimate (minimum, most likely, or maximum).

c. Specified: From system requirements.

d. Derived: From knowledge or calculation from the general physical characteristics of the system (a value or expression from given or known set of data).

e. Measured: From direct knowledge (empirical readings) or calculation from the actual RWS.

Understanding the data quality is critically important to the credibility of an analysis and spans the full spectrum from low (notional) to high (officially accepted operational or test data). The most authoritative sources are officially designated and documented, while less authoritative sources are not quite so formal. Less formal sources are not necessarily inferior; the intent of this qualification of the data source is to clearly understand where the data originates and whether it is a good source.

Test data can be superior to historical or quality record data, but should be used cautiously as the use case, RWS, assumptions, and external factors may have been significantly different. Test data obtained from a DoE generally make it possible to determine means and spreads accurately, while data with confusing changes in inputs and multiple outliers can make it difficult or impossible to perform rigorous data analysis.

Even data from the best source may not have the highest quality, depending on factors such as the life cycle phase of the RWS and the availability of historical or analogous data. Early in a project’s life cycle, notional data are sometimes used for initial analyses. Whenever notional data are used, these data should be clearly noted. The best case is for analysis accomplished on an RWS in operation for an extended time with plenty of officially documented data. If data are obtained from an analogous RWS, then the level of data similarity should be documented. If the data are obtained from another model or analysis, the data credibility is tied directly to the credibility of the model or analysis from which the data were obtained. In such cases, the input pedigree credibility level is limited to the credibility level of the model from which the data are obtained.

5.6.1.3.3 Diversity and Quantity of Data Source

The basic idea of source data diversity is that data are increasingly and statistically more acceptable coming from more than one instance, item, or test. Information obtained from an SME may be simply a single value for a given parameter in a model, e.g., a minimum, an average, a maximum, or a range of potential values. It is better if the source is empirical, operational, or test data. Even if M&S input data are single (deterministic) values, it is better if that value is derived (calculated) from a set of data than from only one value. If the data set from which the input is derived includes data from a variety of real-world instances, then the resulting input will be more representative of the population.

As an example, if the desired input to a model is the processing time for a spacecraft in a processing facility, then the input will be more representative of the population if data are obtained from multiple spacecraft and various mission flows, i.e., process iterations. The more supporting data for a specific model input, the higher the quality of that input. Statistically, an average obtained from a set of 50 data points is much better than an average obtained from 10 data points. The same can be said of statistically determined probability distributions. This aspect of the quantity of data directly relates to the upcoming topic of uncertainty, with smaller data sets having statistically larger uncertainty than larger data sets.

Small sample sizes, particularly in historical data, give relatively inaccurate estimates of the true mean and typically underestimate true variability. For example, the more you drive your car, the more likely you are to drive in all types of conditions; if you only measured drive time on a few sunny days, the effect of rain is missing.

5.6.1.3.4 Form of Input Used

As implied above, the input used in an analysis can take many forms, from textual to logical to numerical or mathematical. A deterministic (single-valued) input may be obtained directly or derived from a set of source data. If derived, the method of derivation should be made known.

A more interesting and complete analysis may be obtained by using a span of possible parameter values in a Monte Carlo run of an M&S. For example, a model may be run with the values of certain parameters stepped through increments from the possible minimum to maximum values or using parameter values randomly selected within some number of standard deviations of the mean. Appropriate statistical analysis is to then be applied to the results, and the interpretation thereof.

Similarly, using probabilistic parameter values may provide even more insights, although care must be taken in its application to ensure results are representative of the RWS performance domain. If a set of data is available for a given parameter; statistical analysis of the data may produce a probability density function (pdf) that accurately represents the original data set but in a more general way. Stochastic data, or data representing how a process varies over time, are another probabilistic source. Such statistical functions are then used for the parameter(s) in parameter sampling (for example Monte Carlo or Latin hypercube sampling) runs of the M&S by drawing random variates from the defined probability distribution. In the case of multiple parameters, the pdf's may be sampled independently if the parameters are independent, or they may need to be sampled dependently using estimates of parameter covariance (examples are Copulas and the Gaussian Process). Probabilistic and stochastic analyses are more complex, requiring specific statistical methods for analyzing the outputs of multiple model runs. Beneficially, the results also include a statistically calculated uncertainty.

Models typically use multiple inputs with a variety of pedigrees. Ideally, the effect of all the inputs is to be considered when determining the overall input pedigree for a given M&S-based analysis. As a matter of pragmatism, a rigorous assessment as to the most influential inputs to an M&S is helpful in reducing the effort in this task.

5.6.2 Model Use (Setup and Execution)

Upon the accepted use of the model, work begins toward setting up and executing (or using) the model. This portion of the Model Use Phase has three primary activities:

a. Model setup.

b. Model execution (Application).

c. Sensitivity studies.

Note: In some studies, the relevant information for decision making is not generated directly by the M&S but is collected elsewhere. This is common in live M&S and virtual M&S studies. For example, the relevant information may be the performance of human test subjects operating the modeled RWS under one or more scenarios. This situation will be addressed within the three activities.

5.6.2.1 Model Setup

Model setup encompasses two primary activities: setting up an M&S system for use and developing the scenarios specific to the desired results expected by the customer. If not already accomplished, the equipment (hardware and software) for the model to work is gathered and configured for use. If the developers and the users are different, the developers may also provide regression tests with the M&S release that users execute to verify installation of the M&S. As the particulars for each type or implementation of model varies greatly, the user's guide for the model or model implementation platform (e.g., COTS user's guide) are to be consulted. Possible model setup choices are shown in Table 7, Model Setup Definition Options. Stochastic models also include other settings and increment the amount of data collected for each replication. The data used to develop input for the model use and the rationale for model setup and execution are required documentation per [M&S 24] and [M&S 25], respectively, and documentation of any supporting software used in the preparation of input is recommended (NASA-STD-7009B, section 4.3.2d). This helps to create traceability and evidence of the operation, which is particularly useful if changes are needed later in the analysis and decision making. Process components may include the platform the model was executed on (e.g., Window or Linux), the version/revision of any models or software used, compiling options, etc. Model calibrations are considered part of model setup for specific use and should be documented along with the domain of calibration (NASA-STD-7009B, section 4.3.2c).

Table 7—Model Setup Definition Options

Run Length.
Time Step or Frequency.
Animation Run Speed.
Initial Conditions.
Warm-up Period.
Number or Replications.
Start Time.
Stopping Conditions.
Output to collect (e.g., model run statistics).
Output Recording Frequency. Numerical method configuration (e.g., integrator selection, convergence tolerance, floating point equality tolerance)

When the M&S is not the generator of the data for decision making, then users must establish methods and procedures for capturing the information during (or after) M&S execution. For example, in human-in-the-loop studies, this information may be captured using audiovisual equipment (video and/or audio recording), biometric sensors, surveys (post-execution of M&S), or witness observations (e.g., instructor making notes). Similarly, hardware-in-the-loop studies may use signal analyzers, network sniffers, data recorders, or human observers to capture information. Human-in-the-loop studies may require subject matter expertise in human factors to define the M&S setup, the data gathering methods and procedures, and the data analysis methods.

5.6.2.2 Model Execution (Application)

Once the model is set up, the scenarios are executed. This can be a very straightforward process, if diligent attention was given to setting up the model and developing the set of scenarios to execute, including those that provide insight into the sensitivities and uncertainties associated with the scenarios. The execution of a model can take on a life of its own, with learning and adjustments to scenarios occurring in the moment. It is important in all cases to ensure either all executions are conducted within the permissible limits of operation, or the results are placarded for executions outside the permissible limits [M&S 26].

Another task to accomplish during Model Use, initially discussed in Considerations in Model Verification (section 5.5.2.2b), is Solution Verification. This is similar to what is accomplished in verification testing, but for the model's current use. Solution Verification is 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. Confirmation that this or other methods were employed is advisable when reviewing M&S results.

As such an environment can be very dynamic, it is very valuable to carefully keep track of the versions of the various execution results in association with the scenarios that generated them (NASA-STD-7009B, section 4.3.2f).

Warning or error messages that come about during model execution are to be documented and explained [M&S 27], and all failure modes, points of failure, and associated messages should be documented and explained (NASA-STD-7009B, section 4.3.2h). Users can also inspect the output to ensure that any timed or conditional events occurred during M&S execution, as defined in the scenario definition, and that the M&S stopped in accordance with the defined stopping conditions.

The as-run procedure – a record of what occurred during model use – should be retained for comparison to the prescribed procedure for M&S use (refer to the list of precursors for the Use Phase, found at the beginning of section 5.6). At a minimum, this could simply be a list of deviations from the prescribed procedure. All differences (deviations) between the intended and actual procedures should be explained along with assessments of any potential impacts to the M&S results.

When the data is gathered outside of the M&S, the data gathering procedures may include checks to conduct after an M&S execution to assure the completeness and quality of the gathered data. The checks help determine whether the execution was successful or needs to be repeated.

5.6.2.3 Sensitivity Studies

As RWSs in operation can deviate from nominal operating conditions, sensitivity studies with a model of the RWS can be quite valuable. Knowing where a model, and by analogy an RWS, is sensitive to changes in operating conditions or parameters provides valuable insight into how strictly controls or mitigations must be pursued. Conversely, studying and analyzing these sensitivities also leads to an understanding of model, and, by analogy, RWS robustness (material, on robustness in NASA/SP-2010-576, NASA Risk-Informed Decision Making Handbook, is instructive). It is equally important, during sensitivity studies, to stay within the permissible uses of the model (unless such excursions are appropriately placarded).

While execution of the model occurs in this sub-phase, the analysis to determine how variation in the output of an M&S can be apportioned to different sources of variation in the model input and parameters occurs after actual model execution and gathering of data from execution. Variations in model input and parameters are best kept within the boundaries of permissible use of the model when performing the sensitivity studies.

Documenting the extent and results of sensitivity studies is required [M&S 30], assessed as one of the operational factors of results credibility [M&S 31], and reported [M&S 35].

5.6.3 Model Post-Use

After completing M&S execution, four major steps remain in the Model Use Phase:

a. Results analysis.

b. Results assessment.

c. Risk assessment.

d. Reporting.

One major purpose of using an M&S is to generate data to support decisions concerning the represented RWS. Before even proceeding with data analysis, it is prudent to ascertain any conditions that may render the results moot. These potential caveats to analyzing, let alone accepting, M&S results are shown in Table 8, Potential Caveats to M&S Results. The existence of any of these caveats are to be reported with the M&S results per requirement [M&S 32].

Table 8—Potential Caveats to M&S Results

NASA-STD-7009B Requirement	**Reporting Requirement**	**Do any of the following exist? (Yes / No)**	**If yes, what are they?**	**Rationale for proceeding with the reported information**
[M&S 32]	**Caveats**			
(a)	Unachieved Acceptance Criteria.			
(b)	Violation of any Assumptions.			
(c)	Violation of the Limits of Operation.			
(d)	Execution Warning and Error Messages.			
(e)	Unfavorable outcomes from the assessed appropriateness of the M&S to the proposed use.			
(f)	Issues encountered during setup and utilization of the M&S.			
(g)	Waivers to Requirements.			
(h)	Outstanding M&S defects or problems			

Note: This list is representative of NASA-STD-7009B's recommended minimum set of reportable caveats but is not all encompassing. The M&S practitioner should make every effort to report caveats that will add necessary value in interpreting the M&S results and that do not negatively impact the recommended approaches in NASA-STD-7009B. As an example, reporting issues with data collection or quality for live and virtual M&S (as defined in *https://www.de-bok.org/glossary) can be categorized as M&S 32(c) and (d) type caveat or it can be viewed as a unique category of caveat for this type of simulation result.*

One method to ensure analysis caveats are noted adequately is to add placards to the results (see Figure 13, Example Placard) per [M&S 26(2)].

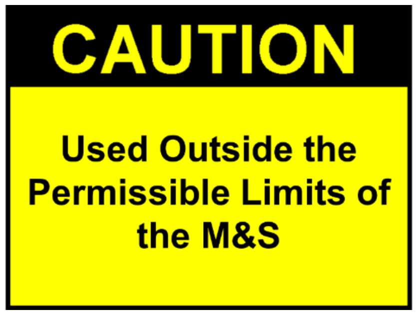


Figure 13—Example Placard

Another example is to note vehicle configuration differences between the M&S, defined analysis scenarios, and the RWS in the caveats.

5.6.3.1 Analyze Data

Producing results is the most obvious task in any M&S effort. Rarely can data from the M&S be used directly in making such decisions. So, the output data is analyzed, statistically or otherwise, or visualized to support specific decisions. This analysis of a set or sets of data gathered from use of the M&S directly depends on the M&S and the type of information needed for application to an RWS. Clearly understanding, and conveying, what the results represent is important (e.g., minimum, most likely, maximum). The additional tasks of solution verification, uncertainty characterization, and sensitivity analysis provide supplemental qualifying information.

5.6.3.1.1 Uncertainty Characterization

Uncertainty Characterization is the process of identifying sources of uncertainty and describing their relevant qualities (qualitatively or quantitatively) in all models, simulations, and experiments (inputs and outputs). The basic premise is that models are abstractions of actual or proposed RWSs, which necessarily induce some uncertainty in the model's ability to replicate system behavior. Uncertainty characterization and quantification are difficult parts of understanding any system or model of a system. Deterministic analyses leave the uncertainties unaddressed and provide incomplete or misleading, if not incorrect, results. Even a deterministic, static model would benefit from a qualitative analysis of uncertainty. *Note: This topic was originally introduced in section 5.2.1.3.3, Nondeterministic Specifications, and illustrated in Figure 5.*

A synopsis for reporting uncertainty characterization is shown in Table 9, Uncertainty Characterization Synopsis.

Table 9—Uncertainty Characterization Synopsis

NASA-STD-7009B Req't	Reporting Req't	Do any of the following exist? (Yes / No)	If yes, what are they?	Rationale for proceeding with the reported information
[M&S 33]	**Uncertainty in Results**			
(1)	Quantitative Estimate.			
(2)	Qualitative Description.			
(3)	No estimate or description given.			
[M&S 34]	**Uncertainty Processes**			
	Processes for obtaining Uncertainties in M&S Input.			
	Processes for obtaining Uncertainties in M&S Results.			
	Processes for obtaining Uncertainties in Quantities Derived from M&S Results.			

Uncertainty comes in many forms and may present itself in a variety of places relevant to the analysis, including the following:

a. System understanding: How well the system is known.

b. Model building: What is and is not included in the model.

c. Input: The amount of good, i.e., attributable, or authoritative, data available and the form the data takes.

d. Running the models: The setup and initialization parameters for running the model. Do they meet the breadth of analyses required? Are the simulation model scenarios accomplished with a well-considered DoE? Are the numerical errors sufficiently small?

e. Output analysis: Does the form of the output portray the breadth of the results obtained?

f. Uncertainties are often classified into two separate types:

(1) Epistemic: A lack of knowledge of the quantities or processes identified with the system, i.e., subjective, reducible, and may be identified with model uncertainty. If the system could be studied more closely, it may be possible to reduce the magnitude of the uncertainty.

(2) Aleatory: The inherent variation in the physical system, i.e., stochastic or irreducible. Systems have inherent differences in their characteristics, which may change on a day-to-day (or moment-by-moment) basis.

