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

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FOREWORD

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

This Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

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

Requests for information, corrections, or additions to this Handbook should be submitted via "Feedback" in the NASA Standards and Technical Assistance Resource Tool at
http://standards.nasa.gov

Original Signed By: *10/18/2013*
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Michael G. Ryschkewitsch   Approval Date
NASA Chief Engineer

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1. SCOPE

1.1 Purpose

The purpose of this 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-7009, Standard for Models and Simulations, this Handbook provides a broader scope of information than may be included in a Standard and promotes good practices in the production, use, and consumption of NASA modeling and simulation products. NASA-STD-7009 specifies what a modeling and simulation activity shall or should do (in the requirements) but does not prescribe how the requirements are to be met, which varies with the specific engineering discipline, or who is responsible for complying with the requirements, which depends on the size and type of project. A guidance document, which is not constrained by the requirements of a Standard, is better suited to address these additional aspects and provide necessary clarification.

This Handbook stems from the Space Shuttle Columbia Accident Investigation (2003), which called for Agency-wide improvements in the "development, documentation, and operation of models and simulations"[1] that subsequently elicited additional guidance from the NASA Office of the Chief Engineer to include "a standard method to assess the credibility of the models and simulations."[2] General methods applicable across the broad spectrum of 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 standardized process for the M&S activity was developed.

The major contents of this Handbook are the implementation details of the general M&S requirements of NASA-STD-7009, including explanations, examples, and suggestions for improving the credibility assessment of an M&S-based analysis.

1.2 Applicability

This 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.

NASA-STD-7009 and this Handbook are intended for use by M&S practitioners, technical reviewers, decision makers, and others in the organization implementing, reviewing, using, or

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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)

receiving the results from an M&S-based analysis. Further, as NASA-STD-7009 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 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 4.2) as a guide to a more complete understanding of the analysis.

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

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

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

Further discussion of the key roles of responsibility is included in section 5.1 of this Handbook.

Anyone may use NASA-STD-7009 or this Handbook in the course of their modeling and simulation activities; however, this use should apply to M&S that meet established risk criteria determined by program/project management in collaboration with the NASA Technical Authority as outlined in Appendix A of NASA-STD-7009. 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 Handbook.

NASA-STD-7009 applies to any point in the program/project lifecycle 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 5.1.1 of this Handbook.

NASA-STD-7009 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 Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers. This Handbook may also apply to the Jet Propulsion Laboratory (JPL) or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

This Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance. When this Handbook contains procedural or process requirements, they may be cited 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 the Handbook.

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

2.1.2   Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov or may be obtained directly from the Standards Developing Organizations or other document distributors.

2.2   Government Documents

Department of Defense (DoD)

	DoD Modeling and Simulation (M&S) Glossary. Retrieved April 12, 2013. http://www.msco.mil/documents/_4_DoD%20M&S%20Glossary%20Combined.pdf
	Conceptual Model Development and Validation, RPG special topic, September 2006. Retrieved March 9, 2012. http://vva.msco.mil/
MIL-STD-3022	Standard Practice Documentation for 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

NASA

	Aerospace Safety Advisory Panel Annual Report for 2008
	Aerospace Safety Advisory Panel Annual Report for 2009
	Bolognese, J. (2009). The FEMCI Book. Retrieved October 25, 2011. 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
NASA TM-2011-215987	A Credibility Assessment Scoring (CAS) Process for Mission Risk Management
NASA-STD-7009	Standard for Models and Simulations
NASA/SP-2007-6105	NASA Systems Engineering Handbook
NASA/SP-2010-576	NASA Risk-Informed Decision Making Handbook
NASA/SP-2010-580	NASA System Safety Handbook, Volume 1, System Safety Framework and Concepts for Implementation
NASA/SP-2011-3422	NASA Risk Management Handbook
NPD 1000.0	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

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

Sandia National Laboratories

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

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

Institute of Electrical and Electronics Engineers (IEEE)

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

Modus Operandi, Inc.

Hagan, T; Walker, J. (2009). *Conceptual Data Model Evolution in Joint Strike Fighter Autonomic Logistics Information System of Systems Engineering.*

The Aerospace Corporation

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

The New England Journal of Medicine

Haynes, A.B.; Weiser, T.G.; Berry, W.R.; Lipsitz, S.R.; Breizat, A-H. S.; Dellinger, E.P.; Herbosa, T.; Joseph, S.; Kibatala, P.L.; Lapitan, M.C.M; Merry, A.F.; Moorthy, K.; Reznick, R.K.; Taylor, B.; and Gawande, A.A. (January 29, 2009). "A Surgical Safety Checklist to Reduce Morbidity and Mortality in a Global Population." *The New England Journal of Medicine.* 360; Vol. 5, pp. 491-499.

