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

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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.

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 NASA Technical Handbook is approved for use by NASA Headquarters and NASA Centers and Facilities. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center (FFRDC), other contractors, recipients of grants and cooperative agreements, and parties to other agreements only to the extent specified or referenced in applicable contracts, grants, or agreements.

This NASA Technical Handbook establishes general guidance to assist in complying with the requirements and recommendations of NASA-STD-7009A, Standard for Models and Simulations, including technical information, application instructions, data, recommended practices, procedures, and methods used in support of NASA-STD-7009A. 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 NASA Technical 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).

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

____Original signed by________   __________05/08/2019____________
Ralph R. Roe, Jr.   Approval Date
NASA Chief Engineer

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1. SCOPE

1.1 Purpose

The purpose of this NASA Technical Handbook is to provide technical information, clarification, examples, processes, and techniques to help institute good modeling and simulation practices in the National Aeronautics and Space Administration (NASA). As a companion guide to NASA-STD-7009A, Standard for Models and Simulations, this NASA Technical 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 modeling and simulation products. NASA-STD-7009A specifies what a modeling and simulation activity shall or should do (in the requirements and recommendations), but does not prescribe how they are accomplished, which varies with the specific engineering discipline, or who is responsible for accomplishing them, which depends on 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 NASA Technical 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 model and simulation (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 NASA Technical Handbook are the implementation details of the general M&S requirements of NASA-STD-7009A, including explanations, examples, and suggestions for improving M&S credibility throughout the M&S life cycle.

1.2 Applicability

This NASA Technical Handbook is applicable to a broad audience, ranging from the variety of M&S practitioners (developers, users, and analysts, for example) and consumers of M&S-based products and analyses to technical reviewers of M&S activities and analyses.

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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)

NASA-STD-7009A and this NASA Technical 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-7009A is primarily focused toward 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 NASA Technical Handbook may be used by anyone, as in the following examples:

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 NASA Technical 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 NASA Technical 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 NASA Technical Handbook to ensure meeting the minimal expectations of a product used for critical analysis.

Anyone may use NASA-STD-7009A or this NASA Technical Handbook in the course of their modeling and simulation activities; however, the use is highly recommended for M&S that meet established risk criteria determined by program/project management in collaboration with the NASA delegated Technical Authority as outlined in Appendix D of NASA-STD-7009A. 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; therefore, the types of possible M&S are not included here, but are discussed briefly in section 4.1 of this NASA Technical Handbook.

NASA-STD-7009A applies to any point in the program/project life cycle to which an M&S-based analysis may be applied. However, 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 NASA Technical Handbook.

NASA-STD-7009A 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.

This NASA Technical Handbook is approved for use by NASA Headquarters and NASA Centers and Facilities. It may also apply to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center (FFRDC)), other contractors, recipients of grants and cooperative agreements, and parties to other agreements, only to the extent specified or referenced in their applicable contracts, grants, or agreements.

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

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section are applicable to the guidance in this NASA Technical Handbook.

2.1.1 The latest issuances of cited documents may apply unless specific versions are designated.

2.1.2 Non-use of a specifically designated version is approved by the delegated Technical Authority.

Applicable documents may be accessed at https://standards.nasa.gov or obtained directly from the Standards Developing Body or other document distributors. When not available from these sources, information for obtaining the document is provided.

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 7120.5	NASA Space Flight Program and Project Management Requirements
NPR 7150.2	NASA Software Engineering Requirements
NPR 8000.4	Agency Risk Management Procedural Requirements
NPR 8715.3	NASA General Safety Program Requirements
NASA-STD-7009A	Standard for Models and Simulations

NASA/SP-2016-6105 Rev 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
	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. http://www.nasa.gov/pdf/55691main_Diaz_020204.pdf
NASA TM-2002-211715, IECEC-2002-20113	"Comparison of ISS Power System Telemetry with Analytically Derived Data for Shadowed Cases", Fincannon, H. James

Department of Defense (DoD)

	DoD Modeling and Simulation (M&S) Glossary. Retrieved May 8, 2018. https://www.msco.mil/MSReferences/Glossary/MSGlossary.aspx
	Conceptual Model Development and Validation, VV&A Recommended Practice Guide special topic, May 18, 2011. Retrieved Feb 21, 2018. https://vva.msco.mil/default.htm?Special_Topics/Conceptual/default.htm
MIL-STD-3022	Standard Practice Documentation of Verification, Validation, and Accreditation (VV&A) for Models and Simulations

Environmental Protection Agency (EPA)

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

Sandia National Laboratories

SAND2003-3769	Oberkampf, W.; Trucano, T.; and Hirsch, C. (February 2003). "Verification, Validation, and Predictive Capability in Computational Engineering and Physics."
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 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

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.

Kelton, W.D.; Sadowski, R.P.; and Sturrock, D.T. (2004). *Simulation with Arena*, Third Edition. New York: McGraw-Hill.

Oberkampf, W.L.; Roy, C.J. (2010). *Verification and Validation in Scientific Computing*. Cambridge, England: Cambridge University Press, Cambridge.

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.

Telford, Jacqueline K. (2013). *A Brief Introduction to Design of Experiments*. Johns Hopkins APL Technical Digest. http://www.jhuapl.edu/techdigest/TD/td2703/telford.pdf

The American Heritage Dictionary of the English Language, 4th ed. (2006). Boston: Houghton Mifflin Co.

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

2.4 Order of Precedence

2.4.1 This NASA Technical 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 NASA Technical Handbook and other documents are resolved by the delegated Technical Authority.

3. ACRONYMS, ABBREVIATIONS, SYMBOLS, AND DEFINITIONS

3.1 Acronyms, Abbreviations, and Symbols

%	percent
®	registered trademark
AHS	The American Helicopter Society International
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute

ASAP	Aerospace Safety Advisory Panel
ASC	American Standards Committee
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
CA	California
CAD	Computer-Aided Design
CAE	ComputerAided Engineering
CAM	Computer-Aided Manufacturing
CM	configuration management
COTS	commercial off the shelf
CRM	continuous risk management
DoD	Department of Defense
DOF	degree of freedom
EPA	Environmental Protection Agency
FEM	finite element model
FEMCI	Finite Element Modeling Continuous Improvement
FFRDC	Federally Funded Research and Development Center
GNC	Guidance, Navigation, & Control
GOTS	government off the shelf
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
HI	Hawaii
I&T	Integration and Test
I/O	Input/Output
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KSC	Kennedy Space Center
M&S	Models and Simulations (See usage note in section 4 of this NASA Technical Handbook.)
M&SCO	Modeling and Simulation Coordination Office
MIL	Military
MOS	Margin of Safety
MOTS	modified off the shelf
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
NIST	National Institute of Standards and Technology
NM	New Mexico

NPD	NASA Policy Directive
NPR	NASA Procedural Requirements
ODE	ordinary differential equatio
OMB	Office of Management and Budget
PDE	partial differential equation
pdf	probability density function
PIRT	Phenomena Identification and Ranking Table
PLD	Programmable Logic Devices
R/r	Requirements or recommendations
Req’t	Requirement
RIDM	risk informed decision making
RWS	Real World System
S/W	Software
SI	System Internationale
SME	Subject Matter Expert
SP	Special Publication
SPIE	The International Society for Optical Engineering
SRQ	System Response Quantities
STD	Standard
SWE	Software Engineering
V&V	Verification and Validation
VCS	Voluntary Consensus Standards
VV&A	Verification, Validation, and Accreditation
w.r.t.	with respect to

3.2 Definitions

The definitions listed below are those used in this document and are in the context of models and simulations (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) Modeling and Simulation Coordination Office (M&SCO), 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.

<u>Abstraction</u>: 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 in, or exclude from, the model. Focusing includes either emphasizing or deemphasizing certain aspects of the RWS when including them in the model. Transforming includes any change in the appearance, character, composition, configuration, expression, or structure of aspects of the RWS (when including them) in the model (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 a model, simulation, or experiment to the true value or the assumed true value.

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

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

Analysis: The examination of a situation or problem in order to understand the item in question and make appropriate recommendations. (**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 a model, the development of simulation scenarios, and the study and reduction of data from use of the M&S into recommendations for the RWS.)

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.)

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 a model with respect to the RWS or presume values for certain parameters in a model.)

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

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

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

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

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

Configuration Management (CM): A management discipline applied over the product's life cycle to provide visibility into and to control changes to performance and to functional and physical characteristics. (**Note:** NPR 7120.5, 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." (NASA-STD-7009A.)

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 (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:** It is applicable to both physical processes and computer simulation models.[3])

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

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

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

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[3] This definition is largely a direct quote from *A Brief Introduction to Design of Experiments*, by Jacqueline K. Telford. Retrieved April 22, 2013. http://www.jhuapl.edu/techdigest/TD/td2703/telford.pdf.

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

Environment of the System (or RWS): The set of elements external to a system. The RWS and its environment may interact through the exchange of properties. (**Note:** Only the interactions relevant to an analysis should be included in the M&S.)

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

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

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 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. (**Note:** 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. (**Note:** NASA-STD-7009A.)

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

[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.

Margin: The allowances carried in budget, projected schedules, and technical performance parameters (e.g., weight, power, or memory) to account for uncertainties and risks. (**Note:** 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. (**Note:** Adapted from ASME V&V 10, Guide for Verification and Validation in Computational Solid Mechanics.)

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

Model: A description or representation of a system, entity, phenomena, or process.[6] (**Note:** A model may be constructed from multiple sub-models; the sub-models and the integrated sub-models are all considered models. Likewise, any data that go into a model are considered part of the model.)

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

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

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

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

Numerical Errors: Errors traceable to various sources, including but not limited to floating point precision, inherent in all computer systems and leading to round off, underflow, and overflow; truncation of infinite series expansions; and approximations of exact solutions inherent in all numerical methods, e.g., approximation of derivatives and integrals by algebraic operations on sampled continuous functions.[7]

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

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

[6] Adapted from Banks, J., ed. (1998). *Handbook of Simulation*. New York: John Wiley & Sons.
[7] Yang, W.Y.; Cao, W.; Chung, T.-S.; and Morris, J. (2005). *Applied Numerical Methods Using MATLAB®.* Hoboken: John Wiley & Sons, Inc.

Probabilistic: Pertaining to non-deterministic events, the outcome of which is described by a measure of likelihood.[8]

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

Real World System: The reality of interest the model is representing, which may include relevant operating conditions or aspects of its environment. (**Note:** The RWS may interact with its environment, i.e. a set of relevant elements external to the RWS, through the exchange of properties. The term RWS is used to differentiate between the "system represented" and the "modeling system" used for the analysis.)

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

Referent: Data, information, knowledge, or theory against which simulation results can be compared. (NASA-STD-7009A; 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 model.)

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

Responsible Party: The group or individual identified as accountable for complying with requirements in NASA-STD-7009A. (**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 as-designed control 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. (**Note:** This definition has been updated from the definition found in NASA-STD-7009A, to the recently revised definition found in NPR 8000.4B, 12/06/2017.)

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 a simulation model. (**Note:** The scenario may include, but is not limited to the set of initial

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

conditions, a set of assumptions, the values of relevant parameters [including system and environmental conditions, locations and quantities of objects, entities, or resources], or a sequence of actions, which may be specified in the model itself. Running the model with the given scenario is the simulation.)

Sensitivity Analysis: The study of how variation in the output of an M&S can be apportioned to different sources of variation in the model input and parameters. (**Note:** The Results Robustness of an M&S-based analysis is obtained via sensitivity analysis (NASA-STD-7009A, 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. (**Note:** 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.

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

Uncertainty: (a) The estimated amount or percentage by which an observed or calculated value may differ from the true value[9]; (b) A broad and general term used to describe an imperfect state of knowledge or a variability resulting from a variety of factors, including but not limited to lack of knowledge, applicability of information, physical variation, randomness or stochastic behavior, indeterminacy, judgment, and approximation (adapted from NPR 8715.3, NASA General Safety Program Requirements); (c) Non-negative parameter characterizing the dispersion of values attributed to a measured quantity.

Uncertainty Characterization: The process of identifying all relevant sources of uncertainties and describing their relevant qualities (qualitatively or quantitatively) in all models, simulations, and experiments (inputs and outputs).

Uncertainty Quantification: The process of identifying all relevant sources of uncertainties; characterizing them in all models, experiments, and comparisons of M&S results and experiments; and quantifying uncertainties in all relevant inputs and outputs of the simulation or experiment. (**Note:** NASA-STD-7009A.)

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

[9] *The American Heritage Dictionary of the English Language, 4th ed.* (2006). Boston: Houghton Mifflin Co.

procedural programming languages, such code fragments are generally functions or subroutines.[10]

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. (**Note:** OMB Circular No. A-119.)

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

4. INTRODUCTION

Note: The acronym M&S is used in a variety of ways in the literature:

a. Model and simulation.
b. Models and simulations.
c. Modeling and simulation.
d. Modeling and simulating.