There are many potential sources of uncertainty in a model, with typical sources listed in Figure 14, Sources of Model Uncertainty, (Oberkampf, et al., 2002). This figure was made from the perspective of models based on PDEs; other types of models will not have some of these sources and yet have other sources of uncertainty. The A and E notations in Figure 14 refer to whether the uncertainty source is aleatory or epistemic. Furthermore, this figure distinguishes between epistemic uncertainties, aleatory uncertainties, and errors. Errors are a "recognizable inaccuracy in any phase or activity of modeling and simulation that is not due to lack of knowledge." (Oberkampf, et al., 2002).

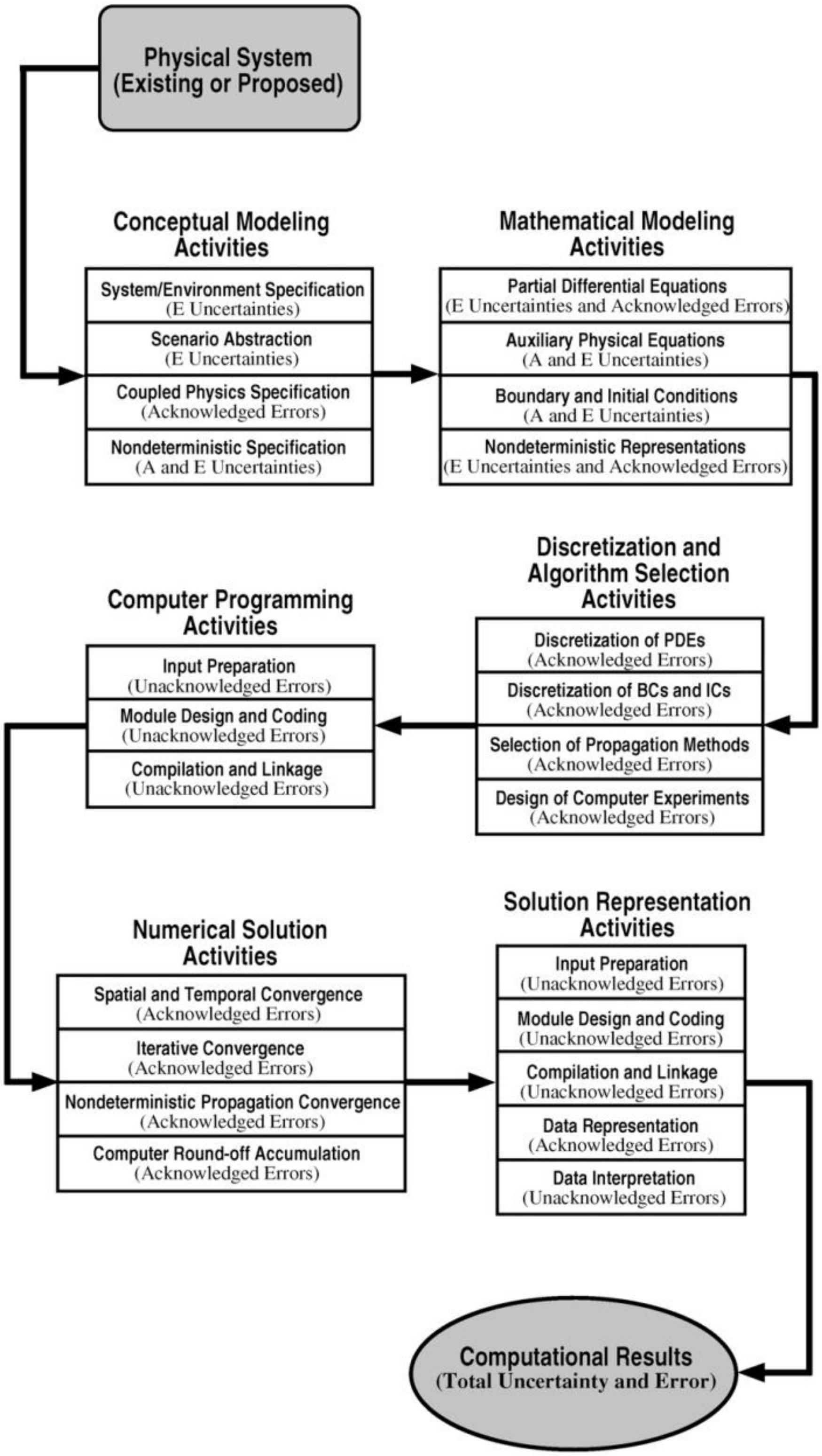


Figure 14—Sources of Model Uncertainty

Identifying, quantitatively expressing, and correctly classifying uncertainties are often the most difficult parts of uncertainty characterization. This is because uncertainty is everywhere, and many people are going to have different opinions on uncertainty sources. Epistemic uncertainty is difficult because often the uncertainty source is not well understood. Quantifying epistemic uncertainty, which can include uncertainties resulting from model simplifications or underlying assumptions, is difficult due to the nature of the uncertainty. Even SMEs may have varying opinions on the amount of uncertainty present in a particular source. When epistemic sources of uncertainty can be identified and their impact on M&S results can be quantified, important decisions can be made regarding the mitigation or even reduction of these uncertainties. Proper detail and adequate attention should be given to epistemic uncertainties to most effectively guide decision making based on M&S results.

Aleatory uncertainty is typically more straightforward in that variations in physical systems are usually obvious and well understood, such as in the case of variation of average velocity because of small turbulent fluctuations in a moving fluid. The only challenge with aleatory uncertainty is having enough information to support a claim that a particular uncertainty source can be classified as aleatory (i.e., irreducible). In some cases, extensive data taken over very large time scales may be necessary to fully understand the uncertainty. Consider variations in atmospheric wind profiles. Years of data at even a single, geographical location are needed to glean even some sense of the variability. Practitioners are encouraged to use caution when claiming an uncertainty source is aleatory. This is typically the easier route in terms of propagating the uncertainty and interpreting the results, but incorrect classification and treatment of uncertainty can produce very misleading results.

Contributions to the uncertainty in M&S results stem from both aleatory and epistemic sources. Generally, M&S practitioners can expect that results uncertainties will include aleatory and epistemic contributions from the input to the model and the model form. The M&S practitioner should recognize that these are not the only sources of aleatory and epistemic uncertainty and that the other sources may be difficult to objectively quantify for each M&S use.

The significance of uncertainty in the results depends on how the results are to be applied in a decision situation. The uncertainty in a given result may not matter in some situations, while in others it may imply that the nominal or best estimate result is suboptimal or even questionable. In the latter case, if the decision stakes are high enough, additional analysis or testing may be appropriate to invest in to reduce the uncertainty.

The following information should be considered when reporting results uncertainty. For large models, it may become necessary to focus on key sources of uncertainty or break the model up into components and give a “system level” summary of the uncertainty.

a. How were the uncertainties determined?

b. How thoroughly were the uncertainties identified and evaluated?

c. Are the sources documented?

d. What are the sources of the uncertainties?

(1) In the system?

(2) Included in the model?

(3) Type of each source (i.e., aleatory vs. epistemic)?

(4) How well is the uncertainty known?

(5) Excluded from the model that induces uncertainty?

(6) In the data for, the parameters of, and the input to the model?

(7) In the results/calculations of the M&S and analysis?

e. What method(s) were used to quantify uncertainty (e.g., Monte Carlo, test data, or Kriging-model-based survey data) including how uncertainty propagates through the model to the results?

f. What is the impact of the uncertainty (e.g., on performance metrics)?

g. Is there an Uncertainty Mitigation Plan?

Uncertainty is characterized throughout the life of an M&S. The *model user* should understand the uncertainties identified during the M&S development process (as identified in NASA-STD-7009B, section 4.2.7) and document uncertainties introduced during the application of the M&S.

Documentation of uncertainties consists of two parts. First is the explanation of how uncertainties are identified and characterized:

> *[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.*

The process for characterizing uncertainty could range from very quantitative (i.e., B-Basis allowable for a material property) to much more qualitative (such as a rule of thumb Model Uncertainty Factor [MUF] applied to analysis results). Explaining why a particular method of uncertainty characterization was used informs the overall credibility of the M&S results and may also point to ways that uncertainty could be reduced by using other methods of characterization.

The second part of documenting uncertainty is to describe and quantify those uncertainties:

> *[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, (c) The quantities derived from M&S results.*

Note that, for model use, uncertainty can be found in the inputs to the M&S, the results of the M&S, and in items derived from the M&S results. For example, a structural analyst is using a finite element model (FEM) to perform an analysis to determine stresses in a structure due to thermal loads. The thermal loads input to the FEM have some uncertainty. The resulting stress values produced from the FEM may have uncertainties due to uncertainties in material properties for coefficient of thermal expansion. Ultimately, the stress results are used to calculate margins of safety (MOS) for the structure. Those derived MOS values could also have uncertainty if, for example, the allowable material yield or ultimate stresses are not well quantified.

Responsible parties should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis (NASA-STD-7009B, section 4.3.4a).

5.6.3.1.2 Sensitivity Analysis

Sensitivity analysis is the study of an M&S's response to variations in input parameters to determine which parameters are key drivers to the M&S's results. This analysis is undertaken with the results obtained from the sensitivity studies accomplished during the actual execution (use) of the M&S. If the response is negligible, then the M&S (at least in the experimental domain), and by inference the RWS, is considered insensitive to those parameters. Understanding the sensitivity to input parameters is key to determining the robustness of the M&S (see Results Robustness factor in NASA-STD-7009B, Appendix E). On the other hand, if the response is not negligible, particularly to minor variations of the input parameters, the M&S is considered sensitive, and the responsible parameters are key drivers to the model results.

The Results Robustness credibility factor is concerned with how thoroughly the sensitivities of the current M&S results are known, with some of these variables and parameters intrinsic to the RWS and others intrinsic to the M&S. Since the model is used to understand how changes in the various parameters may impact the RWS, the sensitivities of the model should be similar to the sensitivities of the RWS (see Note (b) below). The justification for the evaluation and any technical review of Results Robustness is to be documented.

Notes:

a. NASA-STD-7009B defines sensitivity analysis but only references robustness in terms of sensitivity. This can lead to confusion about both terms, so some clarification is provided here. With respect to systems and models, sensitivity and control robustness are opposites. If a system is sensitive to changes in controlled operating parameters or conditions, then it is not considered robust. On the other hand, if the system is found to be insensitive to changes in controlled operating parameters or conditions, then the system is considered robust. Sensitivity analysis is the technique that can be used to better understand system robustness.

b. The closeness of a model's response to the system's response should be part of the M&S validation effort. The Results Robustness credibility assessment factor focuses on the degree to which sensitivity analyses were accomplished. If documentation is provided comparing the sensitivity of model results to the sensitivity of the RWS, then the requirement of NASA-STD-7009B is met.

c. Sensitivity analysis can also be used early in the RWS life cycle, when limited validation data are available, to determine the boundaries for stable system performance. This is also useful when good referent data are not available. If system instability is indicated, then more attention is required to the affected portions of the system as it progresses in development (Kelton, et al., 2004). If system performance is adequately stable, i.e., insensitive to small changes in operating parameters, then margin may be available as the system design matures.

Additional considerations with respect to these key questions are:

a. What are the significant sensitivities of the M&S results?

   (1) Which parameters, when varied, have the largest impacts on the results?

   (2) Do they match the sensitivities of the RWS?

b. How thoroughly are the sensitivities known?

   (1) What percentage of parameters have had their sensitivities evaluated?

   (2) How much testing was performed to characterize the sensitivity fully?

5.6.3.2 Results Assessment

At this point in the M&S life cycle, the results from M&S use are analyzed and ready for reporting. However, merely reporting the results presents an incomplete picture, at best. The requirements and recommendations of NASA-STD-7009B also require the assessment of the results regarding their credibility. The contribution to credibility related to M&S Development is addressed in section 5.5.5 of this Handbook. Per [M&S 31] the Capability Assessment is now followed by a Results Assessment where the activities and achievements throughout the M&S Use phase are evaluated, using factors relevant to this phase. Combined, the outcomes of these two assessments represent the overall credibility, a key element of the potential risks of accepting the results to inform the critical decision (see section 5.6.3.3 of this Handbook). While credibility is not something that can be assessed directly, the factors influencing overall credibility (as defined in NASA-STD-7009B per requirement [M&S 31, 48]) are more readily assessed. Following are notes about the NASA-STD-7009B credibility factors:

a. They are considered a minimum set that are applicable to all types of M&S.

b. They are essentially independent of each other.

c. For a particular type or application of M&S, additional factors may prove useful.

Additional assistance in achieving the assessed credibility levels for each factor in the Capability and Results assessments is provided in Appendix D of this Handbook.

In addition to assessing the level of credibility for each factor, as a matter of practice, it is also recommended for responsible parties to set threshold levels for each factor for the M&S effort to attain (NASA-STD-7009B, section 4.3.7a). These are best set as early as possible in development or use, so as to help the developers or users, respectively, work towards the targeted level. This also supports the insight provided by comparison of the preferred threshold and achieved credibility factor levels (NASA-STD-7009B, section 4.3.7c). Justification and documentation for the assessed levels of each of these factors (NASA-STD-7009B, section 4.3.7b) provide the needed evidence.

5.6.3.3 Model and Simulation (M&S) Risk Assessment

From an M&S perspective, a risk exists in the potential shortfalls in the M&S with respect to sufficiently representing the RWS. The topic of risk is sprinkled throughout NASA-STD-7009B, whose primary purpose is to "reduce the risks associated with M&S-influenced decisions." This starts with the assessment of criticality [M&S 6] which provides an understanding of the influence the M&S has on the RWS and consequences of inadequate RWS representation.

The reporting of M&S associated risks usually occurs at the end of the Use Phase; an effective assessment of risk is best considered during each phase of the M&S life cycle (further explanations are in Appendix E of this Handbook). With the potential for incurring M&S risks anywhere in the M&S life cycle, it is necessary to assess and report them whenever the results of an M&S-based analysis are given. Several of the requirements and recommendations of NASA-STD-7009B are inherently risk oriented. In particular, the reporting of any caveats from M&S use [M&S 32] and the assessed level of credibility for each of the defined factors in the capability and results assessments (Appendix D of this Handbook and NASA-STD-7009B, Appendix E) are to be part of any M&S risk assessment.

In addition, each of the following items, if they exist, may improve the risk posture of the M&S:

a. Developer/Use Qualifications.
b. Technical Reviews.
c. Development/Use Documentation.

While these do not guarantee lower M&S risk, having good developer/user qualifications, technical reviews, and documentation improves the chances of adequate M&S representation of the RWS than if they were less so.

Table 10, M&S Risk Elements, provides a synopsis of potential M&S risk elements with rationales and references.

Table 10—M&S Risk Elements

Major Risk Element	Rationale	NASA-STD-7009B Reference	NASA-HDBK-7009B Reference
Caveats	Communicates areas that may lead to problems or concerns with the M&S results.	[M&S 32]	Section 5.6.3 Table 8
Uncertainty	Communicates that M&S results are estimates with a potential range.	[M&S 33] [M&S 34]	Section 5.6.3.1.2 Table 9
Credibility	Communicates factor assessments that impact the believability of the M&S results.	[M&S 50, 35] Appendix E Tables 3 – 6	Appendix D
Technical Review	Provides independent assessment of various aspects of the development or use of the M&S.	[M&S 36]	Table 11
People Qualifications	Provides an understanding of the education and experience of the people developing and using the M&S.	[M&S 37]	Table 12
M&S Documentation	Ensures clear evidence of what was accomplished in M&S development and use.	[M&S 38], plus all the documentation R/r's	Table 13

These elements are also part of section 5.6.3.4, Table 14, M&S Reporting Synopsis, as potential areas for incurring or mitigating potential M&S risks, which are to be considered in the context of criticality. Further background and explanations of these M&S risk related topics are in Appendix E of this Handbook.

When an M&S is applied by its use to a particular RWS, any associated risks are to become part of the RWS risk management system.

Not all caveats, uncertainties, credibility factor assessments, technical reviews, developer and user qualifications, or documentation adequacies necessarily introduce M&S risk. Each of them is to be evaluated (and reported) as to whether or not they introduce a risk to the adequacy of the M&S results, i.e., introduce unacceptable inadequacies to representing the RWS.

5.6.3.4 Reporting

The information qualifying the M&S results is important to report along with the results themselves. The purpose for the reporting requirements ([M&S 32-39, 50]) in NASA-STD-7009B is to promote a more complete understanding of the results, and the models and processes leading to those results.

In addition to the results (with uncertainty and uncertainty process description) themselves, the list of caveats, and the documented outcomes of the required assessments (capability, results, risk), the report to the decision maker(s) is to include the results of (findings from) any technical reviews (addressing both development and use phases); details pertaining to the qualifications of the developers, testers, users, and analysts; and a specified set of supporting documentation.

Table 11 (Technical Review Synopsis), Table 12 (People Qualifications Synopsis), and Table 13 (Documentation Synopsis) provide additional details regarding this supplemental information. Table 14 then summarizes the complete information package that is to be provided to the decision maker(s).

Table 11—Technical Review Synopsis

NASA-STD-7009B Req't	Reporting Req't	Do any of the following exist? (Yes / No)	If yes, what are they?	Rationale for proceeding with the reported information
[M&S 36]	**Technical Review**			
	Review			
	- What was reviewed?			
	- Depth of Review.			
	- Formality of Review.			
	- Currency of Review.			
	Reviewers			
	- Expertise.			
	- Independence.			

Table 12—People Qualifications Synopsis

NASA-STD-7009B Req't	Reporting Req't	Do any of the following exist? (Yes / No)	If yes, what are they?	Rationale for proceeding with the reported information

[M&S 37]	**People Qualifications**			
	Developers.			
	Testers.			
	Users (Operators).			
	Analysts.			

Table 13—Documentation Synopsis

NASA-STD-7009B Req't	**Record and Reporting Req't**	**Do any of the following exist? (Yes / No)**	**If yes, what are they?**	**Rationale for proceeding with the reported information**
[M&S 38]	M&S Documentation (Synopsis)			
[M&S 40]	Intended Use			
[M&S 6]	Criticality Assessment.			
[M&S 43]	Acceptance Criteria			
[M&S 44]	Unique M&S Information			
[M&S 9]	Technical Reviews.			
[M&S 51]	M&S Defects			
[M&S 10]	Relevant Characteristics of RWS for M&S Development.			
[M&S 11]	Assumptions & Abstractions.			
[M&S 12]	Structure & Math of M&S.			
[M&S 13]	Limits of Operation.			
[M&S 14]	Permissible Uses.			
[M&S 48]	M&S Capability Assessment			
[M&S 16]	Domain of Verification.			
[M&S 18]	Domain of Validation.			
[M&S 19]	Processes for Characterizing Uncertainty in Referent Data.			
[M&S 21]	Incorporated Uncertainties.			
[M&S 22]	Proposed Uses.			
[M&S 23]	Use Assessment.			
[M&S 24]	Input Data.			

NASA-STD-7009B Req't	Record and Reporting Req't	Do any of the following exist? (Yes / No)	If yes, what are they?	Rationale for proceeding with the reported information
[M&S 25]	Setup & Execution Rationale.			
[M&S 27]	Warning or Error Messages.			
[M&S 28]	Processes for Characterizing Uncertainty in Input, Results, Derived Results.			
[M&S 29] (a)	Uncertainties in Input.			
[M&S 29] (b)	Uncertainties in Results.			
[M&S 29] (c)	Uncertainties in Derived Results.			
[M&S 30]	Sensitivity Analyses.			
[M&S 31]	M&S Results Assessment			

Table 14—M&S Reporting Synopsis

NASA-STD-7009B Requirement	Reporting Requirement	Does risk exist w.r.t. this item? (Yes / No)	If yes, describe the risk(s).	If yes, provide the rationale for proceeding with the risk(s).
[M&S 50, 35]	Credibility Assessment (combined Capability Assessment and Results Assessment).			
[M&S 33]	Uncertainty in Results.			
[M&S 34]	Uncertainty Processes.			
[M&S 32]	Caveats.			
[M&S 36]	Technical Reviews.			
[M&S 37]	People Qualifications.			
[M&S 38]	M&S Documentation.			
[M&S 39]	M&S Risk Assessment.			

5.6.4 Products and Expected Outcomes of the Model Use Phase

Final products for the model and its use(s) are to be collected and appropriately archived, and include, but are not limited to, the following:

a. Criticality Assessment Results (pertaining to M&S Use).

b. Use Assessment Results.

c. Scenarios Used.

d. M&S Setup (& Calibrations).

e. Credibility Assessment Results (combined Capability and Results assessments).

f. M&S Use Results (Raw & Processed).

g. As-Run Procedure from M&S Use.

h. Results Uncertainties.

i. Results Sensitivities.

j. Caveats.

k. M&S Use Documentation.
l. Risk Assessment.

m. Data to update M&S Validation (if any) from use.

Note regarding item (m): As stated in section 5.5.3.2.2 (Limits of a Validated Model), models may be used for predictions beyond the range of existing empirical data (as of the M&S Development phase). Should new data become available, for example, because the RWS performed operations outside of the limits of model validation, then the domain of validation for that model can be updated. But, in order to do so, care must be taken to preserve data from the M&S Use phase that can be used to accomplish the requisite comparisons of predictions to data as well as model correlations and calibrations.

5.7 Model and Analysis Archiving (Phase F)

The NASA-STD-7009B requirements and recommendations applicable to the Model and Analysis Archiving phase of the M&S life cycle are found in Appendix A of this Handbook.

Model/Analysis Archiving is the process of storing and cataloging all M&S, including designated development and use artifacts for retrieval and use. The concepts of archiving are integrally bound to configuration management (CM), which establishes, tracks, and controls many of the officially accepted M&S relevant artifacts throughout the M&S life cycle. Relevant archival artifacts often subject to CM include the objectives and requirements defined early in the development and use life cycle phases ([M&S 41]) and any M&S development, use, or retirement plans (NASA-STD-7009B, section 4.1.1.3). The NASA Standard for CM is Configuration Management Requirements for NASA Enterprises (EIA-649-2).

M&S efforts should identify, manage, process, deliver, control, and archive all M&S-related technical data and products, including the M&S and tools, information, and data used in development and use of the M&S as an integral part of work product management (NASA-STD-7009B, section 4.1.2b). Recommended practices for archiving M&S should be identified, documented (NASA-STD-7009B, section 4.1.3a), and considered for use, along with a method for adherence tracking (NASA-STD-7009B, section 4.1.3b(2)), and included as part of training for the M&S (NASA-STD-7009B, section 4.1.4b(1)B and section 4.1.4b(1)C). These practices should include establishing and documenting initial baselines and versioning of archival and controlled items, such as designs and test procedures, and can be extended to evidentiary items such as test reports and model correlation reports (comparing RWS measurements/observations to equivalent model outputs) when applicable. Changes to established baselines of these products should be evaluated, justified, authorized, and implemented with traceability to unique version identifiers. Once Development is completed, the model is officially released with all products and development artifacts archived.

Whenever M&S results are obtained from use, they should be placed in the M&S's CM system (NASA-STD-7009B, section 4.3.9c).

Table 15, Example Archival Products in the M&S Life Cycle, shows examples of products, documents, or artifacts that may require controlling or archiving in each phase of the M&S life cycle.

Table 15—Example Archival Products in the M&S Life Cycle

Phase	**Pre-A**	**A**	**B**	**C**	**D**	**E**	**F**
Name	**Model Initiation**	**Model Concept**	**Model Design**	**Model Construction**	**Model Test**	**Model Use**	**Model & Analysis Archival**
Archival Item	RWS Sub-System, Element, or Aspect Information under consideration. Initial Statement of M&S Intended Use.	M&S Development Plan. M&S System Architecture. M&S Concept Diagrams. M&S Requirements & Specifications. M&S Testing Requirements.	M&S Design. Conceptual Validation Documentation & Results.	The M&S.	Verification Plans & Procedures. Validation Plans & Procedures. Documented domain of Permissible Use. The Released M&S. User's Guide.	Use Plans & Procedures. Proposed Use. Use Assessment & Results. M&S Setup & Input Scenarios. M&S Output. Output Results. Reporting.	All associated M&S baselined products from previous phases are included.

It is up to the programs/projects/individual M&S efforts to determine the type of storage media and follow the NASA Records Management Program Requirements (NPR 1441.1).

6. WORKSHEET

The worksheet accessible at nasa-hdbk-7009b - worksheet.xlsx is intended to assist in the planning, development, and use of M&S, including the reporting of results from use of the M&S. Many, but not all, requirements and recommendations of NASA-STD-7009B are referenced. The information and questions included in this Worksheet are meant to induce a spirit of general M&S inquiry, which is by no means all-inclusive or mandatory in all cases. The intent is to help gain a greater depth of understanding of the M&S-based analysis, per the requirements and recommendations of NASA-STD-7009B.

Use of NASA-STD-7009B, this Handbook, or the Worksheet may be limited to specific phases of the M&S life cycle, or particular organizations developing or using the M&S, for a variety of reasons:

a. An M&S development organization may choose to follow the precepts of NASA-STD-7009B, this Handbook, or Worksheet (e.g., for a broadly applicable M&S), while an M&S user (organization) may not choose to follow.

b. An M&S user (organization) may choose to follow the precepts of NASA-STD-7009B, this Handbook, or Worksheet (e.g., for a specifically defined use of an M&S) when using an M&S that was not developed or documented according to NASA-STD-7009B practices.

For these or any other variety of possible reasons, the Worksheet is organized to allow the relevant sections to be used when needed. Such tailoring is expected depending on the particular development or application, so long as it is clearly understood (if not officially documented, justified, and accepted).

The Worksheet in this Handbook is organized similarly to NASA-STD-7009B, with relevant contextual information (Table 16, Worksheet Organization). The M&S life cycle is defined in NASA-STD-7009B, Appendix F, and discussed in this Handbook, section 4.6.

Table 16—Worksheet Organization

Worksheet Section	Worksheet Section Title	Worksheet Section Description
6.1	Header.	Contextual information about the RWS and the model representing the RWS..
6.2	M&S Planning.	Overarching concepts applicable to planning the M&S development and use (necessarily encompassing all phases of the M&S Life Cycle).
6.3	M&S Development.	Questions and STD references applicable to the phases and key processes of M&S development.

6.4	M&S Use.	Questions and STD references applicable to the key processes of M&S Use.

6.1 Header

Figure 15, Worksheet Header, is organized to mirror similar concepts between the RWS and the M&S.

<table>
<tr><td></td><td colspan="2">NASA-STD-7009B
M&S Life-Cycle Worksheet</td><td></td></tr>
<tr><td colspan="2">System:</td><td>M&S:</td><td>Date:</td></tr>
<tr><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="2">Sub-System, Element, or Aspect of System Under Analysis:</td><td colspan="2">Topic of Analysis (e.g., Production, Ground Ops, Flight, Mission, Entry, Descent, Landing):</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">System Life-Cycle Phase: Pre-A A B C D E F</td><td colspan="2">M&S Life-Cycle Phase: Pre-A A B C D E F</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Responsibility Chain: P/P Mgt & Tech Authority</td><td colspan="2">M&S Responsible Party: Developers, Users, Analysts</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
</table>

Figure 15—Worksheet Header

The left side of the header requests information relative to the system, sub-system, or aspect of the system pertinent to the analysis at hand, along with the system's life cycle phase and the key responsible parties. The System Life Cycle Phase follows the life cycle defined for NASA programs and projects.

The right side of the header requests information relative to the M&S, the topic area of the M&S-based analysis (use), the M&S's life cycle phase (as defined in NASA-STD-7009B, Appendix F), and the key M&S responsible parties.

All of the columns are shown in Figure 16, Worksheet Example of All Columns, for the M&S Planning section as a reference. In the sections that follow, only the first three columns will be shown for improved readability.

Item	STD Ref	Questions	✓	Responses, Comments, Notes, References, Links
M&S Planning				
Intended Use	*[M&S 40]*	*What is the M&S Intended Use in relation to the RWS and its environment?*		
		What is the M&S Intended Use in relation to the Problem / Decision / Situation?		
Criticality Assessment	*[M&S 6]*	*What method was used to perform the criticality assessment for this M&S?*		
		What were the results of the Criticality Assessment?		
Life-Cycle Planning	*[M&S 41]*	*What are the plans for acquisition / development of this M&S?*		
		What are the plans for Use / Maintenance / Retirement of this M&S?		
Best Practices	*4.1.3 a, b*	*What best practices were identified for this M&S?*		
		How were these best practices applied to this M&S?		
Training	*4.1.4 a, b*	*What training was required for M&S developers and operators?*		
		What training was accomplished for M&S developers and operators?		

Figure 16—Worksheet Example of All Columns

Note for sections 6.2, 6.3, and 6.4: the tables in these sections contain the following:

a. *Items to cover.*

b. *References to NASA-STD-7009B.*

c. *Key questions for each item.*

d. *A check column (for use in a checklist manner, if desired).*

e. *Data entry area for resources, comments, notes, references, links, or other pertinent information.*

6.2 Models and Simulations (M&S) Planning Section

The M&S Planning section (Table 17, Worksheet – M&S Planning) includes overarching concepts applicable to the whole life cycle of an M&S, including:

a. Intended Use

b. Criticality assessment.

c. Planning.

d. Use of Best Practices.

e. Training for all those involved with M&S development and use (and potentially even the customers of the M&S).

Table 17—Worksheet – M&S Planning

Item	STD Ref	Questions
M&S Planning		
Intended Use	[M&S 40]	What is the M&S Intended Use in relation to the RWS and its environment?
		What is the M&S Intended Use in relation to the Problem / Decision / Situation?
Criticality Assessment	[M&S 6]	What method was used to perform the criticality assessment for this M&S?
		What were the results of the Criticality Assessment?
Life Cycle Planning	[M&S 41]	What are the plans for acquisition / development of this M&S?
		What are the plans for Use / Maintenance / Retirement of this M&S?
Best Practices	4.1.3 a, b	What best practices were identified for this M&S?
		How were these best practices applied to this M&S?
Training	4.1.4 a, b	What training was required for M&S developers and operators?
		What training was accomplished for M&S developers and operators?

Each of the items in this section could easily be considered or accomplished during development and either be reviewed or re-accomplished during M&S use.

6.3 Models and Simulations (M&S) Development Section

The M&S development section (Table 18, Worksheet – M&S Development) includes questions and references to the requirements and recommendations of NASA-STD-7009B for the applicable phases and key processes of M&S development, including:

a. Model Initiation (Pre-Phase A).

b. Model Concept Development (Phase A).

c. Model Design, including Conceptual Validation (Phase B).

d. Model Construction (Implementation) (Phase C).

e. Model Testing, including both Verification and (Empirical) Validation (Phase D).

f. Model Release (Phase D).