The acronym is additionally confusing in that the term “model” can be used as both a noun and a verb. In the development of NASA-STD-7009A, the decision was to focus on the product of models and simulations, rather than on the process of modeling and simulating. The use of M&S in this NASA Technical Handbook, as in NASA-STD-7009A, refers to models and simulations. There are times when the singular or plural form is intended, which can be inferred from the context.

[10] http://www.saravanansubramanian.com/Saravanan/Articles_On_Software/Entries/2010/1/19_Unit_Testing_101_For_Non-Programmers.html. Retrieved April 22, 2013.

4.1 Background

NASA-STD-7009A holds a unique place in the world of modeling and simulation in that it is generally applicable to all types of M&S and all phases of M&S development and use, though its primary focus is 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. However, 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 NASA-STD-7009A, 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 NASA Technical Handbook, which was initially sponsored by the NASA Engineering and Safety Center (NESC) in December 2009.

Development of this NASA Technical 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-7009A for its use.

The development of this NASA Technical 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 doing 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 RWS project requirements relevant to the M&S.

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

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

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

h. Address M&S limits of operation.

i. Provide guidance on coupled models.

The questions related to implementation of the requirements of NASA-STD-7009A 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 NASA Technical Handbook. While implementation of NASA-STD-7009A 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:

- M&S primarily based on differential equations or difference equations.
- A relative geometry model of various objects over time.
- Regression models from empirical data.
- Various system data relationship models.
- 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. Therefore, one essential consideration in the development of the NASA Technical Handbook was to provide guidance and explanations about the requirements and recommendations included in NASA-STD-7009A and thus ease and broaden its use. Understanding the development and use phasing of the NASA-STD-7009A 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."[11] Studies were also accomplished in the area of 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 NASA Technical Handbook combines aspects of both worksheets and checklists.

Note: This NASA Technical 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 Applicability

The question of the applicability NASA-STD-7009A often arises in new programs, projects, or M&S efforts. The wording in NASA-STD-7009A 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-7009 is highly recommended.

d. NASA-STD-7009 becomes required when so specified in program, project, organization, or office directives.

4.3 Interpreting and Tailoring

Any general standard necessarily requires either interpretation or tailoring to a particular application. Both are acceptable, as long as they are justified, approved (as necessary), and

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

documented (see Table 4 in section 4.8 for more on Program/Project Management and delegated Technical Authority Responsibilities). 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 provide no handling for uncertainties that always exist in an RWS, which means the uncertainty characterization requirements might justifiably be eliminated.

4.4 Compliance with NASA-STD-7009A

Key aspects of M&S development and use are clarified when the requirements and recommendations of NASA-STD-7009A 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 both verification and validation.

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-7009A, Appendix D).
(2) Uncertainty of the Results.
(3) Caveats to the Results.

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-7009A, Appendix E).

(5) Results from any Technical Reviews.
(6) People Qualifications (Developers, Users, Analysts).
(7) M&S Documentation (adequacy thereof).
(8) M&S Risk.

Note: The documentation requirements and recommendations of NASA-STD-7009A 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 (MIL-STD-3022, Standard Practice Documentation of Verification, Validation, and Accreditation (VV&A) for Models and Simulations, and DoD Modeling and Simulation (M&S) Glossary) 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-7009A and additional explanations are available in this NASA Technical Handbook (relevant sub-sections of section 5).

4.5 Models – Key Concept

NASA-STD-7009A 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) Exact knowledge about the RWS is rarely complete and usually uncertain.
(2) Details are not sufficiently characterized so as 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 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; however, the intent is to include the pertinent representations necessary for the model's intended purpose. The key concept is that models and simulations are not exact representations, and therefore, 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

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 NASA Technical Handbook, pedigree and provenance are synonymous.

NASA-STD-7009 and this NASA Technical 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-7009. The ability to reference a specific M&S life cycle and address the processes and products of each phase of that life cycle (section 5) is emphasized in both the Standard and the 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-7009A 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 a number of 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: (1) Executing a simulation using a thermal model of the system; (2) Transferring (mapping) the predicted temperatures to a structural model of the system; (3) Executing a simulation of the temperature-induced elastic deformations of the structure using this structural model; (4) Transferring the structural deformations into an optical model; (5) Transferring the predicted temperatures to the optical model to account for temperature-dependent index-of-refraction of lens elements, if any; and (6) 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-7009A to the individual M&S and, subsequently, to the linked or integrated M&S as a whole. The level definitions for the input pedigree factor in the credibility assessment anticipate exactly this scenario.

Surrogate models are sometimes synonymous with 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 similar to that used to construct empirical models, where data from observations (measurements) are used as the basis for approximating the relationships between independent and dependent variables. For surrogate models, simulation data replaces observations as the source of data. Two typical methods for creating empirical and surrogate models are statistical regression and neural networks. Surrogate models are usually developed because of their significant performance advantage over more detailed, application- or discipline-specific (e.g., physics-based) model implementations. However, surrogate models not only take on all the assumptions and limitations of the models on which they are based, but also incorporate additional limitations from their specific implementation.

4.5.3 NASA’s Motivation to Model

In the development of aerospace systems outside NASA, e.g., in commercial aviation, the risk associated with models 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 the system.
f. Not meeting stakeholder requirements (e.g., for reliability or affordability).

Because of these impacts and a relatively high-risk profile, testing of operational systems in operational environments, e.g., flight tests, is typically limited. NASA's engineering processes, therefore, 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.

4.6 The Modeling (and Simulation) Process/Life Cycle

An M&S life cycle was introduced in Revision A 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. 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 7120.5E, Fig. 2-5) with its familiar phases and their designations. Therefore, 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 (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	Model Initiation	Model Concept Development	Model Design	Model Construction	Model Testing	Model Use	Model & 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 Cycle in an RWS Life Cycle, depicts an entire M&S life cycle within the Conceptual Studies phase 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.

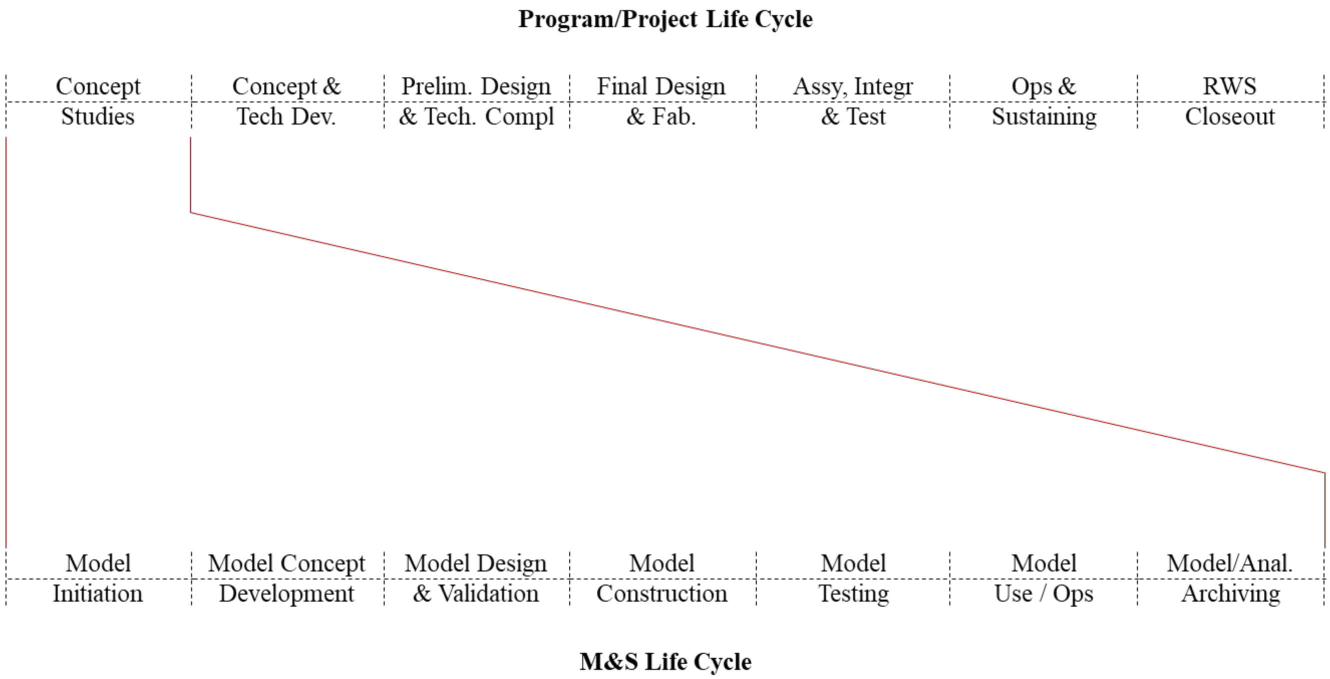


Figure 1—M&S Life Cycle in an RWS Life Cycle

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 NASA Technical Handbook.

Table 2—M&S Life-Cycle Phase Descriptions

Phase	Name	Brief Description
Pre-A	Model 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	Model 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	Model Design	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 Model Construction (Phase C).
C	Model 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	Model 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	Model 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	Model & Analysis Archival	The process of storing and cataloging all M&S and designated development and use artifacts for retrieval and use.

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

a. It is understood that actual execution of these 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-7009A. 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.

b. Many of the 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) 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.

c. 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 NASA Technical Handbook follows these life-cycle phases.

4.7 Relation to NPR 7150.2

Models, particularly analytical models, are usually implemented in software. Section 4 of NASA-STD-7009A 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 (Table 3, Classes of NASA Software):

Table 3—Classes of NASA Software

Class	Software Description
A	Human-Rated Space Software Systems
B	Non-Human Space-Rated 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 and Research and Technology Software
F	General Purpose Computing, Business and IT Software (Multi-Center or Multi-Program/Project)
G	General Purpose Computing, Business and IT Software (Single Center or Project)
H	General Purpose Desktop Software

NPR 7150.2, Appendix D, defines each class in detail; and 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, the NPR 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 the NPR are (or at least may be, under certain conditions) 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-7009A 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-7009A. 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 also likely unknown to M&S practitioners, NPR 7150.2 states:

> *In this directive, "software" is defined as the computer programs, procedures, scripts, rules, and associated documentation and data pertaining to the development and operation of a computer system. This definition applies to software developed by NASA, software developed for NASA, software maintained by or for NASA, commercial off-the-shelf (COTS) software, government off-the-shelf (GOTS) software, modified off-the-shelf (MOTS) software, reused software, auto-generated code, embedded software, the software executed on processors embedded in programmable logic devices (see NASA-HDBK-4008, Programmable Logic Devices (PLD) Handbook), legacy, heritage, and open-source software components.*

This means that requirements for Class D/E (e.g., engineering CAD/computer-aided engineering CAE) software apply to commercial tools (e.g., SOLIDWORKS®, the structural analysis system (NASTRAN), internally developed tools, or combinations thereof).

Finally, note that NASA-STD-7009 is referenced in the NPR (in section 4.5.7 of NPR 7150.2B) 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 verification and validation techniques and the analysis of models and simulations can be found in NASA-STD-7009 and NASA-HDBK-7009.*" In NPR 7150.2, a software engineering (SWE) number designates a requirement.

Neither NASA-STD-7009 nor NASA-HDBK-7009 provide *specific V&V techniques* (other than a few simple examples contained in NASA-HDBK-7009), but leave such details to discipline-specific recommended practices. Also note, while the definitions of verification and validation in NASA-STD-7009 and NPR 7150.2 are similar, their interpretations may be different. For an M&S to be valid, its results are to compare favorably with referent (or RWS) data (per [M&S 8] (4)).

4.8 Program/Project Management and Delegated Technical Authority Responsibilities

Throughout NASA-STD-7009A, there are a number of explicit and implicit responsibilities on either program/project management or the delegated 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 Technical Authority Responsibilities, for easy reference. On the other hand, the requirements in NASA-STD-7009A are addressed to "the responsible party," since it is likely different for each model. The seventh row after the title row in Table 4 indicates the program/project management responsibility to identify “the responsible party” for each requirement.

Table 4—Program/Project Management and Delegated Technical Authority Responsibilities

Program/ Project Management Responsibility	Delegated Technical Authority Responsibility	Topic	Sections	Requirements	Rec. Sections
Defines	Approves	Acceptance Criteria	1	-	-
Specifies	-	Required application of NASA-STD-7009	1.2	-	-
Documents	-	Precedence over VCSs	1.2	[M&S 1]	-
Documents	Approves	Tailoring	1.3	[M&S 2]	-
-	Approves	Non-Use of latest cited Applicable Documents	2.1.1, 2.1.2	[M&S 3], [M&S 4]	-
-	Resolves conflicts	Requirement Conflicts	2.4.2	[M&S 5]	-
ID's & Document	-	Responsible Parties	4	-	-
ID's & Document	ID's & Document	Criticality / Critical Decisions / M&S In Scope	3.2 (Critical Decision), 4.1	[M&S 6], [M&S 7]	-
ID's & Document	ID's & Document	Level of Formality	4	-	-
-	Assure appropriate outcomes	Objectives & Req'ts for M&S Products	-	[M&S 8]	-
Deem achievement	-	Mission Success Criteria	3.2 (Mission Success Criteria)	-	-
Accepts	Concurs / Approves	Waivers	3.2 (Waivers)	-	-
-	Assures appropriate outcomes	Use Assessment	4.3.1	[M&S 23]	-
-	Establishes & Assures appropriate outcomes	Credibility Assessment	4.3.6	[M&S 31]	4.3.7-a, c (thresholds)
Is informed by	-	Risk	4.3.8	[M&S 39]	-

5. M&S LIFE CYCLE PROCESSES

As introduced in section 4.6, this NASA Technical Handbook is structured according to the M&S life cycle, as defined in NASA-STD-7009A, Appendix F. This section of the NASA Technical 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 in 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 are identified.