Table 18—Worksheet – M&S Development

Item	STD Ref	Questions
M&S Development		
M&S Initiation (Phase Pre-A)	*[M&S 10]*	What is the RWS?
		What is the RWS environment?
		What is the RWS problem/decision/situation for the M&S?
		What is the RWS Intended Use?
Model Concept Development (Phase A)	*[M&S 11], [M&S 12]*	What is the M&S approach? (Is it known how to model what is to be modeled?)
	[M&S 46]	What are the units, vector coordinate frames, or other representative characteristics for all parameters in the M&S?
	[M&S 12]	What's included in the M&S, including model environment influences?
	[M&S 11]	Is there anything significant to this analysis not included in the M&S or scenarios?
		What assumptions & abstractions are included in the M&S and Analysis?
Model Design (Phase B)	*[M&S 21]*	What uncertainties are included in the M&S?
	[M&S 42], [M&S 43], [M&S 44]	What are the Requirements or Specifications for the M&S?
	[M&S 12]	What are the Implementation Mechanisms (e.g., Math Models)?
	[M&S 45], [M&S 47](d)	What is the Implementation Architecture (e.g., Platform-Software)?
Conceptual Validation (Phase B)	*[M&S 17]*	Have the Model Design and Architecture been Conceptually Validated? (e.g., Reviewed by SMEs, both RWS and M&S?)
Implementation (Phase C)		What is the implementation status of the M&S?
Verification (Phase D)	*[M&S 41] 4.1.3b (3) 4.2.4a*	What are the verification practices, methods, and requirements?
	[M&S 15]	Has the model construction been verified? (i.e., Code Verification)?
		Has the model operation or output been verified? (i.e., Solution Verification)?
	4.1.2b	What artifacts (evidence) of verification are available?
Empirical Validation (Phase D)	*[M&S 41] 4.1.3b (3) 4.2.6a*	What are the validation practices, methods, and requirements?
	4.1.2b	What artifacts (evidence) of validation are available? Who reviewed/verified the RWS (Referent System) data?
	[M&S 42], [M&S 43]	What is the accuracy, precision, sensitivity, uncertainty, and bias of the model? Does it satisfy the requirements?
	[M&S 21]	What uncertainties are characterized in the model and how do they compare to the RWS Uncertainties?
	4.2.8	What uncertainties are not characterized in the model and what are those uncertainties in the RWS?
		What are the model sensitivities? How do they compare to Sensitivities of the RWS?
Permissible Use (Phase D)	*[M&S 14]*	What are the Permissible Uses of the M&S?
	[M&S 48]	Data Pedigree

Item	STD Ref	Questions
M&S Development		
Capability Assessment (Phase D)		Verification
		Validation
		Development Technical Review
		Dev Process/Product Management
Model Release (Phase D)	*4.1.2b*	What version of the model is released for use?
	4.1.2b	Where are the model and its development artifacts archived?
	[M&S 48]	Was a User's Guide produced and formally released with the model?

6.4 Models and Simulations (M&S) Use Section

The M&S Use section (Table 19, Worksheet – M&S Use) includes questions and references to the requirements and recommendations of NASA-STD-7009B or the M&S Use phase and the key processes of M&S Use, including:

a. Use Processes.

b. Use assessment, comparing the proposed and permissible uses of the M&S.

c. M&S Setup, scenarios for use, and use (execution) of the M&S.

d. Analysis of M&S results.

e. Uncertainty Characterization.

f. Sensitivity Analysis.

g. Reporting of results, including:

(1) Caveats.

(2) Requirements compliance.

(3) M&S Results Credibility via Results & Capability credibility factor assessments

(4) Development and Use Technical reviews.

(5) People Qualifications.
(6) M&S-based Risk.

h. M&S Product Archiving.

Table 19—Worksheet – M&S Use

Item	STD Ref	Questions
		M&S Use
Use Processes (Phase E)	*4.3.2e*	What are the processes for using the model?
	[M&S 47]	Is a User's Guide available?
Proposed Use (Phase E)	*[M&S 22]*	What is the Proposed Use for the Model?
Use Assessment (Phase E)	*[M&S 23]*	Does the M&S type & permissible use match the proposed use?
		Do the modeling methods (abstractions, assumptions, mechanisms) provide the needed fidelity (level of detail, accuracy, precision, & uncertainty)?
		Is the proposed range of use within the permissible model limits?
		Are the expected M&S outputs (results) appropriate & within the needed accuracy, precision, and uncertainty?
Scenarios (Phase E)	*[M&S 24]*	What are the Scenarios for model use?
Setup (Phase E)	*[M&S 25]*	What are the model setups?
Execution (Phase E)		What is the execution status for the use?
Analysis (Phase E)	*[M&S 28] (c)*	How was the output (data) analyzed?
M&S Results (Phase E)		What are the best-estimate results provided by the analysis?
		How well (how directly) do the analysis results address the problem statement?
Uncertainty in Estimate (Phase E)	*[M&S 29]*	What are the uncertainties in the results of this analysis?
Sensitivities (Phase E)	*[M&S 30]*	What are the Sensitivities in the results of this analysis?
Caveats (Phase E)	*[M&S 32] (a)*	Unachieved Acceptance Criteria?
	[M&S 32] (b)	Violation of Assumptions?
	[M&S 32] (c)	Violation of Limits of Operation?
	[M&S 32] (d)	Warning or Error Messages?
	[M&S 32] (e)	Unfavorable Proposed Use Assessments?
	[M&S 32] (f)	Unfavorable Setup/Execution Assessments?
	[M&S 32] (g)	Waivers to Requirements?
	[M&S 32] (h)	Outstanding M&S defects or problems
Requirements Compliance (Phase E)	*[M&S 32] (a)*	Give details on non-compliances with all M&S requirements and their consequences.
Results Assessment *(Phase E)*	*[M&S 31]* *4.3.7*	Use Assessment.
		Input Pedigree.
		Uncertainty Characterization.
		Results Robustness.
		M&S Use/Analysis Tech Review
		M&S Use Process / Product Management.

Item	STD Ref	Questions
M&S Use		
Credibility Assessment (Phase E)	*[M&S 35], [M&S 50]*	Report the M&S Credibility by providing the Capability and Results assessments of this analysis.
Technical Reviews (Phase E)	*[M&S 36]*	Provide a summary of the Technical Reviews performed on this M&S/Analysis.
People Qualification	*[M&S 37]*	What are the qualifications & experience of the people developing, testing, & using this M&S?
M&S Risk (Phase E)	*[M&S 39]*	What are the risks of basing this decision on the M&S-based analysis?
Results Archiving (Phase F)	*4.3.9c*	Were the M&S results (and related artifacts) archived?

APPENDIX A: REQUIREMENTS AND RECOMMENDATIONS PER LIFE CYCLE PHASE

A.1 Purpose

This Appendix provides guidance as to which M&S life cycle phase each NASA-STD-7009B requirement and recommendation is likely accomplished.

A.2 When to Achieve Each Requirement and Recommendation

While some of the requirements and recommendations in NASA-STD-7009B are inherently accomplished (satisfied) in one life cycle phase, there are many that may be accomplished (satisfied) in one or more phases. Additionally, there are times in the M&S life cycle where the requirements and recommendations are best accomplished but may be accomplished at a later time. There are also instances where an R/r is to be accomplished both from M&S Development and M&S Use. If a requirement or recommendation is not accomplished in the indicated phase, it becomes incumbent on the subsequent phases to make up that shortfall. Note there are some broad R/r's applicable to all phases of the M&S life cycle.

The primary table in this Appendix (Table 21, R/r per M&S Life Cycle Phase) indicates when the requirements and recommendations of NASA-STD-7009B are best to be accomplished, with abbreviated designations defined in Table 20, R/r M&S Life Cycle Phase Designations.

Table 20—R/r M&S Life Cycle Phase Designations

Designation	Description
-	Indicates the results of R/r satisfaction may be updated from earlier results (this may be true for many requirements but is particularly so for R/r's between B_e and B_{nlt} phase designations).
B	The M&S life cycle phase where the R/r is best accomplished.
B_e	The earliest M&S life cycle phase where the R/r is best accomplished.
B_{nlt}	The latest M&S life cycle phase where the R/r may be accomplished.
C-Val	Conceptual Validation (Credibility Factor).
Dev	The development phase of the M&S life cycle where the R/r is best accomplished.
DP	Data Pedigree (Credibility Factor)
E-Val	Empirical Validation (Credibility Factor)
Hist	M&S History (Credibility Factor)
I	R/r's that provide information for planning purposes (in M&S Development) but are not necessarily required until the Use Phase.
IP	Input Pedigree (Credibility Factor).
Mgt	Process/Product Management (Credibility Factor).
RR	Results Robustness (Credibility Factor).
T	R/r's that are satisfied by test of the M&S.
UC	Uncertainty Characterization (Credibility Factor).
Ver	Implementation and Solution Verification (Credibility Factor).

For the credibility factor abbreviated designations, the actual reporting of credibility is not required until late in the Use Phase for the M&S. At least the initial (baseline) assessment of the development focused factors (i.e., data pedigree, verification, and validation) are best accomplished during the phase in which they occur.

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
Section #	Section Title												
4.1.1	**General M&S Programmatics**												
1	[M&S 40] A record of the intended use of M&S shall be maintained.	B											
2	[M&S 6] A record of the assessed criticality associated with M&S use shall be maintained.	B (Dev)								B (Use)			
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.	B (Dev)								B (Use)			
4	[M&S 42] A record of the programmatic and technical metrics for the M&S shall be maintained.		B (Dev)							B (Use)			
5	[M&S 43] A record of acceptance criteria for the M&S shall be maintained, including:		B							B (Use)			
	(a) Criteria for Verification		B							B (Use)			
	(b) Criteria for Validation.	B	B										
	(c) Criteria for Uncertainty.		B							B (Use)			
	(d) Criteria for Sensitivity.		B							B (Use)			
	(e) M&S assessment level thresholds (for the M&S capability assessment and M&S results assessment).		B (DP, C-Val, E-Val, D-Tech, D-Mgt)							B (IP, UC, RR, U-Tech, U-Mgt)			
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]).		B	B	B	B	B	B	B				

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
7	[M&S 9] A record of results of technical reviews accomplished during the life cycle of the M&S shall be maintained.		B	B	B	B	B	B	B	B	B	B	
8	[M&S 51] A record of M&S defects or problems from discovery through closure shall be maintained.			B	B	B	B	B	B		B	B	B
4.1.2	**General M&S Programmatic Recommendations**												
a	Record the M&S waiver processes.		B										
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 CM and M&S support and maintenance.		B	B	B	B	B	B	B	B	B	B	B
4.1.3	**M&S Best Practices Recommendations**												
a	Identify and document any recommended practices that apply to M&S for the program/project.		B (Dev)							B (Use)			
b	At a minimum, consider the recommended practices for the following:												
	(1) Data and M&S input verification, validation, and pedigree.		B (Data)							B (Input)			
	(2) An auditing method of tracking adherence to recommended practices.		B							B			
	(3) V&V processes for the M&S.				B (C-Val.)		B (Ver.)	B (E-Val.)				B (Ver.)	
	(4) Uncertainty characterization methods for the M&S.			B	B	B	B	B		B			
	(5) Sensitivity analysis methods for the M&S.							B		B			
	(6) Understanding of the disciplines incorporated in the M&S.		B							B			

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
	(7) Analyzing and interpreting the M&S results, including documentation of inference guidelines and statistical processes used.									B			
	(8) Recognizing and capturing the need for any changes or improvements in the M&S.					B	B	B		B	B	B	
	(9) Reporting procedures for results.		I							B			
	(10) Best practices for user interface design to constrain the operation of the M&S to within its limits of operations.			B		B							
4.1.4	**M&S Training Recommendations**												
A	Determine the depth of required training or equivalent experience (i.e., qualifications) for developers, operators, and analysts.		B							B			
B	Should document the following:												
	(1) Training topics required for developers, operators, and analysts of M&S, which should include the following:		B							B			
	A. The limits of operation for M&S, with implications and rationale.		B							B			
	B. CM requirements.		B (Dev)							B (Use)			
	C. Documentation requirements and recommendations as specified in this NASA Technical Standard.		B							B			
	D. How to recognize unrealistic results from simulations.						B	B		B			
	E. Feedback processes to improve M&S processes and results, including providing feedback for results that are not credible, are unrealistic, or defy explanation.				B		B	B		B			
	F. Sensitivity analysis.							B		B			

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
	G. Uncertainty characterization.		B							B			
	H. Verification and validation (V&V).				B (C-Val.)		B (Ver.)	B (E-Val.)				B (Ver.)	
	I. How to report simulation results to decision makers.									B			
	J. Statistics and probability.		B							B			
	K. Discipline-specific recommended practices. Other applicable Agency policy, procedural requirements, and standards.		B							B			
	L. Basic modeling structures, mathematics, assumptions, and abstractions.		B							B			
	(2) Process and criteria for verifying that training requirements are met.		B							B			
4.2.1	**General M&S Development**												
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)	B								B			
2	[M&S 45] The data sets and supporting software used in M&S development shall be maintained.			B						B			
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).		B										
4	[M&S 11] 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.		B										

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
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.		B	B		B							
6	[M&S 13] A record of the M&S limits (e.g., boundary conditions) shall be maintained.		B	B		B	T	T					
7	[M&S 14] A record of the permissible uses of the M&S shall be maintained.								B_{nlt}				
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									
	(b) M&S Verification.						B						
	(c) M&S Validation.				B			B					
	(d) M&S Development Technical Review.		B										
	(e) M&S Development Process/Product Management.	B											
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			
	(b) Obsolescence criteria.								B				
	(c) Parameter calibrations.								B				
	(d) Computational requirements.								B				

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	**Pre-A**	**A**	**B**		**C**	**D**			**E**			**F**
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
4.2.2	**General M&S Development Recommendations**												
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	B		B							
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.		B										
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.			B		B	T						
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.					B							B
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.						B (Ver. Cases)	B (Val. Cases)					B
f	Provide a feedback mechanism for users to report unusual results to M&S developers or maintainers.					B							
g	Maintain (conceptual, mathematical, and computational) models, simulations, and associated records in a controlled CM system.		B	B		B			B				B
h	Maintain the data sets and supporting software referenced in [M&S 45] and the associated records in a controlled CM system.		B_e	-	-	-	-	-	B_{nlt}				B
i	Convey serious concerns about M&S to project managers (and decision makers, if appropriate) as soon as they are known.		B	B	B	B	B	B	B_{nlt}				

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
4.2.3	**M&S Verification**												
1	[M&S 15] The M&S shall be verified.						B					B (Ver.)	
2	[M&S 16] A record of the domain of verification of the verified M&S shall be maintained.						B						
4.2.4	**M&S Verification Recommendations**												
a	Record verification techniques used.						B						
b	Record numerical error estimates (e.g., numerical approximations, insufficient discretization, insufficient iterative convergence, finite-precision arithmetic) for the results of the computational model.						B						
c	Record the verification status of conceptual, mathematical, and computational models.						B						
d	Record aspects of M&S not verified.						B						
4.2.5	**M&S Validation**												
1	[M&S 17] The M&S shall be validated.				B (C-Val)			B (E-Val)					
2	[M&S 18] A record of the domain of validation of the validated M&S shall be maintained.							B					
4.2.6	**M&S Validation Recommendations**												
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					
b	Record the validation metrics, referents, and data sets used for M&S validation.							B					

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
c	Record the studies conducted, and the status and results of, M&S validation.							B					
d	Record the aspects of the M&S not validated.				B (C-Val)			B (E-Val)					
4.2.7	**Uncertainty Characterization in M&S Development**												
1a	[M&S 19] A record of the processes and rationale for characterizing uncertainty in the referent data shall be maintained.		B										
2	[M&S 21] A record of the qualitatively described or quantitative uncertainties incorporated into the M&S shall be maintained.			B (as designed)		B (as built)							
4.2.8	**Uncertainty Characterization in M&S Development Recommendation**												
a	The responsible party should record significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.			B									
4.3.1	**M&S Use Requirements**												
1	[M&S 22] record of the proposed use(s) of the M&S shall be maintained..									B			
2	[M&S 23] A record of the appropriateness of the M&S relative to its proposed use(s) shall be maintained.									B			
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.									B			
4	[M&S 25] A record of the processes and rationales for setting up and utilizing the M&S shall be maintained.										B		
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		

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
	(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.										B		
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.										B		
4.3.2	**M&S Use Recommendations**												
a	Record the relevant characteristics of the system that is the subject of the M&S-based analysis.									B			
b	Record the computational M&S used (including revision numbers) in the simulation/analysis.										B		
c	Record the parameter calibrations and the domain of calibration.										B		
d	Record the data sets and supporting software used in input preparation.									B			
e	Record the processes for conducting simulations and analyses for generating results reported to decision makers.									B_{nlt}			
f	Record the versions of M&S results.										B		
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).										B		
h	Record and explain all failure modes, points of failure, and messages indicating such failures.										B		

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
4.3.3	**Uncertainty Characterization in M&S Use**												
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			
	(b) The results from an M&S.										B		
	(c) The quantities derived from M&S results.											B	
b	[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			
	(b) The results from an M&S.										B		
	(c) The quantities derived from M&S results.											B	
4.3.4	**M&S Uncertainty Characterization Recommendation**												
	Responsible parties should record significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.									B			
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.										B		
4.3.6	**M&S Results Assessment**												

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
1	[M&S 31] A record of the assessed M&S results shall be maintained according to each of the following factors:			B (DP)	B (C-Val.)		B (Ver.)	B (E-Val.)		B (IP)		B	
	a. M&S Use Assessment.										B		
	b. M&S Input Pedigree.										B		
	c. M&S Uncertainty Characterization.										B		
	d. M&S Results Robustness.										B		
	e. M&S Use/Analysis Technical Review.										B		
	f. M&S Use Process/Product Management.									B			
2	[M&S 49] A record of the assessed risks associated with the use of the M&S-based analysis shall be maintained.											B	
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].			B (DP)	B (C-Val.)		B (Ver.)	B (E-Val.)		B (IP)		B	
4.3.8	**M&S Results Reporting**												
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	
	(b) Violation of assumptions of the M&S used (as specified in [M&S 11]).											B	
	(c) Violation of the M&S limits (as specified in [M&S 13]).											B	

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
	(d) Execution warning and error messages (see [M&S 27]).											B	
	(e) Unfavorable outcomes from the assessed appropriateness of the M&S to the proposed use (described in [M&S 23]).											B	
	(f) Issues encountered during setup and utilization of the M&S (described in [M&S 25]).											B	
	(g) Waivers to the requirements in this Standard (or the requirements specific to the M&S).											B	
	(h) Outstanding M&S defects or problems (described in [M&S 51]).												
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	
	(b) A qualitative description of the uncertainty in the M&S results, or											B	
	(c) A clear statement that no quantitative estimate or qualitative description of uncertainty is available.											B	
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.											B	
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.											B	
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.											B	

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	Pre-A	A	B		C	D			E			F
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
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.											B	
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.											B	
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.											B	
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.											B	
4.3.9	**M&S Results Reporting Recommendations**												
a	Should include concluding remarks stating whether the M&S results are credible enough for the actual use.											B	
b	Should identify how to access more detailed backup material, including high-level descriptions of the models used and key assumptions for limits of validity.											B	
c	Should place M&S results in the CM system.										B	B	B
d	Should summarize deviations from established recommended practices.											B	
e	Should include dissenting technical opinions regarding the credibility of the results or any recommended actions.											B	

Table 21—R/r per M&S Life Cycle Phase

	Phase -->	**Pre-A**	**A**	**B**		**C**	**D**			**E**			**F**
	Phase Name -->	Model Initiation	Model Concept Development	Model Design		Model Construction	Model Testing			Model Use (Ops)			Model / Analysis Archiving
	Sub-Phase -->			Design	Conceptual Validation		Verification	Empirical Validation	Release	Pre-Ops	Use (Ops)	Post-Ops	
f	Should convey serious concerns about M&S or its use to project managers (and decision makers, if appropriate) as soon as they are known.									B	B	B	

APPENDIX B: QUALITY OF REFERENT DATA USED IN EMPIRICAL VALIDATION

B.1 Purpose

This Appendix provides guidance on the quality of referent data used in empirical validation.

B.2 Quality of Referent Data

An important and often overlooked item regarding the quality of the referent data acquired and used to validate an M&S is the assurance that all sources of error, especially those that are difficult to detect, are eliminated or mitigated to acceptable levels. Understanding and accounting for the differences between the referent and RWS is essential, but equally essential is that data obtained from the referent, and the methodologies used to acquire these data, are compatible with, or convertible to, data needed to correctly validate an M&S. More often than not the referent is either:

a. An experiment that is designed to simulate or replicate an RWS or a portion thereof.

b. An operating or prototype RWS equipped with instrumentation and data acquisition systems to maintain its safe, reliable, and proper operation.

The instrumentation, data acquisition systems, and the methodologies used to obtain data from a referent are often different from those needed to properly validate an M&S. Generally, instrumentation used to provide data for physical systems has the purpose of monitoring system health, preventing unsafe operating conditions, or predicting the need for preventative maintenance or repairs. More often than not these data are different, where many differences are subtle and can easily remain undetected or have higher allowed errors/uncertainties when compared with data that is needed for M&S validation.

Additionally, errors in instrumentation measurements and data obtained from these measurements are common whenever a high level of rigor, similar to the level of rigor applied to M&S verification, is not exercised to assure all possible sources of error are identified and taken into account or reduced to acceptable levels. A non-exhaustive list of examples of unresolved/uncorrected empirical data acquisition errors and their root causes includes:

a. Pressure sense line taps being positioned/configured such that true static (or stagnation) pressure is not measured.

b. Unaccounted effects of head pressures due to elevation differences.

c. High frequency and amplitude pressure oscillations in the system coupled with measurement response time delays causing false readings.

d. Measurement response time delays masking out transients that need to be measured.

e. Nearby or contacting heat sinks or sources skewing thermocouple (or other types of temperature instrument) readings.

f. Instruments themselves in the flow stream/passages altering flow characteristics.

g. Data transmission rates (number of readings per unit of time) from instrument measurements exceeding limits of data processing equipment.

In a number of instances, facility environments also contribute significant thermal, mechanical, optical, or other forms of background “noise” to the critical measurements required for model validation. Left unchecked, these noise sources limit the domain of validation, requiring extrapolation of the model for predictions applied in the actual RWS environment. Alternatively, facility noise sources may be attenuated through the use of specially designed test fixtures. These test fixtures must then be included in the model when replicating ground testing and often complicate or add uncertainty to model validation efforts. These are then removed when replicating flight (mission) conditions.

An example would be the use of mechanical isolation systems to mitigate vibrations generated by facility machinery, such as vacuum and fluid pumps. The isolation system would have to be added to the appropriate (e.g., structural, thermal, optical) models of the RWS (or portion thereof) under test, followed by careful identification and separation of its contribution to measurements obtained during the test.

To further compound these problems and work against the likelihood of them being corrected, the M&S developers are generally working in organizations that are separate and independent of the organizations where experimental systems and RWS designers and operators work. Such separate and independent organizations do not always communicate effectively, especially when large and complex systems, or large quantities of detailed information and data, are involved. Added to this situation are the budgetary and schedule constraints, universal to all projects and programs, where decision-makers can be strongly influenced or driven to use data obtained from past (historical) experiments and RWSs, where incorrect assumptions of data compatibility are made. (Oberkampf, W.L.; Roy, C.J. (2010), Chapters 10 and 11, provide further details and a substantiating case study.) The referent data and the methodologies to obtain these data are to be checked for compatibility with data needed for M&S validation, and the verification of referent data is to be performed with the same rigor and level of scrutiny as the verification of an M&S prior to validation of the M&S.

The concepts of “model builder’s risk” (or type 1 error) and “model user’s risk” (or type 2 error) (discussed in Oberkampf, W.L.; Roy, C.J. (2010), Chapter 12, Section 12.2.2) also need to be understood and addressed during M&S validation. “Model builder’s risk” is the problem where the validity of an M&S is rejected when it is actually valid. “Model user’s risk” is the opposite, an M&S being accepted as valid when it is not. Type 1 errors can lead to recalibrating or tuning an M&S to provide acceptable agreement with invalid referent data. This is likely to result in continued and expanded use and acceptance of (and reliance upon) an invalid M&S for subsequent applications and projects/programs. Type 2 errors are potentially the most dangerous because errors in the referent data can result in acceptable (good to excellent) agreement with data from an invalid M&S. When this occurs, there is little or no incentive to pursue and uncover undetected errors and biases with the net result being a false sense of security (that is until a major mishap or catastrophe occurs). This is depicted in Table 22, M&S vs. Referent Data/Results Relationship.

Table 22 is a simple 2x2 matrix of conditions and outcomes that includes type 1 and type 2 errors. While not similarly labeled, the upper-right quadrant also represents a type of error. Here, the model and referent do not agree, but the consensus is that the referent is valid. Assuming the model was verified before the comparison to the referent was made, the conclusion is then that the conceptual model (or its architecture, requirements, and other inputs to the Model Design Phase) are not valid.

The best remedy to mitigate or prevent “model builder’s risk” and “model user’s risk” is complete, effective, and fully transparent communications between M&S developers and the designers and operators of the experiment, test article, prototype, or RWS to be used as the referent for M&S validation. While the M&S and data from the referent are separately and independently verified, the M&S developer or validator needs to fully understand the referent and how data is acquired. Additionally, the designers and operators of the systems used as a referent need to fully understand the types of data and data acquisition requirements needed by the M&S developers. Proper validation still requires that no transfer/communication of actual data and results between people performing verification of the M&S and those performing verification of data from the referent prior to M&S validation.

Table 22—M&S versus Referent Data/Results Relationship

<table>
<tr><td colspan="2" rowspan="2"></td><th colspan="2">M&S Data/Results</th></tr>
<tr><th>Valid</th><th>Invalid</th></tr>
<tr><th rowspan="2">Referent (Empirical) Data/Results</th><th>Valid</th><td>M&S is Correctly Validated *</td><td>M&S Data/Results and Referent Data/ Results being in Agreement is not possible *

If M&S Data/Results and Referent Data/ Results are not in Agreement, M&S to be corrected or replaced and then re-verified</td></tr>
<tr><th>Invalid</th><td>M&S Data/Results and Referent Data/ Results being in Agreement is not possible *

M&S Data/Results and Referent Data/ Results are not in Agreement, Type 1 Error exists, and Source(s) of referent data/results need to be corrected or replaced and then re-verified **</td><td>If M&S Data/Results and Referent Data/ Results are in Agreement, Type 2 Error exists.

Whether or not M&S Data/Results and Referent Data/Results are in Agreement, M&S needs to be corrected or replaced and then re-verified <u>and</u> source(s) of referent data/results need to be corrected or replaced and then re-verified **</td></tr>
</table>

Notes:

* Domain of M&S verification is within domain of referent data verification and all verifications have been done correctly.

** Sources of referent data having unacceptably high errors can be the result of:

1. The source(s) of referent data (e.g., prototype of system, experimental system or setup, simulation of RWS, RWS being tested in different operating environment) is not a sufficiently correct representation of RWS being modeled.

2. Unknown and undiscovered phenomena are acting on and skewing data and results obtained from the source(s) of referent data.

3. The instrumentation, the way instrumentation is connected/installed into the RWS or system representing/simulating the RWS, or methods that data is acquired are not compatible with data required to validate the M&S.

APPENDIX C: MODELS AND SIMULATIONS (M&S) USER'S GUIDE OUTLINE

C.1 Purpose

This Appendix provides guidance on the content of an M&S user's guide, but the content and organization of this appendix are only suggestions and not intended as a prescription.

C.2 Models and Simulations (M&S) User's Guide

Development of a User's Guide for an M&S is a recommendation of NASA-STD-7009B, section 4.2.2e: *Should document guidance on proper use of the model.*

C.3 Models and Simulations (M&S) User's Guide Content

The content listed below should be located somewhere in the User's Guide and easily found by Table of Contents or indices.

1. General Information
    a. Table of Contents, Figures, and Tables.
    b. User's Guide Revision History.
    c. Model applicable glossary.
    d. Model applicable acronyms.
    e. Model applicable references.
2. Model Identification
    a. Official model name (or designator).
    b. Applicable revision.
    c. Description of model.
    d. Location of the model and relevant artifacts repository.
3. Intended Use (see section 5.1.1.2 of this Handbook)
    a. What the model is.
    b. What the model is used for (i.e., its purpose).

    c. What the model should *not* be used for.

4. M&S Conceptual Diagram (Conceptual Model)
    a. Model Contents.
    b. Sequence of Processes & Computations (as needed).
    c. Description of Model Capabilities.
    d. Sources and General Description of Key Equations and Systems of Equations to use (or used) in the model, especially those most critical to modeling the RWS or those that could prove difficult to implement.
5. Technical Background of How the Model Works
    a. M&S Architectural Diagram.
    b. Primary Governing Concepts (possibly equations and systems of equations), along with their pedigree of use.
    c. M&S Abstractions & Assumptions.
    d. How uncertainties are handled in
        i. The construction of the model.
        ii. The use of the model:
            1. In the Input.
            2. In the Output.
    e. Technical Metrics
        i. Accuracy and Precision of the Released Model.
        ii. Model Setup criteria to obtain desired level of accuracy or precision.
    f. User Interface.
6. Permissible Uses of the Model, as constrained by

a. The Intended Use.

b. Limits of Operation (boundary conditions for model use):

  i. As Designed, determined by:

    1. Abstractions.

    2. Assumptions.

    3. Modeling choices.

  ii. As Verified.

  iii. As Validated.

c. Include Obsolescence Criteria.

7. Processes for Model Use

a. Model Use/Analysis Plan.

  i. Suggestions from a “model perspective” of what to include in the Use/Analysis Plan, with the Developer’s Scope of Use in mind.

b. Use Assessment.

c. Setup.

  i. M&S Architectural Diagram.

  ii. Requirements and Instructions for setting up (installing) the model for use.

d. Inputs.

  i. What all the inputs are.

  ii. What the permissible range for each input is.

e. User Interface.

f. Use.