Note: The concept of Data Pedigree, the first factor of the Credibility Assessment, is directly influenced in this early phase of 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 8 (2)] 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.

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.

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 any and 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 also higher-level program/project planning and resource allocations. Appendix D of NASA-STD-7009A 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 the determination 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) 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-7009A 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.

However, 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 of 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.

(As a matter of current interest, 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. These experiments 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, or validate M&S results.

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.

f. Initial model development plans.

All of this 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 model. 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.

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 (i.e., the Intended Use, preliminary RWS information, preliminary modeling approaches, and RWS empirical data) and develops them further into concepts, information, or specifications to continue model development and enable detailed model design, including:

a. RWS refinement and data collection.
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.

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/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. An expanded diagram (Figure 2, Overall Representative System Expanded Diagram (SLS example)), of the overall representative system, which is the subject of the model, 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 Enviroment), which includes all (physical, chemical, behavioral, and other types of) events 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."

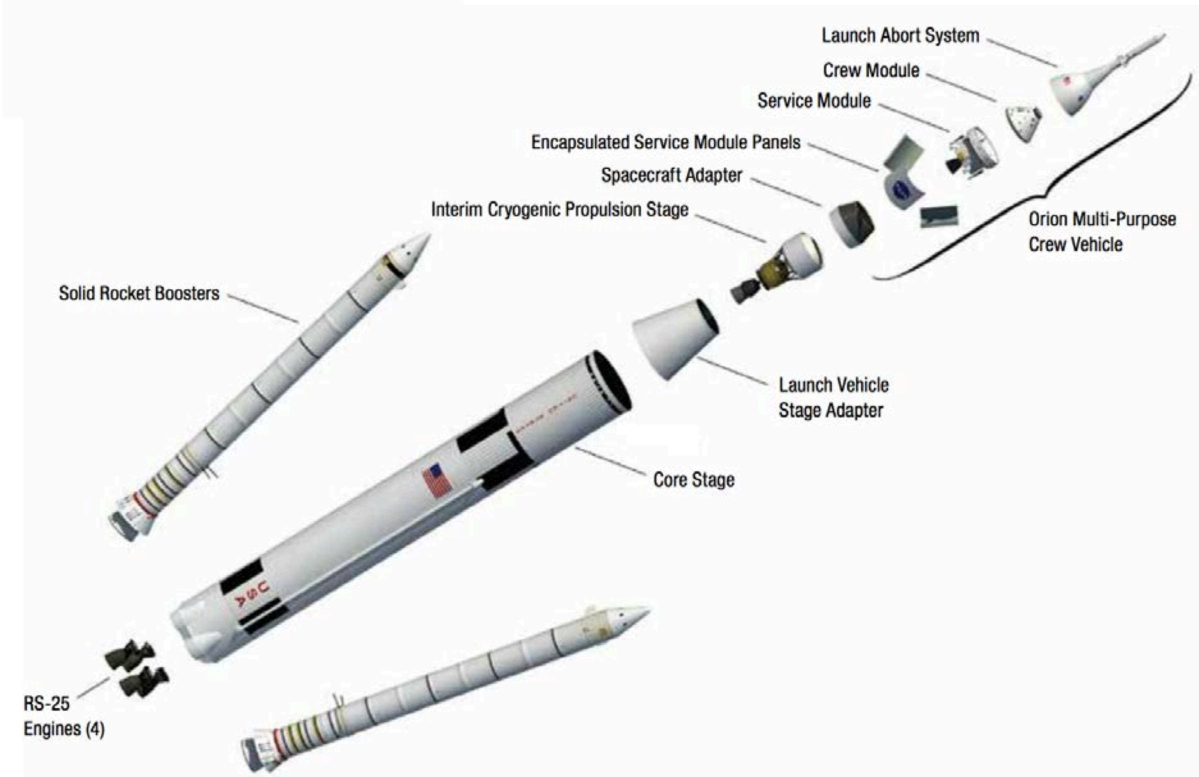
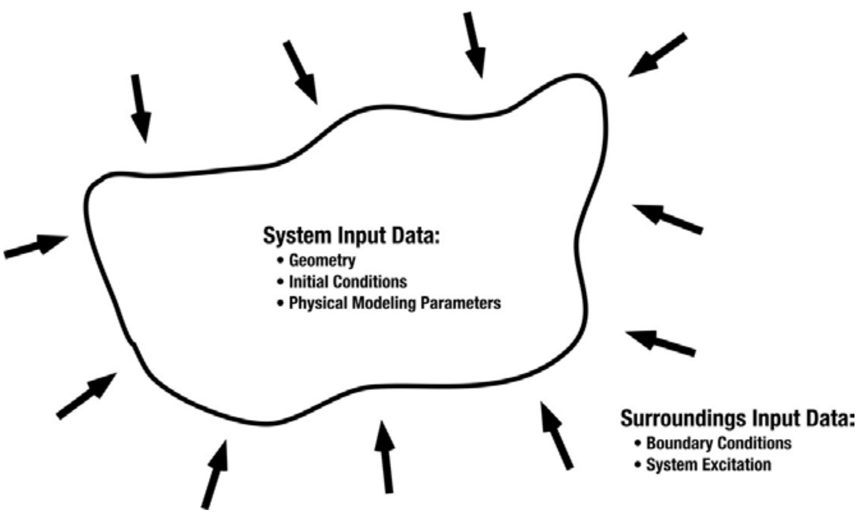


Figure 2—Overall Representative System Expanded Diagram (SLS example)



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

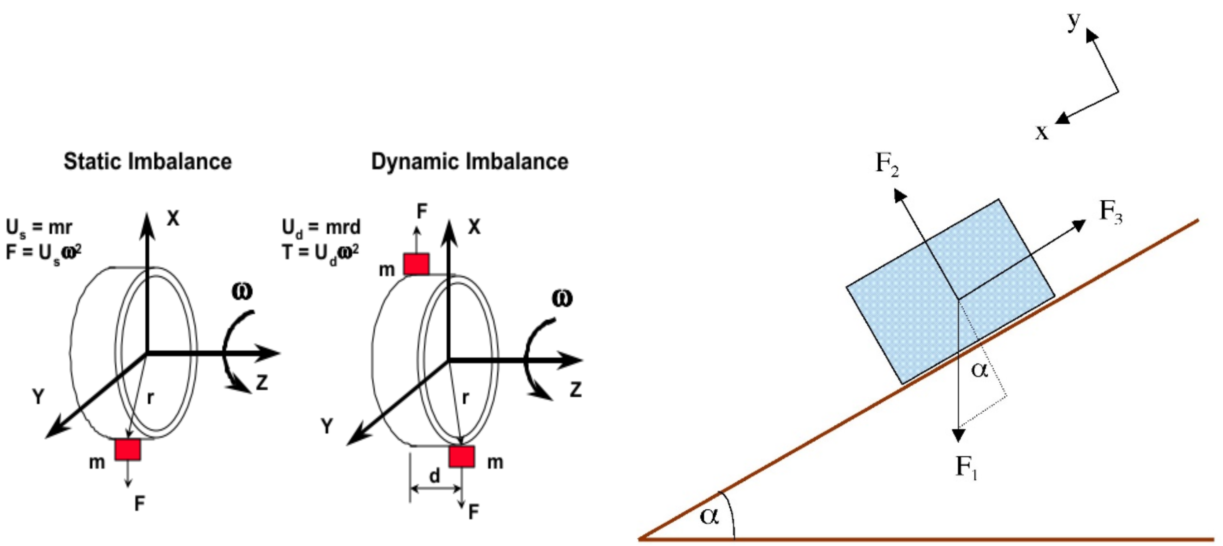
Figure 3—Distinguishing the RWS and its Environment

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 (or 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 M&SCO provides some background information on conceptual model development (Conceptual Model Development and Validation, VV&A Recommended Practice Guide special topic, https://vva.msco.mil/default.htm?Special_Topics/Conceptual/default.htm).



(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. 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 support 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 5.3.2 c).

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, and resources. The following overarching concepts may be considered:

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

"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.

"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 of or in M&S results, the following should be considered and evaluated:

a. Programmatic considerations (constraints):

    (1) Model development-use schedule.
    (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.

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).

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).

(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 aspect 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 types 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 (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. Uncertainties about the operating environment.

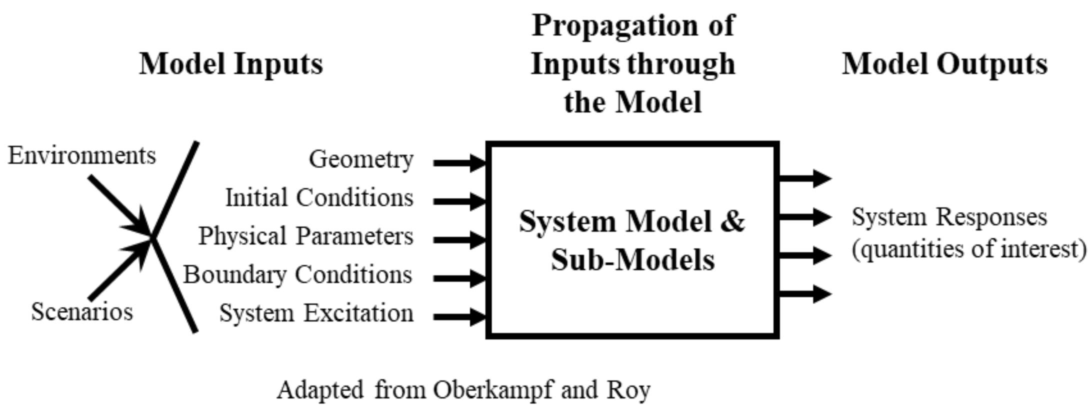


Figure 5—General Model Diagram with Nondeterministic Elements

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).

5.2.2 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.

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 a 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 therefore 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 in order 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. However, 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-7009A, 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.

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

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

f. 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.

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

h. 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.

i. 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?

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

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

5.3.3 Model Concept (Design) Validation

All of the work performed in the above steps 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.

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 (verified and validated). 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 modern 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 verified and validated 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 so as 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.

5.4.2 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 verification and validation credibility factors, as discussed in NASA-STD-7009A, 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).

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 verification and validation, 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.

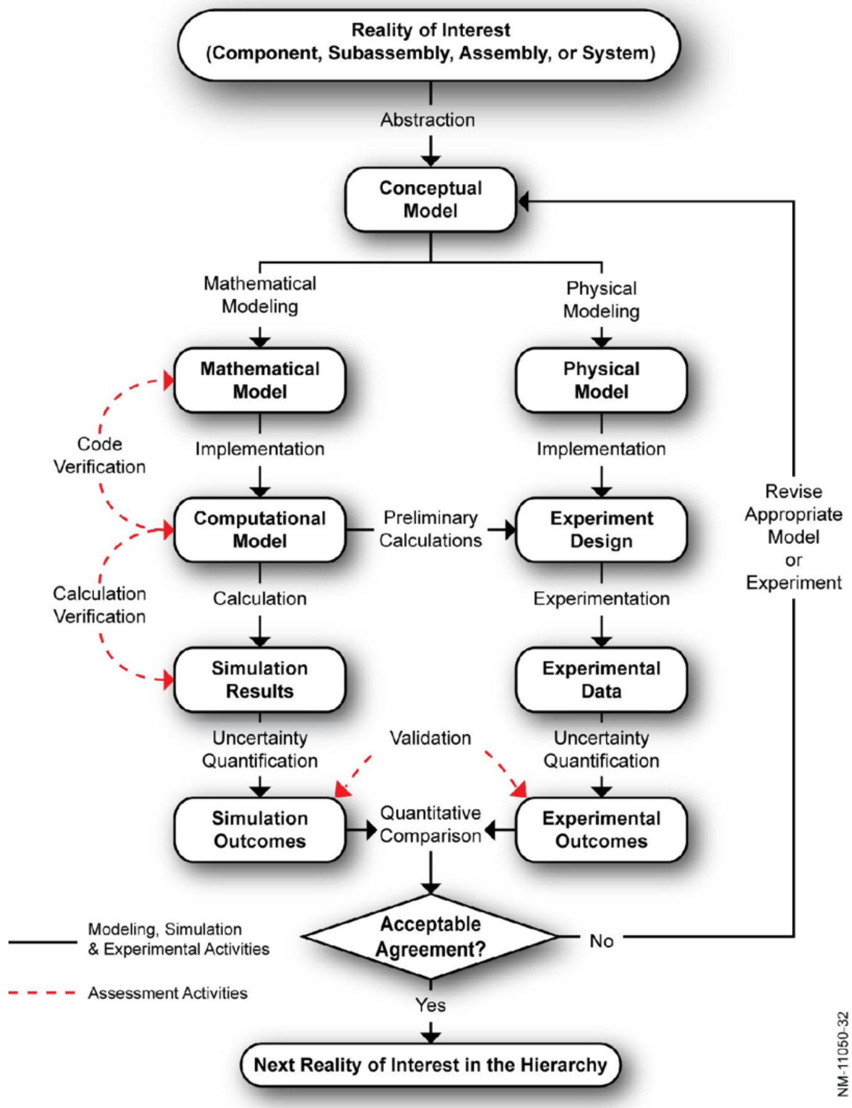
b. Will not establish a reliable basis that the model will work for any scenario other than those used for validation.

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, is to be avoided, and induces inefficiencies requiring repeated verification and validation 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) in order 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 verification and validation 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 verification and validation 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, 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 8] (4).
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 (What is Considered During Verification?)

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

a. 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 intended purpose (in accordance with the 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 therefore 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 still 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. However, 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 in order 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 8] (4), 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 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 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 and also known as the “Validation Domain” [M&S 18].

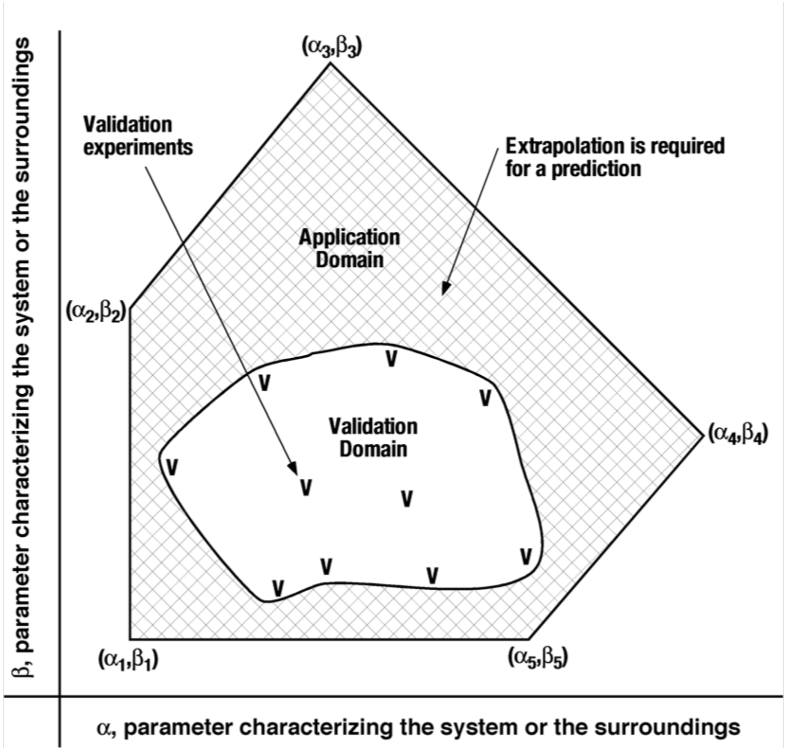


Figure 7—Domain of Validation

(*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)*

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-7009A provides the following definitions:

> 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.”

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

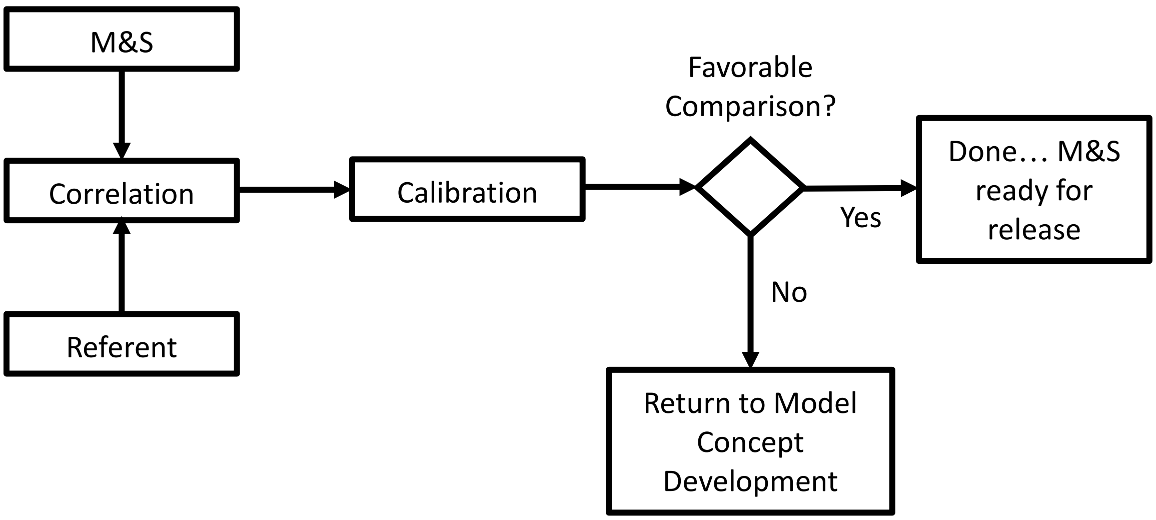


Figure 8—Empirical Validation Process, Including Correlation and Calibration

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. However, this is not always possible or affordable. The pre-defined acceptance criteria for the M&S [M&S 8] (1) 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) And, therefore, 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 machine learning 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 (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. Therefore, 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 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.

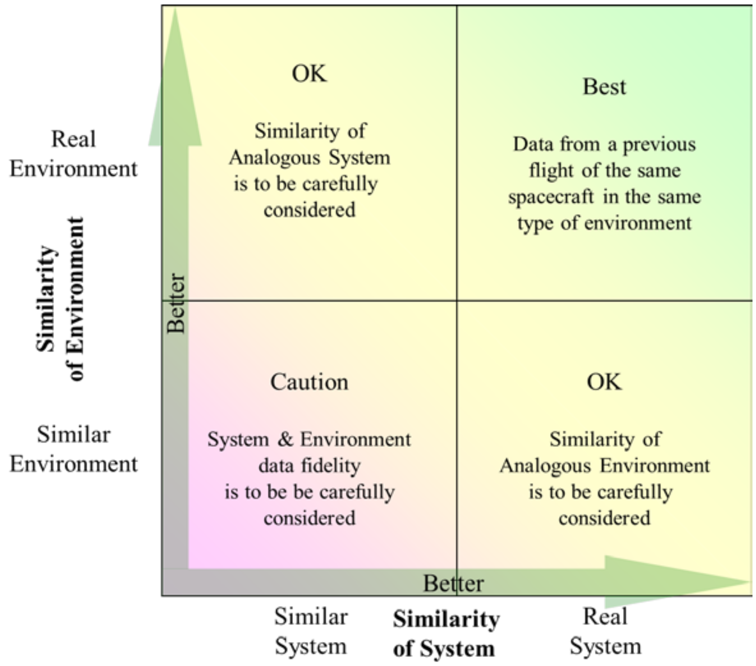


Figure 9—RWS to Referent Similarity

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, in order 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.

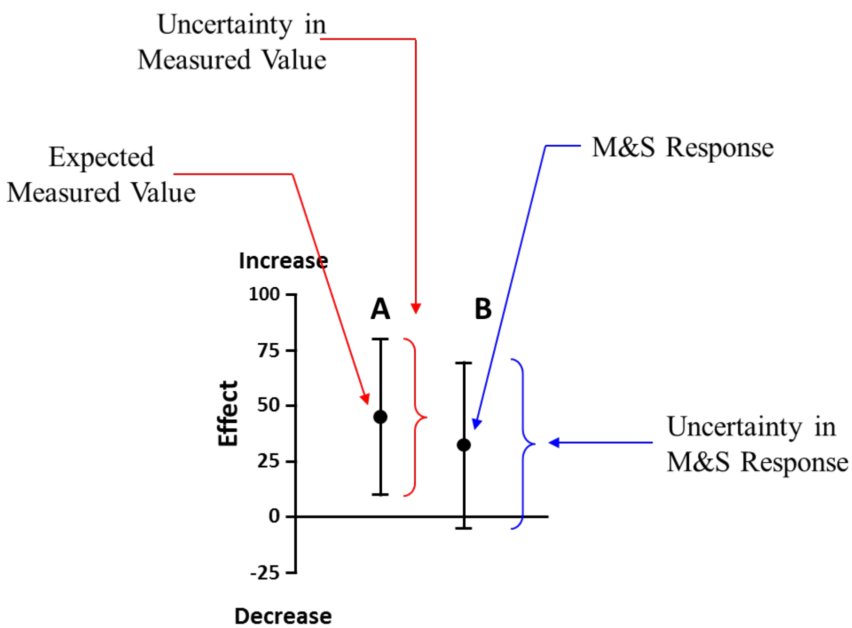


Figure 10—Simple Comparison of Uncertainty Bounds Between M&S and Referent

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. However, 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.

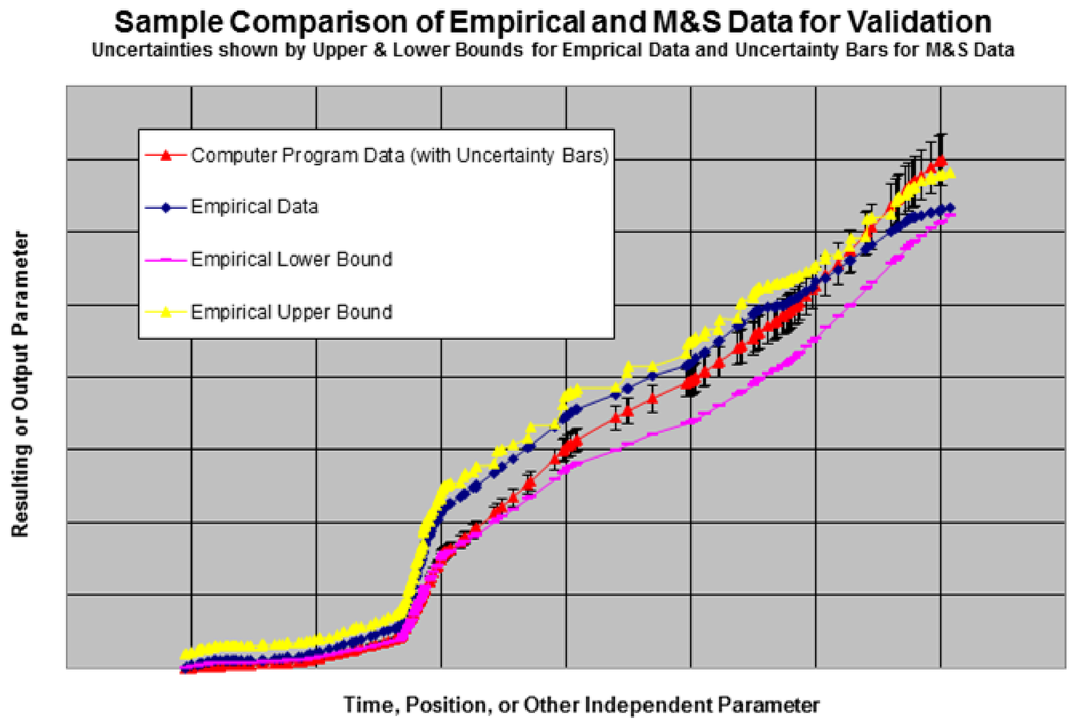


Figure 11—Comparison of Uncertainty Bounds Between M&S and Referent over Range of Input Values

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, 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 for 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 a 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, 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 a RWS will likely have its domain of validation updated.

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 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).