8. Expected Results from Use

a. Example Results (Samples).

b. Comparison with referent empirical data.

    i. Provide examples of results with good and poor comparison to referent data.

c. Uncertainties with upper and lower bounds in the overlay of plotted data.

    i. Associated input uncertainties with their pedigree.

d. Potential Areas of Sensitivity.

9. Other M&S Development Information Relevant to M&S Use

    a. Potential Caveats.

        i. Unachieved Acceptance Criteria.

        ii. Waivers to Development Requirements.

    b. Development Related Credibility Factors

        i. Data Pedigree.

        ii. Verification.

        iii. Validation.

        iv. M&S (Revision) History.

        v. M&S Process/Product Management.

    c. Potential areas of Risk.

    d. Findings from Technical Reviews.

    e. Where to find Development Artifacts.

10. Operator/User/Analyst Requirements/Recommendations

    a. Education.

    b. Experience.

c. Training.

11. Developer Qualifications

12. Help

a. Where to go for help.

i. Include website or info location where there are FAQs, etc., that may also lead a user to a CM/repository system (section 2d) where the files are stored.

b. Who to Contact for Help, Comments, or Suggestions.

i. M&S Developer.

ii. Configuration Manager.

APPENDIX D: ASSESSING AND INFLUENCING MODEL AND SIMULATION (M&S) RESULTS CREDIBILITY

D.1 Purpose

This Appendix provides guidance for performing the M&S Capability Assessment and M&S Results Assessment, and provides information on how each M&S life cycle phase may affect each of the credibility factors defined for the two assessments.

D.2 Overall Model and Simulation (M&S) Credibility

M&S Results Credibility is a key tenet of NASA-STD-7009B. The idea is challenging, as it may take on a variety of meanings depending on the context of the M&S, but it is a natural part of any decision-making process. As credibility cannot be measured directly, the methodology developed as part of NASA-STD-7009B formalizes this assessment with a minimum set of criteria contributing to M&S-based analysis credibility.

As discussed throughout sections 5.5 and 5.6 of this Handbook, the outcomes of two assessments combine to convey the overall credibility assessment. The Capability Assessment occurs at the end of the development phase, focusing only on the activities which take place throughout that life cycle phase. The Results Assessment occurs at the end of the use (operations) phase, focusing mainly on the activities which take place throughout that life cycle phase. However, the Use Assessment necessitates a look back at the accomplishments of the development phase, informed to a large degree by the outcome of the Capability Assessment, to determine how well-aligned the proposed use (or re-use) of the model is with respect to the established capabilities.

Details to consider as to the credibility of the results of an M&S-based analysis are included in section 4.2, section 4.3, and Appendix E of NASA-STD-7009B, which addresses key development, usage, and supporting aspects of an M&S activity.

When assessing either the capability or the results, consider the following:

a. There may be other key aspects to a particular type of M&S that are not included in the assessment. Including those additional aspects along with the more broadly applicable credibility factors defined in NASA-STD-7009B is acceptable and encouraged. The factors included in NASA-STD-7009B's credibility assessments are considered to be a minimal set for a majority of M&S. If a factor is not considered relevant to a particular M&S, tailoring is permitted, with the approval of the program/project delegated NASA Technical Authority. (See section 1.3 of NASA-STD-7009B.)

b. There is no correlation between compliance with the requirements of NASA-STD-7009B and the achievement of particular levels for the various factors in the credibility assessments. Attaining the various levels of credibility relate to the technical aspects and are defined on a case-by-case basis.

c. Many, if not most, of the factor level definitions are compound statements where more than one success criteria are provided. These level definitions are to be strictly interpreted using an “inclusive requirement”, i.e., all criteria specified must be satisfied in order for that level to be achieved.

What can reasonably be accomplished for each of the credibility factors depends on where the M&S effort is within the M&S life cycle. Perhaps with the exception of input pedigree, all credibility factors are affected by what has occurred throughout more than one of the life cycle phases. Table 23, How M&S Life Cycle Phase Affects Credibility Factors, is an overview of when in the life cycle these influences occur. Explanations for how each life cycle phase affects each credibility factor are included in subsequent sections of this appendix.

The acceptable level for the overall credibility and contributing factors is determined by the program/project management in association with the delegated NASA Technical Authority (NASA-STD-7009B, section 4.3.7), as appropriate for the current state of the RWS and the M&S and the criticality of the decision being made. The expectation for analyses is that they improve as:

a. The system development matures.

b. Data become available from relevant phases of the program/project.

c. The M&S matures and is used.

The assessment of overall M&S credibility should include the following:

a. A tabular or graphical display of the credibility factors indicating the assessed levels (with thresholds if available, refer to [M&S 43] and Appendix E in NASA-STD-7009B regarding factor thresholds).

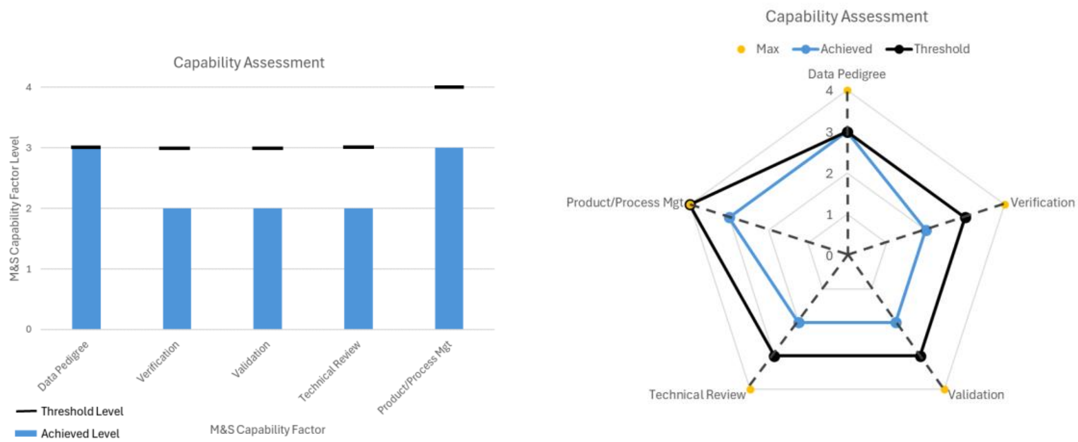
b. The role of the person/team performing the credibility assessment in the development, operation, or analysis using the M&S.

c. A summary of the evidence and supporting rationale. (A reference to another document may suffice.)

Table 23—How M&S Life Cycle Phase Affects Credibility Factors

Phase	Pre-A	A	B	C	D	E	F
Name	Model Initiation	Model Concept	Model Design	Model Construction	Model Test	Model Use	Model & Analysis Archival
M&S Development Factors							
Data Pedigree	X	X	X	X			
Verification		X	X	X	X		
Validation		X	X	X	X		
Development Technical Review	X	X	X	X	X		
Development Product/Process Management	X	X	X	X	X		
M&S Use (Operations) Factors							
Use Assessment	X	X	X	X	X	X	
Input Pedigree						X	
Uncertainty Characterization		X	X	X	X	X	
Results Robustness					X	X	
Use/Analysis Technical Review						X	
Use Product/Process Management						X	X

Examples for reporting a synopsis of a Capability Assessment in graphical form are shown in Figure 17, Example Credibility Assessment Synopsis. The graphical forms for a Results Assessment would have the same general appearance, only the factors would differ. Note that these examples include the achieved factor levels and the optional factor thresholds.



a. Bar Chart b. Spider (Radar) Plot

Figure 17—Example Capability Assessment Synopsis

Note: Details on bar and spider plot construction can be found in NASA-STD-7009B, Appendix E.

Note: The scaling of levels is intended to depict a range of possible assessments from nothing (zero) to perfect or nearly so (four). It is only possible for an M&S to achieve an assessed credibility Level 4 with considerable effort in M&S development and use, and with adequate data from the RWS. For example, many NASA scientific missions consist of a single flight vehicle. The only way to attain a Level 4 assessment for validation is by comparison with results from the actual RWS; any time before the first mission, an assessment of Level 3 is the highest possible for validation. The purpose for such an assessment is to discuss the factors influencing the credibility of the analysis results. It is the decision maker's responsibility, in conjunction with the delegated NASA Technical Authority, to ascertain the acceptability of this information.

D.3 Data Pedigree

The Data Pedigree factor strives to address the adequacy and quality of the data (or information) used to develop the model, including their completeness, breadth, and accuracy. The central idea is to clearly communicate the credibility of the data used in developing the model.

The following attributes are to be considered for all data used to develop an M&S:

a. Source of the data.

   (1) SME.

   (2) Document.

   (3) Database.

b. Quality of the source.

(1) Notional.

(2) Informed.

(3) Specified.

(4) Derived.

(5) Measured.

(6) Similarity of analogous data source.

c. Diversity of the data source; greater is often better, but not always.

(1) Single values, e.g., a minimum, maximum, or average from a particular source.

(2) A set of historical values for this input from a number of sources.

(3) Single versus multiple instances.

d. Quantity of source data.

(1) A single value.

(2) A set of values.

e. Form of the data used.

(1) Deterministic.

(2) Deterministic with spread.

(3) Probability distribution or stochastic data.

The determination of the significance of each of these attributes is context dependent. For instance, for measured data in an analog test stand, the sensor calibration history, the traceability (i.e. conformance to the NASA-STD-8739.12, "METROLOGY AND CALIBRATION") may constitute a necessary factor to consider. Determining the credibility level for the data used to develop an M&S is interdependent on the attributes discussed above. These details of data pedigree are to be considered in determining the overall data pedigree credibility level.

Table 24, Data Pedigree Credibility Achievement, is to be read from the bottom up (like the credibility assessment), with the general idea that improvement is achieved when ascending the table. Note that these sub-factors for data pedigree are not strictly ordered and should be considered as part of the discussion in the overall assessment of data pedigree.

Table 24—Data Pedigree Credibility Achievement

Source[1]		Quality[2]	Diversity/Quantity[3]	Form of Input[4]
RWS		Official		
Another Model/Analysis		Analogous		Stochastic (pdf) or Empirical Function
Analogous System		Historical	Variety of Process Iterations	Average with Spread
SME		Unofficial	Variety of Instances	Range of Values
None		Notional	Amount of Data	Deterministic

Notes:

1. *Source: The data obtained from an analogous real-world source may be better than that obtained from another model or analysis; the reverse can also be true.*
2. *Quality: The data quality from an analogous source may be as good as data quality from the historical system.*
3. *Diversity/Quantity: Having data from a variety of instances, e.g., Orbiter tail numbers, may be as good as having data from one instance over many process flows.*
4. *Form of Input: Form, correct units, and appropriateness to scenario.*

For guidance regarding achieving the credibility levels for the Data Pedigree factor, refer to NASA-STD-7009B, Appendix E3.2, which includes Table 7, Level Definitions for the M&S Data Pedigree Factor.

Table 25, Life Cycle Phase Influence on Data Pedigree, shows how data pedigree is affected by the various M&S life cycle phases.

Table 25—Life Cycle Phase Influence on Data Pedigree

Phase	Name	Data Pedigree is affected by
Pre-A	Model Initiation	• The initial information gathered to direct model development.
A	Model Concept Development	• The additional/supplemental data is gathered to support the conceptualization of the model and establish requirements for model fidelity and performance. • The data supporting (justifying) the use of specific modeling methods, e.g., methods used on similar problems, can substantiate the use of specific methods over others.
B	Model Design	• Any remaining RWS data not previously gathered to allow the completion of Model Design.
C	Model Construction	• The actual data, including its form, used in the model.
D	Model Test	N/A
E	Model Use	N/A
F	Model & Analysis Archival	N/A

D.4 Verification

The process of verification ensures the computational model (or simulation model) is correctly implemented. Verification does not ensure the M&S matches the RWS or addresses the problem of interest.

a. The M&S can be considered verified when the following two conditions are satisfied:

(1) The M&S meets its specifications. These specifications start with the conceptual/mathematical model and include additional requirements for functions, e.g., user interfaces and data I/O.

(2) All significant sources of numerical errors inherent in the implementation are identified, quantified, and within assigned upper bounds.

b. A review should examine the documented evidence relating to these two aspects of verification and address questions, including:

(1) What actions demonstrated the model functions exactly as intended, as specified by the conceptual model or other model requirements? What were the results of these actions?

(2) What process was used to quantify numerical errors resulting from any algorithms, and what were the results?

(3) What process was used to quantify numerical errors resulting from factors such as sampling or quantization, the step size chosen for the numerical integration of

differential equations in a time-domain simulation, and the methods and intervals used for interpolation of model parameters; what were the results?

For guidance regarding achieving the credibility levels for the Verification factor, refer to NASA-STD-7009B, Appendix E3.3, which includes Table 8, Level Definitions for the M&S Verification Factor.

Table 27, Life Cycle Phase Influence on Verification, shows how verification is affected by the various M&S life cycle phases. While verification does not occur until Phase D, information that helps establish model design, which is the basis for verification, is influential. As Model Initiation typically only gathers preliminary information, it is not included as formally influential to verification.

Table 26—Life Cycle Phase Influence on Verification

Phase	Name	Verification is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	• As RWS & modeling concepts mature, requirements for the model are determined to scope and guide subsequent phases of development, which are checked in Verification.
B	Model Design	• The design of the model is the basis upon which the model is implemented and verified.
C	Model Construction	• This phase produces the model, based on the design requirements of Phase B, which is checked in Verification. • As implementation choices are made during model construction, specifics for verification planning and procedures are determined.
D	Model Test	• The first part of this phase is Verification. • The goals of attaining the various credibility levels of verification are achieved.
E	Model Use	N/A
F	Model & Analysis Archival	N/A

D.5 Validation

The process of validation ensures the M&S is an acceptably accurate representation of the real world from the perspective of the intended uses of the M&S. The complete handling of validation occurs in two distinct parts: Validation of the M&S design (conceptual validation) and validation of the implemented M&S (empirical validation).

Note: It is advantageous to accomplish verification before empirical validation. Accomplishing verification before empirical validation precludes the discovery of M&S implementation issues while trying to ascertain the accuracy or fidelity of the M&S with respect to the RWS. Validating an unverified M&S assumes the model is working as designed.

For guidance regarding achieving the credibility levels for the Validation factor, refer to NASA-STD-7009B, Appendix E3.4, which includes Table 9, Level Definitions for the M&S Validation Factor.

Table 27, Life Cycle Phase Influence on Validation, shows how validation is affected by the various M&S life cycle phases. While validation does not occur until Phase B (Conceptual/Design Validation) and Phase D (Model Validation), information that helps establish model design, which is the basis for validation, is influential. As Model Initiation typically only gathers preliminary information, it is not included as formally influential to validation.

Table 27—Life Cycle Phase Influence on Validation

Phase	Name	Validation is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	• RWS Conceptual Elements to include in the model design are determined, which are checked in Conceptual Validation (end of Phase B). • Potential scenarios for use of the model may be determined in this Phase, which are checked in Validation (Phase D).
B	Model Design	• The design of the model may incorporate aspects of the RWS or features to allow specified scenarios to be run, which will be implemented and validated.
C	Model Construction	• This phase produces the model to run specific types of scenarios that will be validated.
D	Model Test	• The second part of this phase is Validation, which tests against RWS scenarios. • The goals of attaining the various credibility levels of Validation are achieved.
E	Model Use	N/A
F	Model & Analysis Archival	N/A

D.6 Development Technical Review

While NASA-STD-7009B does not require technical reviews in support of, or in association with, 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].