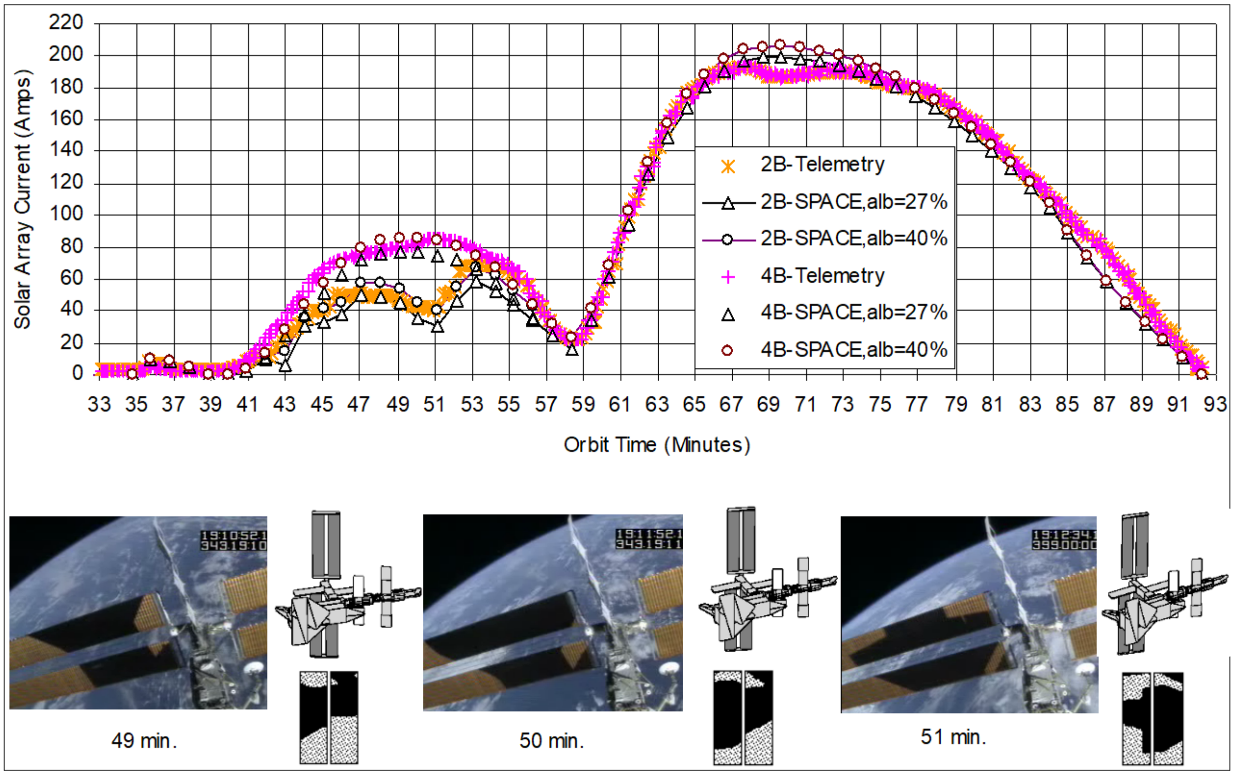


Figure 12—ISS Power Prediction
(NASA TM-2002-211715, IECEC-2002-20113, "Comparison of ISS Power System Telemetry with Analytically Derived Data for Shadowed Cases", Fincannon, H. James)

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 probably re-accomplishment of verification and validation, of the model may be needed.

5.5.4 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 model and guidance for proper use (e.g., User's Guide). All requisite development artifacts are to be archived when the model 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.

5.5.4.1 Accomplishing Model Release

Along with the release of the model, 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-7009A, along with guidance on appropriate ways (methods) in which to use the model (NASA-STD-7009A, section 4.2.2e) and the specifics of model calibrations (NASA-STD-7009A, section 4.2.2f). The criteria for determining permissible uses of an M&S include:

a. Intended use [M&S 8(2)].
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].

5.5.4.2 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.

5.5.4.3 Products and Expected Outcomes of Model Release

At the conclusion of model release, all of the products and expected outcomes from verification and validation 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.

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. This section discusses each of these sub-phases in the context of the requirements and recommendations provided in NASA-STD-7009A, 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. Procedures for M&S Use.
g. Proposed Use (obtained at any point prior to commencing with the Model Use Phase).

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; therefore, 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-7009A).

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-7009A).

c. Thoroughly understand the user's guide for the specific M&S, if one is available (per Recommendation section 4.2.2e of NASA-STD-7009A). Suggested content for the user's guide is in Appendix C. 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-7009A.

(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; but if that has not occurred, they can also be established at the beginning of Model Phase E (recommendations are sections 4.1.2c and 4.3.2e of NASA-STD-7009A).

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 M&S release (section 5.5.4.1). 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. However, 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. • Validation.		Desired Domain of Use. • With respect to the RWS. • Parameter values the model is expected to represent.
Types of Outputs (Results) Produced, including: • Accuracy. • Precision. • Uncertainty.		Type of Results Needed, including: • Accuracy. • Precision. • Uncertainty of Results.

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. However, 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 or sets of conditions (e.g., parameter values) that define or control the function of a model during use, which 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 a 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 (Figure 5, General Model Diagram with Nondeterministic Elements) 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, however, 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 or journal articles.
c. Test results.
d. Operational data.
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 design of experiments 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. So, 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. Additionally, 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 particular 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.

An even better analysis is accomplished using probabilistic parameter values. 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 Monte Carlo-type runs of the M&S by drawing random variates from the defined probability distribution. Probabilistic and stochastic analyses are more complex, requiring specific statistical methods for analyzing the outputs of multiple model runs. Beneficially, however, the results also include a statistically calculated uncertainty.

Models typically use multiple inputs with a variety of pedigrees. Ideally, the effect of all of 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 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.

5.6.2.1 Model Setup

Model setup encompasses two primary activities: Setting up 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. 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-7009A, 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 also should be documented along with the domain of calibration (NASA-STD-7009A, section 4.3.2 c).

Table 7—Model Setup Definition Options

Run Length.
Animation Run Speed.
Initial Conditions.
Warm-up Period.
Number or Replications.
Start Time.
Stopping Conditions.
Output to collect (e.g., model run statistics).

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. Often times, the execution of a model takes 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 placarded for executions outside the permissible limits [M&S 26].

Another task to accomplish during the course of 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-7009A, section 4.3.2 f).

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-7009A, section 4.3.2 h).

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 a 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 in NASA/SP-2010-576 on robustness 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, two major steps remain in the Model Use Phase:

a. Results analysis.
b. Results assessment and 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 MS 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

7009 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**			
(1)	Unachieved Acceptance Criteria.			
(2)	Violation of any Assumptions.			
(3)	Violation of the Limits of Operation.			
(4)	Execution Warning and Error Messages.			
(5)	Unfavorable outcomes from the proposed use assessments.			
(6)	Unfavorable outcomes from Setup/Execution Assessments.			
(7)	Waivers to Requirements.			

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

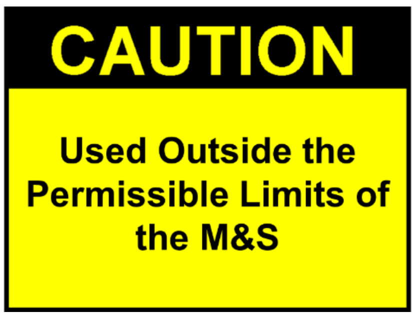


Figure 13—Example Placard

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 modeling and simulation effort. However, rarely can data from the M&S be used directly in making such decisions, and so the output data is analyzed, statistically or otherwise, 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 a 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.

Table 9—Uncertainty Characterization Synopsis

7009 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 design of experiments? 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; however, errors are a form of epistemic uncertainty whether they are quantified or not.

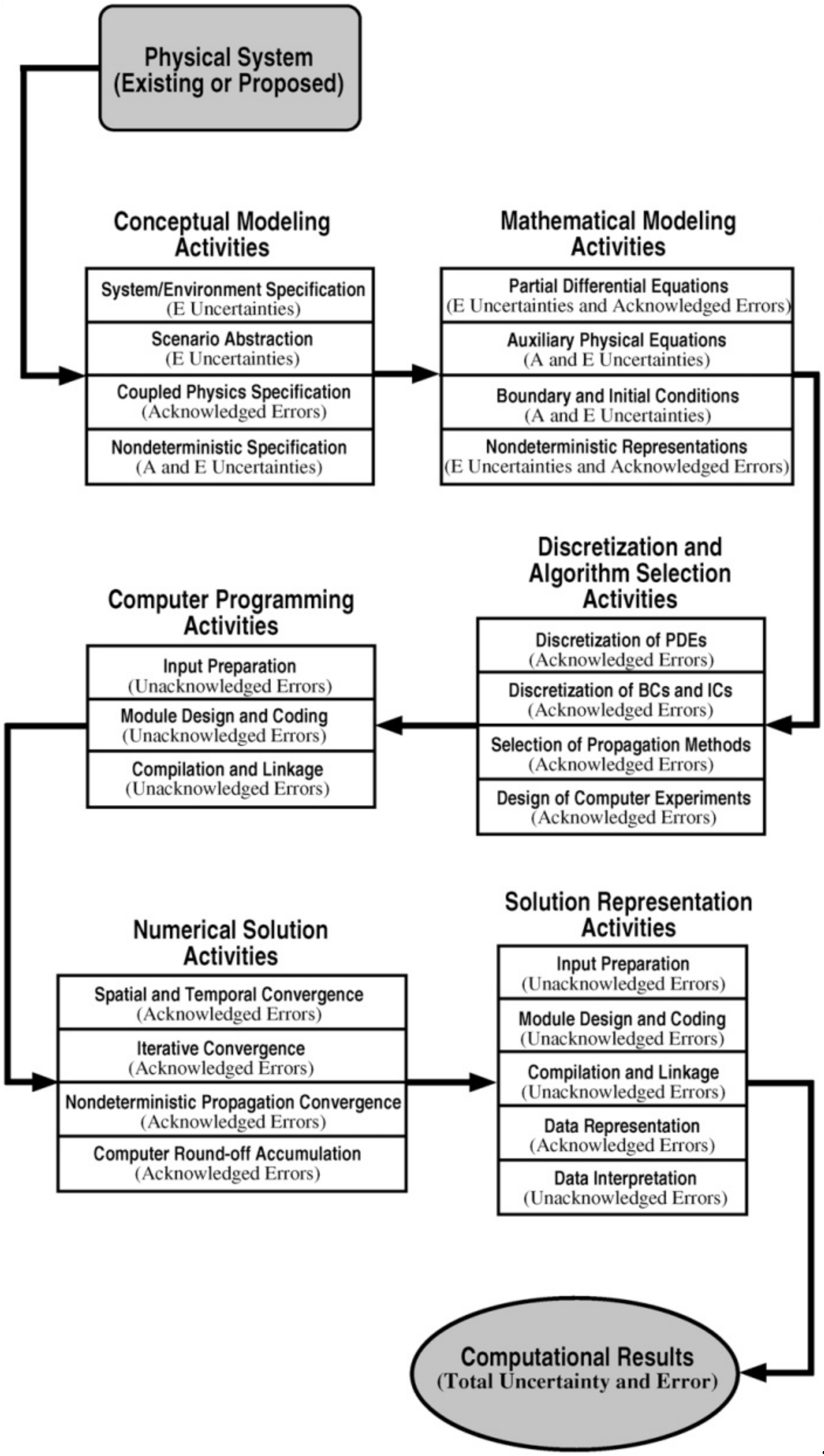


Figure 14—Sources of Model Uncertainty

Identifying, quantitatively expressing and correctly classifying uncertainties is often the most difficult part of uncertainty characterization. This is because uncertainty is everywhere and many people are going to have different opinions on uncertainty sources. Epistemic uncertainty in particular is difficult because often times the uncertainty source is not well understood. Quantifying epistemic uncertainty is often difficult simply due to the nature of the uncertainty. Even SMEs may have varying opinions on the amount of uncertainty present in a particular source. However, 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. The only challenge with aleatory uncertainty is actually having enough information to support a claim that a particular uncertainty source can be actually 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, therefore, treatment of uncertainty can produce very misleading results.

Note: Uncertainty in M&S results may occur in many ways (Table 10). Generally, M&S results uncertainties either come from the model or the input to the model, not necessarily both. A deterministic model with nondeterministic inputs can produce nondeterministic results. A nondeterministic model will always produce nondeterministic results.

Table 10—Uncertainty in M&S Results

	Deterministic Model	**Nondeterministic Model**
Deterministic Inputs	Deterministic Results.	Nondeterministic Results.
Nondeterministic Inputs	Nondeterministic Results.	Nondeterministic Results.

On the other hand, with the inevitable analysis of model output, post-processing can produce either deterministic or nondeterministic results.

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 "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-7009A, 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] Shall document any processes and rationale for characterizing uncertainty in: (1) The input to an M&S. (2) The results from an M&S. (3) The quantities derived from M&S results

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 particular uncertainties:

> *[M&S 29] Shall document any uncertainties (qualitatively described or quantitative) in: (1) The input to an M&S. (2) The results from an M&S. (3) 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 also items derived from the M&S results. For example:

A structural analyst is using a FEM to performing 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-7009A, section 4.3.4 a).

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 the M&S (see Results Robustness factor in NASA-STD-7009A, 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 2 below). The justification for the evaluation and any technical review of Results Robustness is to be documented.

Notes:

(1) NASA-STD-7009A 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.

(2) 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-7009A is met.

(3) 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 Assessing and Reporting Results

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-7009A also require the assessment of the results as to their credibility and potential risks of accepting them as they are. Everything that has occurred during the M&S life cycle has the potential to impact the acceptability (credibility) of the final results of M&S use and risk for the object (i.e., the RWS) of M&S-based analysis. Additionally, the reporting of technical review results (Table 11), qualifications of the developers, testers, users, and analysts (Table 12), and supporting documentation (Table 13) is required.

Table 11—Technical Review Synopsis

7009 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

7009 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

7009 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 38]	**M&S Documentation** (Synopsis)			
[M&S 6]	Criticality Assessment.			
[M&S 7]	M&S in Scope of 7009.			
[M&S 9]	Technical Reviews.			
[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 16]	Domain of Verification.			
[M&S 18]	Domain of Validation.			
[M&S 19]	Processes for Characterizing Uncertainty in Referent Data.			
[M&S 20]	Methods of Uncertainty Propagation in M&S.			
[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] (1)	Uncertainties in Input			
[M&S 29] (2)	Uncertainties in Results.			
[M&S 29] (3)	Uncertainties in Derived Results.			
[M&S 30]	Sensitivity Analyses.			

5.6.3.2.1 Results Credibility Assessment

The credibility of M&S results is influenced by all the activities in an M&S life cycle. While credibility is not something that can be assessed directly, the factors influencing overall credibility (as defined in NASA-STD-7009A per requirement [M&S 31]) are more readily assessed.

Following are notes about the NASA-STD-7009A 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 is provided in Appendix D.

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-7009A, section 4.3.7 a). 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-7009A, section 4.3.7 c). Justification and documentation for the assessed levels of each of these factors (NASA-STD-7009A, section 4.3.7 b) provide the needed evidence.

5.6.3.2.2 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-7009A, 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 is not an element of risk, but does provide 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; however, an effective assessment of risk is best considered during each phase of the M&S life cycle (further explanations are in Appendix E). 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-7009A 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 (this NASA Technical Handbook, Appendix D; NASA-STD-7009A, 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 14 provides a synopsis of potential M&S risk elements with rationales and references.

Table 14—M&S Risk Elements

Major Risk Element	**Rationale**	**NASA-STD-7009A Reference**	**NASA-HDBK-7009A 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 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 actually accomplished in M&S development and use.	[M&S 38], plus all of the documentation R/r's	Table 13

These elements are also part of section 5.6.3.2.3, Table 15, 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.

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 are 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.

5.6.3.2.3 Reporting

Reporting the results of an M&S goes without saying, but there can be a lot of information qualifying those results. The purpose for the reporting requirements ([M&S 32] through [M&S 39]) in NASA-STD-7009A is to promote a more complete understanding of the results, and the models and processes leading to those results. A synopsis of reporting information is provided in Table 15, which is supported by a more detailed coverage of each item in the following portions of this section.

Table 15—M&S Reporting Synopsis

NASA-STD-7009A 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 32]	Caveats.			
[M&S 33]	Uncertainty in Results.			
[M&S 34]	Uncertainty Processes.			
[M&S 35]	Credibility Assessment.			
[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 includes, 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.
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.

5.7 Model and Analysis Archiving (Phase F)

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

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 the officially accepted M&S and all relevant artifacts throughout the M&S life cycle. The relevant artifacts include the objectives and requirements best defined, per [M&S 8](6), early in the development and use life-cycle phases and included in any M&S development, use, or retirement plans (NASA-STD-7009A, section 4.1.2 a). 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-7009A, section 4.1.2c). Recommended practices for M&S archival should be identified, documented (NASA-STD-7009A, section 4.1.3a), and considered for use, along with a method for adherence tracking (NASA-STD-7009A, section 4.1.3b(2)), and included as part of training for the M&S (NASA-STD-7009A, section 4.1.4b(1)B and section 4.1.4b(1)C). This includes establishing and documenting initial baselines and versioning of controlled items, such as designs, test procedures, test reports, and model correlation reports (comparing RWS measurements/observations to equivalent model outputs). Changes to established baselines are to 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-7009A, section 4.3.9c).

Table 16 shows examples of products, documents, or artifacts that may require controlling or archiving in each phase of the M&S life cycle.

Table 16—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 is 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-7009a_-_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-7009A 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-7009A.

Use of NASA-STD-7009A, NASA-HDBK-7009, 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-7009A, this NASA Technical 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-7009A, this NASA Technical 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-7009A 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).

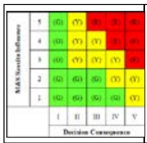
The Worksheet in this NASA Technical Handbook is organized similarly to NASA-STD-7009A, with relevant contextual information (Table 17, Worksheet Organization). The M&S life cycle is defined in NASA-STD-7009A, Appendix F, and discussed in this NASA Technical Handbook, section 4.6.

Table 17—Worksheet Organization

Worksheet Section	Worksheet Section Title	Worksheet Section Description
6.1	Header.	Contextual information about the RWS and the model representing the RWS, including pictorial renderings of the criticality and credibility assessments.
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 largely similar to the version found in the baseline of this NASA Technical Handbook, but reorganized to mirror similar concepts between the RWS and the M&S.



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

Figure 15—Worksheet Header

The graphics at the top left and right are reminders of two important elements when developing and applying an M&S: The criticality of the situation under the purview of the M&S, and the credibility of the M&S results.

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-7009A, Appendix F), and the key M&S responsible parties.

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-7009A.

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.

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				
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	*4.1.2 a*	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 and applied to 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 devleopers and operators?		

Figure 16—Worksheet Example of All Columns

6.2 M&S Planning Section

The M&S Planning section (Table 18, Worksheet – M&S Planning) includes overarching concepts applicable to the whole life cycle of an M&S, including:

a. Criticality assessment.
b. Planning.
c. Use of Best Practices.

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

Table 18—Worksheet – M&S Planning

Item	STD Ref	Questions
M&S Planning		
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	4.1.2 a	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 M&S Development Section

The M&S development section (Table 19, Worksheet – M&S Development) includes questions and references to the requirements and recommendations of NASA-STD-7009A 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 19—Worksheet – M&S Development

Item	STD Ref	Questions
		M&S Development
M&S Initiation	*[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?
	[M&S 8] (2)	What is the M&S Intended Use in relation to the RWS Problem/ Decision/ Situation?
Model Concept Development	*[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 12]	What's included in the M&S, including model environment influences?
	[M&S 11]	Is there anything significant to this analysis <u>not</u> included in the M&S or scenarios?
		What assumptions & abstractions are included in the M&S and Analysis?
Model Design	*[M&S 20], [M&S 21]*	What uncertainties are included in the M&S?
	[M&S 8]	What are the Requirements or Specifications for the model?
	[M&S 12]	What are the Implementation Mechanisms (e.g., Math Models)?
	4.2.2 m	What is the Implementation Architecture (e.g., Platform-Software)?
Conceptual Validation	*[M&S 17]*	Have the Model Design and Architecture been Conceptually Validated? (e.g,. Reviewed by SMEs, both RWS and M&S)?
Implementation		What is the implementation status of the M&S?
Verification	*4.1.2 a* *4.1.3 b (3)* *4.2.4 a*	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)?
	4.1.2 c	What artifacts (evidence) of verification are available?
Empirical Validation	*4.1.2 a* *4.1.3 b (3)* *4.2.6 a*	What are the validation practices, methods, and requirements?
	4.1.2 c	What artifacts (evidence) of validation are available? Who reviewed/verified the RWS (Referent System) data?
	[M&S 8] (1), (3), (4)	What is the accuracy, precision, sensitivity, uncertainty, and bias of the model? Does it satisfy the requirements?
	[M&S 20], [M&S 21]	What uncertainties are characterized in the model <u>and</u> how do they compare to the RWS Uncertainties?
	4.2.8 a	What uncertainties are <u>not</u> characterized in the model <u>and</u> what are those uncertainties in the RWS?
		What are the model sensitivities? How do they compare to Sensitivities of the RWS?
Permissible Use	*[M&S 14]*	What are the Permissible Uses of the M&S?
Model Release	*4.1.2 c*	What version of the model is released for use?
	4.1.2 c	Where are the model and its development artifacts archived?
	4.2.2 e	Was a User's Guide produced and formally released with the model?

6.4 M&S Use Section

The M&S Use section (Table 20, Worksheet – M&S Use) includes questions and references to the requirements and recommendations of NASA-STD-70009A 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.
    (4) Technical reviews.
    (5) People Qualifications.
    (6) M&S-based Risk

h. M&S Product Archiving.

Table 20—Worksheet – M&S Use

Item	STD Ref	Questions
M&S Use		
Use Processes	*4.3.2 e*	What are the processes for using the model?
	4.2.2 e	Is a User's Guide available?
Proposed Use	*[M&S 22]*	What is the Proposed Use for the Model?
Use Assessment	*[M&S 23]*	Does the M&S type & purpose of 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	*[M&S 24]*	What are the Scenarios for model use?
Setup	*[M&S 25]*	What are the model setups?
Execution		What is the execution status for the use?
Analysis	*[M&S 28] (3)*	How was the output (data) analyzed?
M&S Results		What are the best-estimate results provided by the analysis?

Item	STD Ref	Questions
M&S Use		
		How well (how directly) do the analysis results address the problem statement?
Uncertainty in Estimate	*[M&S 29]*	What are the uncertainties in the results of this analysis?
Sensitivities	*[M&S 30]*	What are the Sensitivities in the results of this analysis?
Caveats	[M&S 32] (1)	Unachieved Acceptance Criteria?
	[M&S 32] (2)	Violation of Assumptions?
	[M&S 32] (3)	Violation of Limits of Operation?
	[M&S 32] (4)	Warning or Error Messages?
	[M&S 32] (5)	Unfavorable Propose Use Assessments?
	[M&S 32] (6)	Unfavorable Setup/Execution Assessments?
	[M&S 32] (7)	Waivers to Requirements?
Requirements Compliance	[M&S 32] (1)	Give details on non-compliances with all M&S requirements and their consequences.
Credibility Assessment	[M&S 31] 4.3.7 a, b, c	Data Pedigree.
		Verification.
		Validation.
		Input Pedigree.
		Uncertainty Characterization.
		Results Robustness.
		M&S History.
		M&S Process / Product Management.
Technical Reviews	[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	[M&S 39]	What are the risks of basing this decision on the M&S-based analysis?
Results Archiving	*4.3.9 c*	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-7009A 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-7009 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 a 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 22, R/r per M&S Life-Cycle Phase [accessible at nasa-std-7009a_reqts_and_recs_per_life_cycle_phase.xlsx]) indicates when the requirements and recommendations of NASA-STD-7009A are best to be accomplished, with abbreviated designations defined in Table 21, R/r M&S Life-Cycle Phase Designations.

Table 21—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 between 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	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. However, 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 22—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**												
a	[M&S 6] Shall perform and document the criticality assessment for the M&S.	B (Dev)								B (Use)			
b	[M&S 7] Shall identify and document if the M&S is in scope of this NASA Technical Standard.		B							B			
c	[M&S 8] Shall define the objectives and requirements for M&S products including the following:		B										
	(1) The acceptance criteria for M&S products, including any endorsement for the M&S.		B							B (Use)			
	(2) Intended use. The intended uses may be updated throughout the model development.	B											
	(3) Metrics (programmatic and technical).		B							B (Use)			
	(4) Verification, validation, and uncertainty characterization (see [M&S 15-16], [M&S 17-18], [M&S 19-21]).		B							B (UC only)			
	(5) Reporting of M&S information for critical decisions (see [M&S 32-39]).		I							B			

Table 22—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) Configuration management (CM) (artifacts, timeframe, processes) of M&S.		B (Dev)							B (Use)			
d	[M&S 9] Shall document any technical reviews accomplished in regard to the development, management (control), and use of the M&S.		B	B	B	B	B	B	B	B	B	B	
4.1.2	**General M&S Programmatic Recommendations**												
a	Should develop a plan (including identifying the responsible organization(s)) for the acquisition, development, operation, maintenance, or retirement of the M&S.	B (Dev)								B (Use)			
b	Should document M&S waiver processes		B										
c	Should document the extent to which an M&S effort exhibits the characteristics of work product management, process definition, process measurement, process control, process change, and continuous improvement, including CM and M&S support and maintenance		B	B	B	B	B	B	B	B	B	B	B
4.1.3	**M&S Best Practices Recommendations**												
a	Should identify and document any recommended practices that apply to M&S for the program/project.		B (Dev)							B (Use)			
b	At a minimum, recommended practices for the following should be considered:												

Table 22—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) 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) Verification and validation processes for the M&S.				B (C-Val.)		B (Ver.)	B (E-Val.)					
	(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			
	(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			
	(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	Should determine the depth of required training or equivalent experience (i.e., qualifications) for developers, operators, and analysts.		B							B			

Table 22—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	Should document the following:												
	(1) Training topics required for developers, operators, and analysts of M&S, which should include the following:												
	A. The limits of operation for M&S, with implications and rationale.		B							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			
	F. Sensitivity analysis.							B		B			
	G. Uncertainty characterization.		B							B			
	H. Verification and validation.				B (C-Val.)		B (Ver.)	B (E-Val.)					
	I. How to report simulation results to decision makers.									B			
	J. Statistics and probability		B							B			