For additional guidance regarding achieving the credibility levels for the Development Technical Review factor, refer to NASA-STD-7009B, Appendix E3.5, which includes Table 10, Level Definitions for the M&S Development Technical Review Factor.

Table 28, Life Cycle Phase Influence on Development Technical Review, shows how these technical reviews are affected by the various M&S life cycle phases.

Table 28—Life Cycle Phase Influence on Development Technical Review

Phase	Name	Development Technical Review is affected by
Pre-A	Model Initiation	• Intended Use, Criticality Assessment, M&S plan, Programmatic/Technical Metrics, Acceptance Criteria
A	Model Concept Development	• Description of RWS, including the environment, relevant operational scenarios, and relevant performance or mission success criteria • Conceptual Model including assumptions and caveats • M&S Limits (boundary conditions)
B	Model Design	• Model specifications • Model construction plan • V&V plans and success criteria
C	Model Construction	• Model construction artifacts
D	Model Test	• V&V products • Capability Assessment
E	Model Use	N/A
F	Model & Analysis Archival	N/A

D.7 Development Process/Product Management

Process/Product Management in both the Development and Use phases conveys 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. There is the potential for any process or product in the entire M&S life cycle to be formally managed or controlled.

For guidance regarding achieving the credibility levels for the Development Product/Process Management factor, refer to NASA-STD-7009B, Appendix E3.6, which includes Table 11, Level Definitions for the M&S Development Product/Process Management Factor.

Table 29, Life Cycle Phase Influence on M&S Development Product/Process Management, shows how development product/process management is affected by the various M&S life cycle phases.

Table 29—Life Cycle Phase Influence on Development Product/Process Management

Phase	Name	Development Product/Process Management is affected by
Pre-A	Model Initiation	• RWS info/data is gathered to support model development.
A	Model Concept Development	• RWS info/data. • Modeling concepts chosen.
B	Model Design	• Official baseline model design is established.
C	Model Construction	• Official baseline model is established.

Phase	Name	Development Product/Process Management is affected by
D	Model Test	• Plans, procedures, & scenarios for testing (verification or validation) are established to accept the model. • Capability Assessment • Documentation of permissible uses and user documentation (e.g., User's Guide) is formally established. • The "accepted" model is deemed ready for use.
E	Model Use	N/A
F	Model & Analysis Archival	N/A

D.8 Use Assessment

The M&S Use phase begins with a specific use for the M&S being proposed, followed by the Use Assessment in which the proposed use is compared to the M&S's permissible uses. The permissible uses for the M&S are determined during the M&S Development phase, taking the following into consideration:

a. The intended use [M&S 40].

b. The model's assumptions and abstractions [M&S 11].

c. The M&S limits [M&S 13].

d. The domain of verification [M&S 16].

e. The domain of validation [M&S 18].

f. Any additional constraints resulting from implementation methods.

Another factor-level evaluation for Use Assessment is the record of the "use history" of the M&S. Maintaining a record of the use history is a recommendation (4.3.2.g) in NASA-STD-7009B. Ideally, both the proposed use of the M&S and the RWS are identical or at least very similar to previous uses and systems. Often, however, the best that can be stated is that the proposed use and RWS are only somewhat similar to (i.e. "in family with") the prior instances, and of course there are cases in which the M&S, the RWS, or both are novel. The evaluation of the history of the M&S also looks at the "change history", which provides insight into the stability of the model implementation, if not the stability of the model concept itself.

The most essential outcome of the Use Assessment is the conclusion that either:

a. The proposed use is in accordance with the permissible uses <u>and</u> within the domains of V&V for the M&S, or;

b. The proposed use is <u>not</u> in accordance with the permissible uses <u>or</u> within the domains of V&V for the M&S.

In the event of outcome (b) the analysis results are to be placarded [M&S 26] 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. This warning is to 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.

For guidance regarding achieving the credibility levels for the Use Assessment factor, refer to NASA-STD-7009B, Appendix E4.2, which includes Table 15, Level Definitions for the M&S Use Assessment Factor.

Table 30, Life Cycle Phase Influence on M&S Use Assessment, shows how use assessment product/process management is affected by the various M&S life cycle phases.

Table 30—Life Cycle Phase Influence on M&S Use Assessment

Phase	Name	Use Assessment is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	N/A
B	Model Design	N/A
C	Model Construction	N/A
D	Model Test	• Capability Assessment • Permissible Use • Domain of Verification • Domain of Validation
E	Model Use	• M&S History • Proposed Use
F	Model & Analysis Archival	N/A

D.9 Input Pedigree

The input pedigree factor strives to address the adequacy and quality of the inputs to the model during use, including their completeness, breadth, and accuracy for use in a particular simulation, and the eventual analysis recommendations. Models are generally considered as encapsulations of certain system characteristics to which a set of data is applied for a specific analysis. The input to a model broadly refers to the data used to obtain simulation and analysis results. The input does not address the model mathematics or structure, the processing of information within the model, or statements of uncertainty accompanying the results. The data can include specific modifying parameters, with or without uncertainty, to the model or be used to set up and initialize the model.

The attributes to consider for each input are the same as those for Data Pedigree in section D.3, but with respect to M&S input data. Refer to those attributes in section D.3 through Table 25 and its accompanying notes.

For guidance regarding achieving the credibility levels for the Input Pedigree factor, refer to NASA-STD-7009B, Appendix E4.3, which includes Table 16, Level Definitions for the M&S Input Pedigree Factor.

Table 31, Life Cycle Phase Influence on Input Pedigree, shows how input pedigree is affected by the various M&S life cycle phases. As mentioned earlier, input pedigree is perhaps the only credibility factor not affected by more than one life cycle phase.

Table 31—Life Cycle Phase Influence on Input Pedigree

Phase	Name	Input Pedigree is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	N/A
B	Model Design	N/A
C	Model Construction	N/A
D	Model Test	N/A
E	Model Use	• Data to analyze for model setup and input is gathered. • Model Input is used to produce Model Output & Results.
F	Model & Analysis Archival	N/A

D.10 Uncertainty Characterization

Uncertainty Characterization is the process of identifying sources of uncertainty and describing their relevant qualities (qualitatively or quantitatively) in all models, simulations, and experiments (inputs and outputs).

a. Characterizing the uncertainty of M&S results can be accomplished qualitatively or quantitatively depending on:

(1) The maturity of the RWS.

(2) The availability of RWS data.

(3) The fidelity of the M&S.

(4) The time and resources available to characterize the uncertainty.

b. Details associated with the types of information needed to more fully understand uncertainty in M&S, include the following, which can be tracked using a table similar to Table 32, Sample Table for the Uncertainties of a Process:

(1) Name: Uniquely identifying an uncertainty.

(2) Sources: Listing what is not known or not fully known in an M&S is a beginning. Each item can then be enhanced with some qualifying information.

(3) Location: Knowing where uncertainties are located in the RWS aids in understanding it and also in determining whether or not these uncertainties should be included in the model, e.g., if the magnitude of an uncertainty is small relative to other parameters in the system or inconsequential to the outcome, then it may not be needed. Knowing the architecture of the M&S and the locations of the uncertainties can help in understanding how uncertainty propagates through the model to the results.

(4) Inclusion in the M&S: Indicating whether or not the (RWS) uncertainty is included in the M&S.

(5) Type: Classifying the type of uncertainty (e.g., epistemic or aleatory).

(6) How well known: An analyst may know there is something not known about a part or parameter of the RWS, but not know anything else. Conversely, much may be known about a given part or parameter of an RWS with a lot of supporting data.

(7) Magnitude: The magnitude of an uncertainty may be given in qualitative or quantitative form. If little is known about a particular system, then knowing that a parameter may vary in a small or large way is useful. For example, knowing the clearance height of a high-value satellite processing facility door requires more than qualitative specification.

(8) Uncertainty Mitigation Plan: For critical parameters with uncertainty, it may be useful to develop a plan for reducing that uncertainty.

Table 32—Sample Table for the Uncertainties of a Process

Name[1]	Source[2]	Location[3]	Included in M&S?[4]	Type[5]	How Well Known[6]	Magnitude[7]	Mitigation Plan[8]

The amount of uncertainty analysis is dependent on the criticality of the situation, though the exact amount is not generically determinable. As with the other credibility assessment factors, this is accomplished on a case-by-case basis. Uncertainties may be identified and analyzed or assessed in data/information from the RWS or in the methods of modeling various aspects of the model.

For guidance regarding achieving the credibility levels for the Uncertainty Characterization factor, refer to NASA-STD-7009B, Appendix E4.4, which includes Table 17, Level Definitions for the M&S Uncertainty Characterization Factor.

Table 33, Life Cycle Phase Influence on Uncertainty Characterization, shows how uncertainty characterization is affected by the various M&S life cycle phases.

Table 33—Life Cycle Phase Influence on Uncertainty Characterization

Phase	Name	Uncertainty Characterization is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	• Uncertainties from the RWS are identified, analyzed, and assessed for inclusion in the model. • Uncertainties induced from particular modeling methods.
B	Model Design	• The model is designed to incorporate (or allow the incorporation of) uncertainties. • The design of the model will also solidify uncertainties induced by modeling methods.
C	Model Construction	• Capabilities to incorporate uncertainties, or modeling methods that induce uncertainties, are built into the model.
D	Model Test	• Uncertainties are characterized in the model under test conditions.
E	Model Use	• Uncertainties from model use are characterized and reported.
F	Model & Analysis Archival	N/A

D.11 Results Robustness

The robustness of model results is determined from the analysis of model sensitivities. These inherent sensitivities may first be assessed during model testing to characterize the sensitivity of the model (in other words, to characterize the robustness of model response). The ideal outcome from sensitivity analysis are results that indicate the model sensitivities are the same as that of the RWS. When the model is operationally used, sensitivities are again analyzed to determine the specific robustness of the model results to the scenarios undertaken.

For guidance regarding achieving the credibility levels for the Results Robustness factor, refer to NASA-STD-7009B, Appendix E4.5, which includes Table 18, Level Definitions for the M&S Results Robustness Factor.

Table 34, Life Cycle Phase Influence on Results Robustness, shows how results robustness is affected by the various M&S life cycle phases.

Table 34—Life Cycle Phase Influence on Results Robustness

Phase	Name	Results Robustness is affected by
Pre-A	Model Initiation	N/A

Phase	Name	Results Robustness is affected by
A	Model Concept Development	N/A
B	Model Design	N/A
C	Model Construction	N/A
D	Model Test	• Sensitivities are first assessed during model testing to characterize the sensitivity of the model (in other words, to characterize the robustness of model response). The ideal outcome from sensitivity analysis is results that indicate the model sensitivities are the same as that of the RWS.
E	Model Use	• Sensitivities are analyzed with respect to the specific scenarios used to determine the specific robustness of the model results.
F	Model & Analysis Archival	N/A

D.12 Use/Analysis Technical Review

While NASA-STD-7009B does not require technical reviews in support of, or in association with, M&S use/analysis, 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].

For guidance regarding achieving the credibility levels for the Use/Analysis Technical Review factor, refer to NASA-STD-7009B, Appendix E4.6, which includes Table 19, Level Definitions for the M&S Use/Analysis Technical Review Factor.

Table 35, Life Cycle Phase Influence on Use/Analysis Technical Review, shows how these technical reviews are affected by the various M&S life cycle phases.

Table 35—Life Cycle Phase Influence on Use/Analysis Technical Review

Phase	Name	Use/Analysis Technical Review is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	N/A
B	Model Design	N/A
C	Model Construction	N/A
D	Model Test	N/A
E	Model Use	• Use Assessment • User's Guide • Use/Analysis results, including warnings and error messages
F	Model & Analysis Archival	N/A

D.13 Use Process/Product Management

M&S Process/Product Management in both the Development and Use phases conveys 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. There is the potential for any process or product in the entire M&S life cycle to be formally managed or controlled.

For guidance regarding achieving the credibility levels for the Use Product/Process Management factor, refer to NASA-STD-7009B, Appendix E4.7, which includes Table 20, Level Definitions for the M&S Use Product/Process Management Factor.

Table 36, Life Cycle Phase Influence on Use Product/Process Management, shows how Use Product/Process Management is affected by the various M&S life cycle phases.

Table 36—Life Cycle Phase Influence on Use Product/Process Management

Phase	Name	Use Product/Process Mgt is affected by
Pre-A	Model Initiation	N/A
A	Model Concept Development	N/A
B	Model Design	N/A
C	Model Construction	N/A
D	Model Test	N/A
E	Model Use	• Proposed Uses, Use Assessments, & Outcomes. • Scenarios for model use and definition of model setup established for the specific use. • Output and Results obtained & reported.
F	Model & Analysis Archival	• Processes & products are defined at specific collection points throughout the M&S life cycle.

APPENDIX E: MODEL AND SIMULATION (M&S) RISK ASSESSMENT

E.1 Purpose

This Appendix provides guidance for assessing M&S risks.

E.2 Model and Simulation (M&S) Risk

The discussion of M&S risk is usually focused on the RWS the M&S is representing. One major reason for developing or using an M&S is to accomplish RWS analyses using a surrogate for the RWS, thus, removing risk from the RWS. Due to expense, availability, or cost of performing an analysis on the RWS, using a surrogate is often preferred. Such surrogates are often non-operational replicants, test fixtures, emulators, analysis systems, and, increasingly, M&S. These surrogates potentially remove many, most, or all of the risks to the RWS.

The RWS situation (i.e., operations or processes) are then performed using the M&S (as a surrogate), with the risks experienced on the surrogate instead of the RWS. What becomes a concern, then, is the ability of the surrogate to fully (completely and accurately) represent the RWS. If the M&S is insufficient for a proposed use, the implications indicated from the use of an M&S (e.g., analysis) may not be useful (or directly transferrable) to the RWS. M&S risk is a measure of the potential inability of an M&S to correctly represent the RWS. Given the M&S risk, the decision maker ascertains the risk to the RWS. This inability is necessarily associated with how the M&S is used to represent the RWS, the likelihood that the representation will be inadequate, and the consequences if it occurs.

Note: A common risk mitigation strategy employed by programs/projects is the use of more than one M&S to perform analyses supporting critical decisions, where the results from the individual M&S are cross-compared. Ideally, NASA-STD-7009B is applied to the development and use of any additional M&S involved such that the cross-comparison can also include the outcomes of the key M&S assessments (Capability, Use, Results, and Risk).

M&S risks are discussed throughout NASA-STD-7009B (Table 37, Risk Related Topics in NASA-STD-7009B) and may be introduced during in any phase of the M&S life cycle (see Table 38, Examples of Possible Risks throughout the M&S Life Cycle).