Table 22—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	
	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**												
a	[M&S 10] Shall document the relevant characteristics, including data, about the RWS used to develop the model, including its pedigree (see Data Pedigree in Appendix E).	B											
b	[M&S 11] Shall document the assumptions and abstractions underlying the M&S, including their rationales.		B										
c	[M&S 12] Shall document the basic structure and mathematics of the model (e.g., equations solved, behaviors modeled, and conceptual models).		B	B		B							
d	[M&S 13] Shall document the limits of operation (e.g., boundary conditions) of models.		B	B		B	T	T					
e	[M&S 14] Shall document the permissible uses of the M&S.								B_{nlt}				
4.2.2	**General M&S Development Recommendations**												

Table 22—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	
a	Should document data sets and any supporting software used in model development		B										
b	Should document units and vector coordinate frames (where applicable) for all input/output variables in the M&S		B				T						
c	Should document any methods of uncertainty characterization <u>and</u> the uncertainty in any data used to develop the model or incorporated into the model.		B	B		B							
d	M&S should be designed and constructed so that, in the event of a failure, messages detailing the failure mode and point of failure are provided.			B		B	T						
e	Should document guidance on proper use of the M&S.			B		B	T	T	B_{nlt}				
f	Should document any parameter calibrations and the domain of calibration.					B	T	T					
g	Should document updates of the model (e.g., solution adjustment, change of parameters, calibration, and test cases) and assign unique version identifier, description, and the justification for the updates.					B							B
h	CM records should contain test cases that span the limits of operation for the M&S defined by the program or project.						B (Ver. Cases)	B (Val. Cases)					B
i	Should document obsolescence criteria and obsolescence date of the model.		B										

Table 22—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	
j	Should provide a feedback mechanism for users to report unusual results to model developers or maintainers.					B							
k	Should maintain (conceptual, mathematical, and computational) models and associated documentation in a controlled CM system.		B	B		B			B				B
l	Should maintain the data sets and supporting software referenced in Rec. “a” of this section and the associated documentation in a controlled CM system.		B_e	-	-	-	-	-	B_{nlt}				B
m	Should document any unique computational requirements (e.g., support software, main memory, disk capacities, processor, and compilation options).		B			B_{nlt}							B
n	Developers should 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}				
4.2.3	**M&S Verification**												
a	[M&S 15] Shall verify all models						B						
b	[M&S 16] Shall document the domain of verification of all models.						B						
4.2.4	**M&S Verification Recommendations**												
a	Should document any verification techniques used.						B						

Table 22—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	Should document any numerical error estimates (e.g., numerical approximations, insufficient discretization, insufficient iterative convergence, finite-precision arithmetic) for the results of the computational model.						B						
c	Should document the verification status of (conceptual, mathematical, and computational) models.						B						
d	Should document any aspects of M&S that have not been verified.						B						
4.2.5	**M&S Validation**												
a	[M&S 17] Shall validate all models.				B (C-Val)			B (E-Val)					
b	[M&S 18] Shall document the domain of validation of all models.							B					
4.2.6	**M&S Validation Recommendations**												
a	Should document any techniques used to validate the M&S for its intended use, including the experimental design and analysis.							B					
b	Should document any validation metrics and referents, and data sets used for model validation.							B					
c	Should document any studies conducted and results of model validation.							B					
d	Should document any aspects of M&S that have not been validated.				B (C-Val)			B (E-Val)					

Table 22—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	
4.2.7	**Uncertainty Characterization in M&S Development**													
a	[M&S 19] Shall document any processes and rationale for characterizing uncertainty in the referent data.			B										
b	[M&S 20] Shall explain and document any mechanisms or constructs related to the incorporation or propagation of uncertainty in the model.				B (as designed)		B (as built)							
c	[M&S 21] Shall document any uncertainties (qualitatively described or quantitative) incorporated into the M&S.				B (as designed)		B (as built)							
4.2.8	**Uncertainty Characterization in M&S Development Recommendation**													
a	The responsible party should document any significant physical processes, effects, scenarios, or environments not considered in the uncertainty characterization analysis.				B									
4.3.1	**M&S Use Requirements**													
a	[M&S 22] Shall document the proposed use(s) of the M&S.										B			
b	[M&S 23] Shall perform and document an assessment of the appropriateness of the M&S relative to its proposed use.										B			
c	[M&S 24] Shall document data used as input to the M&S, including its pedigree (see Input Pedigree in Appendix E).										B			

Table 22—R/r per M&S Life-Cycle 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	[M&S 25] Shall document the rationale for the setup and execution of the simulation and analysis.										B		
e	[M&S 26] Shall do either of the following:												
	(1) Ensure that simulations and analyses are conducted within the limits of operation of the models, or										B		
	(2) Placard the simulation and analysis results with a warning that the simulation may have been conducted outside the limits of operation and include the type of limit that may have been exceeded, the extent that the limit might have been exceeded, and an assessment of the consequences of this action on the M&S results.										B		
f	[M&S 27] Shall document and explain any observed warning and error messages resulting from the execution of the computational M&S.										B		
4.3.2	**M&S Use Recommendations**												
a	Should document the relevant characteristics of the system that is the subject of the M&S-based analysis.									B			
b	Should document which computational models were used (including revision numbers) in the simulation/analysis.										B		
c	Should document any parameter calibrations and the domain of calibration										B		

Table 22—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	Should document data sets and any supporting software used in input preparation.									B			
e	Should document the processes for conducting simulations and analyses for generating results reported to decision makers.									B_{nlt}			
f	Should document the versions of M&S results.										B		
g	Should document any use history of M&S, in the same or similar applications, which are relevant for establishing the credibility of the current M&S application (see Appendix E.4.3.1, M&S History Factor).										B		
h	Should document and explain all failure modes, points of failure, and messages indicating such failures.										B		
4.3.3	**Uncertainty Characterization in M&S Use**												
a	[M&S 28] Shall document any processes and rationale for characterizing uncertainty in:												
	(1) The input to an M&S.									B			
	(2) The results from an M&S.										B		
	(3) The quantities derived from M&S results.											B	
b	[M&S 29] Shall document any uncertainties (qualitatively described or quantitative) in:												
	(1) The input to an M&S.									B			
	(2) The results from an M&S.										B		

Table 22—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	
	(3) The quantities derived from M&S results.											B	
4.3.4	**M&S Uncertainty Characterization** **Recommendation**												
a	Responsible parties should document any significant physical processes, effects, scenarios, or environments **not** considered in the uncertainty characterization analysis.									B			
4.3.5	**M&S Sensitivity Analysis**												
a	[M&S 30] The responsible party shall document the extent and results of any sensitivity analyses performed with the M&S.										B		
4.3.6	**M&S Results Credibility Assessment**												
a	[M&S 31] The responsible party shall assess the credibility of M&S results for each of the factors described in Appendix E.			B (DP)	B (C-Val.)		B (Ver.)	B (E-Val.)		B (IP)		B	
4.3.7	**M&S Results Credibility Assessment** **Recommendations**												
a	Should set credibility sufficiency threshold levels for each factor as described in Appendix E.5.		B (DP, Ver., Val.)							B (IP, UC. RR, Hist, Mgt)			
b	Should justify and document the credibility assessment for each of the factors referenced in [M&S 31].			B (DP)	B (C-Val.)		B (Ver.)	B (E-Val.)		B (IP)		B	

Table 22—R/r per M&S Life-Cycle 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	Should gain additional insight into the credibility of M&S results by applying the process in Appendix E.5 to determine and report any gaps between the achieved scores and the program/project-defined threshold scores for each of the factors.											B	
4.3.8	**M&S Results Reporting**												
a	[M&S 32] Shall include explicit warnings for any of the following occurrences, accompanied by at least a qualitative estimate of the impact of the occurrence:												
	(1) Any Unachieved Acceptance Criteria (as specified in [M&S 8] (1)).											B	
	(2) Violation of any assumptions of any model (as specified in [M&S 11]).											B	
	(3) Violation of the limits of operation (as specified in [M&S 13]).											B	
	(4) Execution warning and error messages (see [M&S 27]).											B	
	(5) Unfavorable outcomes from the proposed use assessments (described in [M&S 23]).											B	
	(6) Unfavorable outcomes from any setup/execution assessments (described in [M&S 25]).											B	
	(7) Waivers to any of the requirements in this NASA Technical Standard.											B	

Table 22—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	[M&S 33] Shall include an estimate of results uncertainty, as defined in [M&S 29 (1)-(3)], in one of the following ways:												
	(1) A quantitative estimate of the uncertainty in the M&S results, or											B	
	(2) A qualitative description of the uncertainty in the M&S results, or											B	
	(3) A clear statement that no quantitative estimate or qualitative description of uncertainty is available											B	
c	[M&S 34] Shall include a description of any processes used to obtain the estimate of uncertainty as defined in [M&S 28 (1)-(3)].											B	
d	[M&S 35] Shall include the assessment of credibility for the M&S results for each factor specified in [M&S 31].											B	
e	[M&S 36] Shall include the findings from any technical reviews accomplished in regard to the development, management (control), and use of the M&S.											B	
f	[M&S 37] Shall include 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.											B	
g	[M&S 38] Shall show what aspects of modeling and simulation are documented, as shown in Appendix A.											B	

Table 22—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	
h	[M&S 39] Shall include an assessment of and rationale for the risks associated with the use of the M&S-based analysis.											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
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	
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 with regard to 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 a RWS or a portion thereof.

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

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 often 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. Examples of unresolved/uncorrected empirical data acquisition errors and their root causes include:

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

(2) Unaccounted effects of head pressures due to elevation differences.

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

(4) Measurement response time delays masking out transients that need to be measured.

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

(6) Instruments themselves in the flow stream/passages altering flow characteristics.

(7) 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, but these 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.) Therefore, 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 concept 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; 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 23, M&S vs. Referent Data/Results Relationship.

Table 23 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. However, 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 23—M&S versus Referent Data/Results Relationship

		M&S Data/Results	
		Valid	**Invalid**
Referent (Empirical) Data/Results	**Valid**	M&S is Correctly Validated *	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**
	Invalid	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** **	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** **

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

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 M&S User's Guide

Development of a User's Guide for an M&S is a recommendation of NASA-STD-7009A, section 4.2.2e: *Should document guidance on proper use of the model.*

C.3 M&S User's Guide Content

The content listed 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 NASA Technical 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.

       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.

       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.

   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, Comment, or Suggestions.

      i. M&S Developer.
      ii. Configuration Manager.

APPENDIX D

ASSESSING AND INFLUENCING M&S RESULTS CREDIBILITY

D.1 Purpose

This appendix provides guidance for performing the M&S results credibility assessment and provides information on how each M&S life-cycle phase may affect each of the credibility factors.

D.2 Overall M&S Credibility

M&S Results Credibility is a key tenet of NASA-STD-7009A. 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-7009A formalizes this assessment with a minimum set of criteria contributing to M&S-based analysis credibility.

Details to consider as to the credibility of the results of an M&S-based analysis are included in sections 4.3.6, 4.3.7, and Appendix E of NASA-STD-7009A, which addresses key development, usage, and supporting aspects of an M&S activity.

a. When assessing M&S Results Credibility, consider the following:

   (1) There may be other key aspects to a particular type of M&S that are not included in this credibility assessment. Including those additional aspects along with the more broadly applicable credibility factors defined in NASA-STD-7009A is acceptable and encouraged. The factors included in NASA-STD-7009A's credibility assessment are considered to be a minimal set for a majority of M&S. If, however, a factor is not considered relevant to a particular M&S, tailoring is permitted, with the approval of the program/project delegated Technical Authority. (See section 1.3 of NASA-STD-7009A.)

   (2) There is no correlation between compliance with the requirements of NASA-STD-7009A and the achievement of particular levels for the various factors in the credibility assessment. Attaining the various levels of credibility relate to the technical aspects and are defined on a case-by-case basis.

M&S Results Credibility is also affected by each phase in the M&S life cycle. Perhaps with the exception of input pedigree, all credibility factors are affected by more than one of the life-cycle phases. Table 24, M&S Life-Cycle Phase Affects M&S Results 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.

Table 24—M&S Life-Cycle Phase Affects M&S Results 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**
Data Pedigree	X	X	X	X			
Verification		X	X	X	X		
Validation		X	X	X	X		
Input Pedigree						X	
Uncertainty Characterization		X	X	X	X	X	
Results Robustness					X	X	
M&S History			X	X	X	X	
M&S Product/Process Mgt	X	X	X	X	X	X	X

b. The acceptable level for the overall credibility and contributing factors is determined by the program/project management in association with the delegated Technical Authority (NASA-STD-7009A, 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:

(1) The system development matures.
(2) Data become available from relevant phases of the program/project.
(3) The M&S matures and is used.