Table 37—Risk-Related Topics in NASA-STD-7009B

7009 Topic	Addressed …	Location in STD
Credibility	… to reduce risk …	1.1
Definition of Margin	… to account for uncertainties and risks	3.2
Definition of Risk	… potential for shortfalls with respect to achieving explicitly established and stated objectives.	3.2
Credibility Factors	… to *reduce, assess, and communicate risk*	4
Assumptions & Abstractions	*introduces risks*	4.2.1 [M&S 11] Rationale
Unexplained Warning or Error Messages	*increase risk*	4.3.1 [M&S 27] Rationale
More than just the Results	*... the risks associated with accepting the results*	4.3.8
M&S-based Analysis	... assessment of and rationale for the risks associated	4.3.8 [M&S 39]
Prog/Proj Risk	*... inform program/project risk management processes*	4.3.8 [M&S 39] Rationale
M&S Risk Assessment	*These risks may be due to factors inherent to the M&S, or associated with the specific application or use of the M&S*	4.3.8 [M&S 39] Expl. Note
Criticality Assessment	to mitigate potential risks	[M&S 6] & Appendix D

Table 38—Examples of Possible Risks throughout the M&S Life Cycle

Model Phase		**Examples of Influence on Risk**
Designator	**Name**	
Pre-A	Model Initiation	• Amount & Quality of RWS Info Available.
A	Model Concept	• Amount of Time, Money, & Resources Available for Model Development.
B	Model Design	• Trades in Model Design that Affect Fidelity.
C	Model Construction	• Choices in Model Implementation that Affect RWS Representation.
D	Model Test	• Completeness in Verification. • Completeness in Validation.
E	Model Use	• Appropriateness of Proposed Use to Permissible Use. • Amount & Quality of Input Data Available. • Completeness in Model Use to discover accuracy, uncertainties, & sensitivities. • Warning or Errors during Model Use. • Correct & Complete post-use analysis of data.
F	Model & Analysis Archival	• Adherence to Work Product Mgt. • Understanding Model Change History & Past Uses.

While risks incurred in either development or use of the M&S are best understood and mitigated when they occur, any M&S risks having implications to the RWS are to be assessed and reported with the results of any M&S-based results [M&S 39]. These M&S risks are then to inform the applicable program/project risk management processes and procedures (refer to NPR 8000.4) for risk-informed decision making (RIDM) (Figure 18, NASA RIDM Process) and continuous risk management (CRM) (Figure 19, NASA CRM Process).

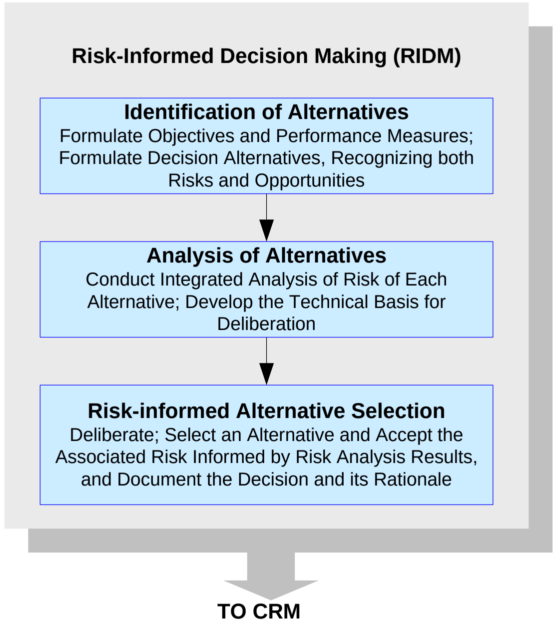


Figure 18—NASA RIDM Process

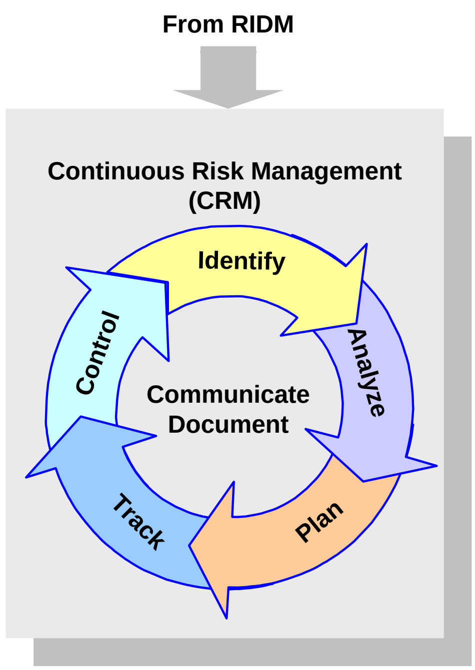


Figure 19—NASA CRM Process

Additional guidelines for the entire NASA risk management approach are found in NASA/SP-20240014019, NASA Risk Management Handbook, and NASA SP-2010-576, NASA Risk-Informed Decision Making Handbook.

E.3 Aspects of Model and Simulation (M&S) Risk

While the emphasis is on RWS risk, the M&S practitioner is to identify what risks are incurred during M&S development and use.

Most, if not all, of the R/r's in NASA-STD-7009B may relate to some aspect of (M&S) risk, either by:

a. Identification of the risk element.

b. Description of the context (of the situation the M&S is representing).

c. Understanding the influence of the specific risk element (to the M&S results and, in turn, the RWS).

d. Clearly communicating risk elements when reporting the results from an M&S-based use.

These aspects of risk, as contained in NASA-STD-7009B, are shown in this Handbook's section 5.6.3.2.2, Table 14. While these elements may not be critical to the correct functioning of the M&S (i.e., the ability of the M&S to produce acceptable or useful results), having them can provide greater clarity than if they were not addressed. The NASA-STD-7009B requirements (including their rationale statements) and recommendations provide additional information as to what is needed to more fully understand each element and Table 11 (Technical Review), Table 12 (People Qualifications), and Table 13 (Documentation) in this Handbook.

A detailed listing of the elements and sub-elements of M&S risk are consolidated in Table 39, Detailed M&S Risk Elements, for convenience.

Table 39—Detailed M&S Risk Elements

7009 Req't	Reporting Req't	Does risk exist w.r.t. this item? (Yes / No)	If yes, describe the risk(s).	If yes, provide the rationale for proceeding with the risk(s).
[M&S 50], [M&S 35]	**Credibility Assessment**			
[M&S 48]	**M&S Capability Assessment**			
	Data Pedigree			
	Verification			
	Validation			
	M&S Development Tech Review			
	Development Process/Product Management			
[M&S 31]	**M&S Results Assessment**			
	Use Assessment			
	Input Pedigree			
	Uncertainty Characterization			
	Results Robustness			
	M&S Use Tech Review			
	M&S Use Process/Product Mgt			
[M&S 32]	**Caveats**			
(a)	Unachieved Acceptance Criteria			
(b)	Violation of any Assumptions			
(c)	Violation of the Limits of Operation			
(d)	Execution Warning and Error Messages			
(e)	Unfavorable outcomes from the assessed appropriateness of the M&S to the proposed use			
(f)	Issues encountered from Setup/Execution Assessments			
(g)	Waivers to Requirements			
(h)	M&S defects or problems			
[M&S 33]	**Uncertainty in Results**			
(a)	Quantitative Estimate			
(b)	Qualitative Description			
(c)	No estimate or description given			
[M&S 34]	**Uncertainty Processes**			
	Processes for obtaining Uncertainties in M&S Input			
	Processes for obtaining Uncertainties in M&S Results			

7009 Req't	Reporting Req't	Does risk exist w.r.t. this item? (Yes / No)	If yes, describe the risk(s).	If yes, provide the rationale for proceeding with the risk(s).
	Processes for obtaining Uncertainties in Quantities Derived from M&S Results			
[M&S 36]	**Development and Use Technical Reviews**			
	Review			
	- What was reviewed?			
	- Depth of Review			
	- Formality of Review			
	- Currency of Review			
	Reviewers			
	- Expertise			
	- Independence			
[M&S 37]	**People Qualifications**			
	Developers			
	Testers			
	Users (Operators)			
	Analysts			
[M&S 38]	**M&S Documentation** (Synopsis)			
[M&S 40]	Intended Use			
[M&S 6]	Criticality Assessment			
[M&S 41]	M&S plan for the acquisition, development, operation, maintenance, and retirement			
[M&S 42]	M&S programmatic and technical metrics			
[M&S 43]	M&S Acceptance Criteria			
[M&S 44]	M&S Unique Information			
[M&S 9]	Technical Reviews			
[M&S 51]	M&S Defects or Problems			
[M&S 10]	Relevant Characteristics of RWS for M&S Development			
[M&S 46]	M&S Units and Vector Coordinate Frames			
[M&S 11]	Assumptions & Abstractions			
[M&S 12]	Structure & Math of M&S			
[M&S 13]	Limits of Operation			
[M&S 14]	Permissible Uses			
[M&S 16]	Domain of Verification			

7009 Req't	Reporting Req't	Does risk exist w.r.t. this item? (Yes / No)	If yes, describe the risk(s).	If yes, provide the rationale for proceeding with the risk(s).
[M&S 18]	Domain of Validation			
[M&S 19]	Processes for Characterizing Uncertainty in Referent Data			
[M&S 21]	Incorporated Uncertainties			
[M&S 22]	Proposed Uses			
[M&S 23]	Use Assessment			
[M&S 24]	Input Data			
[M&S 25]	Setup & Execution Rationale			
[M&S 27]	Warning or Error Messages			
[M&S 28]	Processes for Characterizing Uncertainty in Input, Results, Derived Results			
[M&S 29] (a)	Uncertainties in Input			
[M&S 29] (b)	Uncertainties in Results			
[M&S 29] (c)	Uncertainties in Derived Results			
[M&S 30]	Sensitivity Analyses			

APPENDIX F: M&S USE STATEMENTS

F.1 Purpose

This Appendix provides guidance on the definition and implementation of the M&S use statements.

F.2 Use Statements in the M&S life cycle.

NASA-STD-7009B presents five definitions for terms that include the word “use”. These definitions are presented below (*with added comments in italics*) in the order in which the terms are encountered during the M&S Life Cycle.

1) **Intended Use**: The expected purpose and application of an M&S.
The Intended Use is defined during M&S Initiation and has major impacts upon all aspects of M&S Development (design, construction, verification, validation).

2) **Permissible Use**: The purposes for which an M&S is formally allowed.
The Permissible Use is determined at the conclusion of the M&S Development phase per the outcomes of M&S Verification, M&S Validation, and the M&S Capability Assessment.

3) **Proposed Use**: A desired specific application of an M&S.
The Proposed Use is defined at the start of the M&S Use phase. The Proposed Use may or may not be identical to the Intended Use.

4) **Accepted Use**: The successful outcome of a *Use Assessment* designating the M&S is sufficient for a Proposed Use.
The Accepted Use is determined by the outcome of the Use Assessment, during which the Proposed Use is compared to the Permissible Use. Ideally, the Permissible Use satisfies the Proposed Use, in which case the Proposed Use is <u>accepted</u>. However, should this not be the case, a decision must be made to either revise (de-scope) the Proposed Use or to proceed at risk by accepting a Proposed Use that exceeds the M&S capabilities.

5) **Actual Use**: The specific purpose and domain of application for which M&S are being, or were, used.
The Actual Use is determined per the outcome of the M&S Results Assessment. Ideally, the Actual Use matches the Accepted Use, i.e., all of the objectives defined by the Accepted Use were achieved via direct use of the M&S along with any follow-on analysis activities. However, this may not always be the case.

Figure 20, Use Statement Development During the M&S Life-Cycle, provides the context of these different uses within the M&S Life Cycle

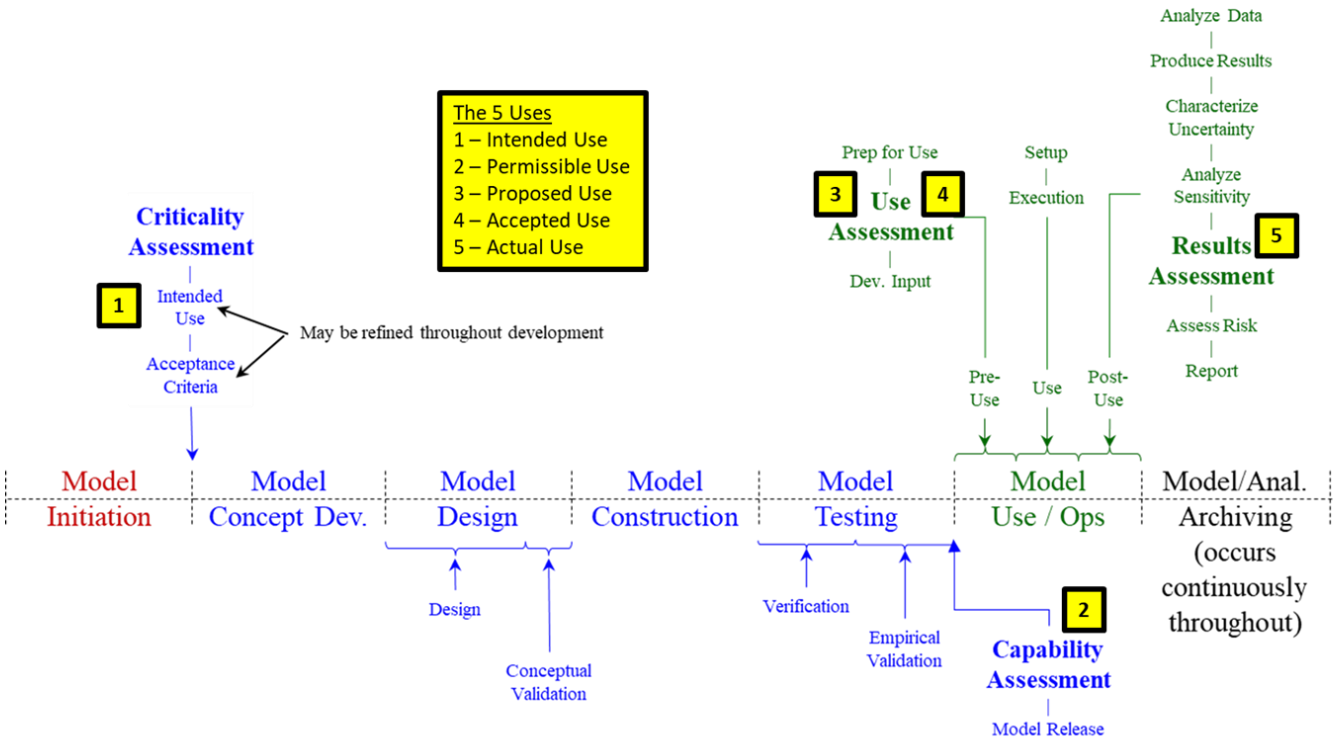


Figure 20—Use Statement Development During the M&S Lfe-Cycle.

APPENDIX G: TECHNICAL WORKING GROUP

G.1 Purpose

This Appendix provides guidance in a list of the individuals in the Technical Working Group who drafted this Handbook and can provide additional guidance, as necessary for implementing the practices in NASA-STD-7009B or this Handbook.

G.2 Technical Working Group

Name	Center
Brian K Kryszczynski	Kennedy Space Center
Wei Lin Jamie Meeroff Ben Margolis	Ames Research Center
Jerry Myers, Ph.D. (Office of Primary Responsibility Designee) Chris Steffen John Gillespie John Yim	Glenn Research Center
Gary Mosier Yaguang Yang, Ph.D.	Goddard Space Flight Center
Mariea Dunn Brown Greg Drayer	Marshall Space Flight Center
Jonathan Borland Raj Prabhu, Ph.D. Mike Conroy John Arellano, Ph.D.	Johnson Space Center
Michael Madden Armando Delgado	Langley Research Center
Timothy Barth, Ph.D.	NASA Engineering and Safety Center (Kennedy Space Center)
Tristan Mooney Laurence de Quay, Ph.D.	Stennis Space Center

For further questions or guidance in the use of this Handbook, contact the Office of Primary Responsibility or other Center representatives listed above.