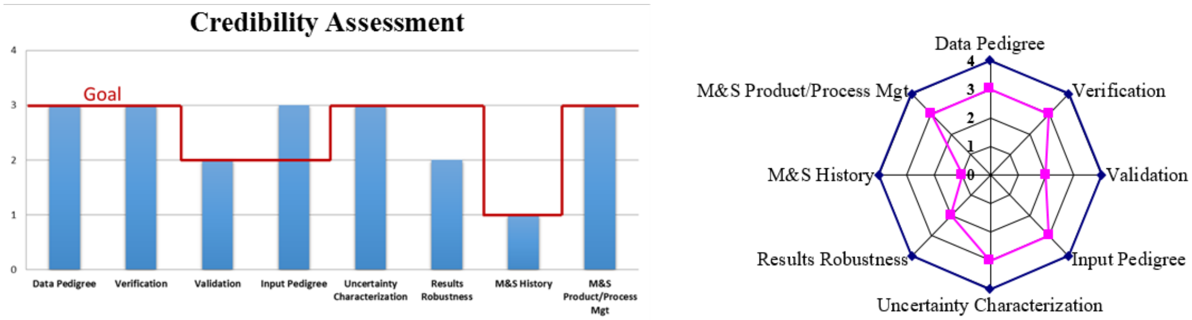
c. The assessment of overall M&S results credibility should include the following:

(1) A tabular or graphical display of all of the credibility factors.

(2) The role of the person/team performing the credibility assessment in the development, operation, or analysis using the M&S.

(3) A summary of the evidence and supporting rationale. (A reference to another document may suffice.)

An example for reporting a synopsis of the credibility assessment is shown in Figure 17, Credibility Assessment Synopsis.



a. Bar Chart b. Spider (Radar) Plot

Figure 17—Credibility Assessment Synopsis

Note: The scaling of levels are 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; therefore, 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 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 communicate clearly 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.

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 25, 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 25—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; however, 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 Data: Form, correct units, and appropriateness to scenario.

NASA-STD-7009A, Table 4, Level Definitions for Factors in the M&S Development Category, provides guidance for achieving the various credibility levels for the data pedigree factor.

Table 26, Life-Cycle Phase Influence on Data Pedigree, shows how data pedigree is affected by the various M&S life-cycle phases.

Table 26—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 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	
E	Model Use	
F	Model & Analysis Archival	

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?

NASA-STD-7009A, Table 4, Level Definitions for Factors in the M&S Development Category, provides guidance for achieving the various credibility levels for the verification factor.

Table 27 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 27—Life-Cycle Phase Influence on Verification

Phase	Name	Verification is affected by
Pre-A	Model Initiation	
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 1st part of this Phase is Verification. • The goals of attaining the various credibility levels of verification are achieved.
E	Model Use	
F	Model & Analysis Archival	

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. NASA-STD-7009A, Table 4, Level Definitions for Factors in the M&S Development Category, provides guidance for achieving the various credibility levels for the Validation Factor.

Table 28 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 28—Life-Cycle Phase Influence on Validation

Phase	Name	Validation is affected by
Pre-A	Model Initiation	
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 2nd 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	
F	Model & Analysis Archival	

D.6 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, however, 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.

NASA-STD-7009A, Table 5, Level Definitions for Factors in the M&S Use (Operations) Category, provides guidance for achieving the various credibility levels for the input pedigree factor.

Table 29, Life-Cycle Phase Influence on input pedigree, shows how validation 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 29—Life-Cycle Phase Influence on Input Pedigree

Phase	Name	Input Pedigree is affected by
Pre-A	Model Initiation	
A	Model Concept Development	
B	Model Design	
C	Model Construction	
D	Model Test	
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	

D.7 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 30, 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 understand 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 a 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 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 30—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.

NASA-STD-7009A, Table 5, Level Definitions for Factors in the M&S Use (Operations) Category, provides guidance for achieving the various credibility levels for the Uncertainty Characterization Factor.

Table 31 shows how Uncertainty Characterization is affected by the various M&S life-cycle phases.

Table 31—Life-Cycle Phase Influence on Uncertainty Characterization

Phase	Name	Uncertainty Characterization is affected by
Pre-A	Model Initiation	
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	

D.8 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.

NASA-STD-7009A, Table 5, Level Definitions for Factors in the M&S Use (Operations) Category, provides guidance for achieving the various credibility levels for the Results Robustness Factor.

Table 32, Life-Cycle Phase Influence on Results Robustness, shows how Results Robustness is affected by the various M&S life-cycle phases.

Table 32—Life-Cycle Phase Influence on Results Robustness

Phase	Name	Results Robustness is affected by
Pre-A	Model Initiation	
A	Model Concept Development	
B	Model Design	
C	Model Construction	
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 are 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	

D.9 M&S History

The M&S History Credibility Factor includes two distinct parts: The change history and the use history of the M&S. The M&S change history is how new or how recently changed the M&S is, while the use history is how the M&S was used. When comparing current uses of the M&S with past uses, the change or revision history of the M&S is also to be considered.

While model development begins with Pre-Phase A and Phase A, the actual model design is not established until Phase B; after which, formal Change History is preferred, if not required.

NASA-STD-7009A, Table 6, Level Definitions for Factors in the Supporting Evidence Category, provides guidance for achieving the various credibility levels for the M&S History Factor.

Table 33, Life-Cycle Phase Influence on M&S History, shows how M&S History is affected by the various M&S life-cycle phases.

Table 33—Life-Cycle Phase Influence on M&S History

Phase	Name	M&S History is affected by
Pre-A	Model Initiation	
A	Model Concept Development	
B	Model Design	• The baseline of the original model's design establishes the beginning of the "real" model.
C	Model Construction	• When model implementation is complete, change tracking is established.
D	Model Test	• Successful model testing (both verification & validation) substantiates the model baseline for use.
E	Model Use	• Use of the model provides real-world application of the model that can further substantiate model validation and support use on similar RWSs or similar RWS scenarios.
F	Model & Analysis Archival	

D.10 M&S Process/Product Management

M&S Process/Product Management 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.

NASA-STD-7009A, Table 6, Level Definitions for Factors in the Supporting Evidence Category, provides guidance for achieving the various credibility levels for the M&S History Factor.

Table 34, Life-Cycle Phase Influence on M&S Product/Process Management, shows how M&S Product/Process Management is affected by the various M&S life-cycle phases.

Table 34—Life-Cycle Phase Influence on M&S Product/Process Management

Phase	Name	M&S Product/Process Mgt 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.
D	Model Test	• Plans, procedures, & scenarios for testing (verification or validation) are established to accept the model. • 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	• 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

M&S RISK ASSESSMENT

E.1 Purpose

This appendix provides guidance for assessing M&S risks.

E.2 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, therefore, 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.

M&S risks are discussed throughout NASA-STD-7009A (Table 35, Risk Related Topics in NASA-STD-7009A) and may be introduced during any phase of the M&S life cycle (Table 36, Examples of Possible Risks throughout the M&S Life Cycle).

Table 35—Risk-Related Topics in NASA-STD-7009A

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	… the probability a program or project will experience an undesired event; and the consequences	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 36—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 (Figure 18, NASA RIDM Process) and continuous risk management (CRM) (Figure 19, NASA CRM Process).

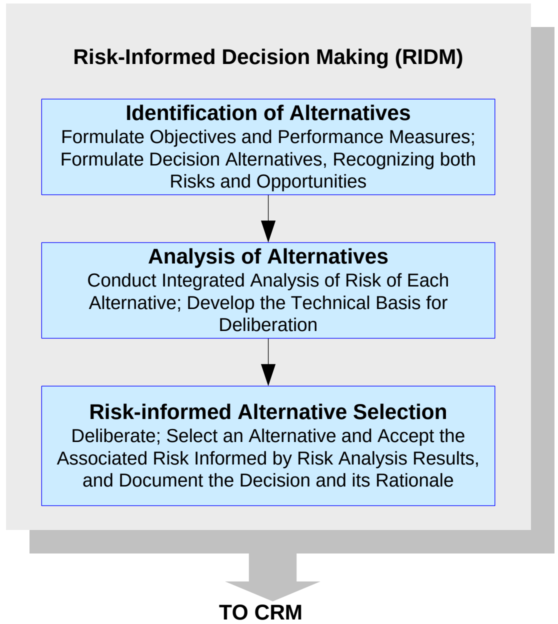


Figure 18—NASA RIDM Process

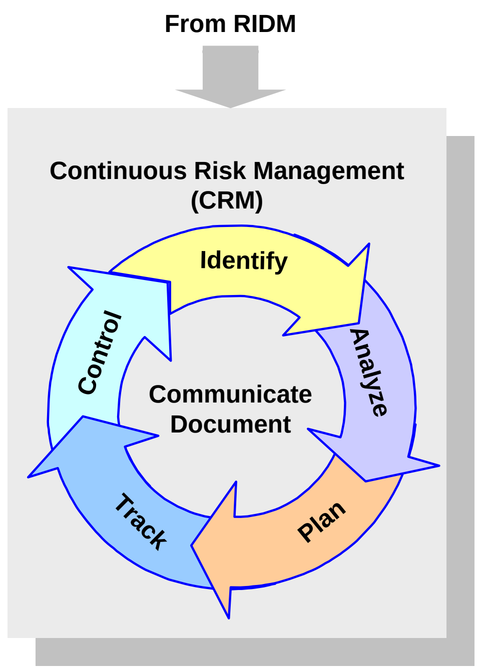


Figure 19—NASA CRM Process

Additional guidelines for the entire NASA risk management approach are found in NASA/SP-2011-3422, NASA Risk Management Handbook, and NASA SP-2010-576, NASA Risk-Informed Decision Making Handbook.

E.3 Aspects of 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-7009A 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-7009A, are shown in this NASA Technical 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-7009A 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 NASA Technical Handbook.

A detailed listing of the elements and sub-elements of M&S risk are consolidated in Table 37 for convenience.

Table 37—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 31]	**Credibility Assessment**			
	Data Pedigree			
	Verification			
	Validation			
	Input Pedigree			
	Uncertainty Characterization			
	Results Robustness			
	M&S History			
	M&S Process/Product Mgt			
[M&S 32]	**Caveats**			
(1)	Unachieved Acceptance Criteria			
(2)	Violation of any Assumptions			
(3)	Violation of the Limits of Operation			
(4)	Execution Warning and Error Messages			
(5)	Unfavorable outcomes from the proposed use assessments			
(6)	Unfavorable outcomes from Setup/Execution Assessments			
(7)	Waivers to Requirements			
[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			

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 36]	**Technical Review**			
	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 6]	Criticality Assessment			
[M&S 7]	M&S in Scope of 7009			
[M&S 9]	Technical Reviews			
[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 16]	Domain of Verification			
[M&S 18]	Domain of Validation			
[M&S 19]	Processes for Characterizing Uncertainty in Referent Data			
[M&S 20]	Methods of Uncertainty Propagation in M&S			
[M&S 21]	Incorporated Uncertainties			
[M&S 22]	Proposed Uses			

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 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] (1)	Uncertainties in Input			
[M&S 29] (2)	Uncertainties in Results			
[M&S 29] (3)	Uncertainties in Derived Results			
[M&S 30]	Sensitivity Analyses			

APPENDIX F

REFERENCES

F.1 Purpose

This appendix provides guidance in the form of additional reference documentation not named in the body of the text but that may provide supplementary information to the reader.

F.2 Reference Documents

F.2.1 Government Documents

DoD

VV&A Recommended Practices Guide Glossary. Retrieved May 20, 2011. http://vva.msco.mil/Mini_Elabs/VVtech-informal.htm#inf3

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.*

NASA

NASA-HDBK-8739.19-3	Measurement Uncertainty Analysis Principles and Methods NASA Measurement Quality Assurance Handbook – ANNEX 3
RP-08-118	NASA Standard for Models and Simulations (M&S): Development Process and Rationale
	Bolognese, J. (2009). The FEMCI Book. Retrieved February 21, 2018. http://femci.gsfc.nasa.gov/femcibook.html
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

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.*
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SAND2016-6465 TR	How to PIRT (July 2016)
SAND2016-6466 TR	What is PIRT? (July 2016)

F.2.2 Non-Government Documents

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APPENDIX G

TECHNICAL WORKING GROUP

G.1 Purpose

This appendix provides guidance in a list of the individuals in the TechnicalWorking Group who drafted this NASA Technical Handbook and can provide additional guidance, as necessary for implementing the practices in NASA-STD-7009A or this NASA Technical Handbook

G.2 Technical Working Group

Name	Center
Martin Steele, Ph.D. (Office of Primary Responsibility Designee)	Kennedy Space Center
Wei Lin	Ames Research Center
Trong Bui, Ph.D. Seung Y. Yoo, Ph.D. Manuel Castro	Armstrong Flight Research Center
Jerry Myers, Ph.D.	Glenn Research Center
Gary Mosier Jeffrey Bolognese, Ph.D.	Goddard Space Flight Center
Steven Cornford, Ph.D.	Jet Propulsion Laboratory
Paul Bielski	Johnson Space Center
Thomas West, Ph.D.	Langley Research Center
Timothy Barth, Ph.D.	NASA Engineering and Safety Center (Kennedy Space Center)
Kenneth Johnson	NASA Engineering and Safety Center (Marshall Space Flight Center)
Laurence de Quay, Ph.D.	Stennis Space Center

For further questions or guidance in the use of this NASA Technical Handbook, contact the Office of Primary Responsibility or other Center representatives listed above.