Other

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

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.

2.4   Order of Precedence

This Handbook provides guidance for promoting good practices in the production, use, and consumption of modeling and simulation products but does not supersede nor waive established Agency requirements/guidance found in other documentation.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

>	greater than
<	less than
≤	less than or equal to
-	minus
%	percent
+	plus
±	plus or minus
®	registered trademark
σ	sigma: standard deviation
SM	service mark
TM	trademark
1-D	one dimensional
2-D	two dimensional
3-D	three dimensional
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
BC	boundary conditions
BSTA	Backplane Stability Test Article
C	Compliant (in the context of the Recommendations Compliance Matrix in Appendix D)
CA	California
CAS	credibility assessment scale
CM	configuration management
CMMI	capability maturity model integration
COTS	commercial off the shelf
CRM	continuous risk management
D	depth
DES	discrete event simulation
DoD	Department of Defense
DOF	degree of freedom
EPA	Environmental Protection Agency
FEM	finite element model
FEMCI	Finite Element Modeling Continuous Improvement
ft	foot (feet)
GOTS	government off the shelf
GSFC	Goddard Space Flight Center
H	height

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HI	Hawaii
Hz	hertz
I/O	input/output
IC	initial conditions
ICD	Interface Control Document
IDD	Interface Definition Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
in	inch(es)
ISO	International Organization for Standardization
ISS	International Space Station
IV&V	independent verification and validation
JEOD	Johnson Space Center Engineering Orbital Dynamics
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
kip	kilopound(s) (1,000 pounds-force) (4,448.2216 Newtons)
KSC	Kennedy Space Center
LISA	Laser Interferometer Space Antenna
M&S	models and simulations (See usage note in section 4 of this Handbook.)
MIL	military
m	meter(s)
mm	millimeter(s)
MOTS	modified off the shelf
MRCR	Model Review Certification Record
MSL	Mars Science Laboratory
N/A	not applicable
N	Newton(s)
NASA	National Aeronautics and Space Administration
NASTRAN	NASA structural analysis system
NC	not compliant
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
OMB	Office of Management and Budget
OPR	Office of Primary Responsibility
OTS	off the shelf
PDE	partial differential equation
pdf	probability density function
PMSA	Primary Mirror Segment Assembly
RIDM	risk informed decision making
RISC	Risk-Informed Safety Case
RMP	risk management plan

RMS	root mean square
RPG	Recommended Practices Guide
RWS	real world system
S/W	software
SINDA	Systems Improved Numerical Differencing Analyzer
SME	subject matter expert
SP	special publication
SPIE	The International Society for Optical Engineering
STD	standard
SW	software
SWE	software engineering
TM	technical memorandum
TMG	thermal model generation
TRL	technology readiness level
TSS	thermal synthesizer system
V	volume
V&V	verification and validation
VIM	International Vocabulary of Metrology
VV&A	verification, validation, and accreditation
W	width

3.2   Definitions

Abstraction: The process of selecting the essential aspects of a reference system to be represented in a model or simulation, while ignoring those aspects that are not relevant to the purpose of the model or simulation[3]

Aleatory Uncertainty: The inherent variation in the physical system; it is stochastic, irreducible.

Analysis: Any post-processing or interpretation of the individual values, arrays, files of data, or suites of executions resulting from a simulation. Analysis spans the whole extent of the M&S process from the study of the RWS and/or its referents, the gathering and reduction of data from the RWS or accepted referents for incorporation into a model, the development of simulation scenarios, and the study and reduction of data from use of the M&S into recommendations for the RWS.

Architectural Diagram: A visual representation including the essential elements of any system and their interrelationships, along with the influences of external (environmental) or interfacing elements.

Assumption: Asserting information as a basis for reasoning about a system. In modeling

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[3] Adapted from *Fidelity ISG Glossary, Vol. 3.0,* Retrieved April 22, 2013.
http://www.sisostds.org/DigitalLibrary.aspx?Command=Core_Download&EntryId=31267.

and simulation, assumptions are taken to simplify or focus certain aspects of a model with respect to the RWS or presume distinct values for certain parameters in a model. Any modeling abstraction carries with it the assumption that it does not significantly affect the intended uses of the M&S.

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

Caveat: To include "an explanation to prevent misinterpretation" and "a modifying or cautionary detail to be considered when evaluating, interpreting, or doing something."[4]

Code Coverage: A method employed to measure how thoroughly software is tested; is commonly expressed on a percentage basis.[5]

Computational Model: The numerical representation of the mathematical model.

Conceptual Model: The collection of abstractions, assumptions, and descriptions of physical processes representing the behavior of the reality of interest from which the mathematical model or validation experiments can be constructed. (NASA-STD-7009, adapted from ASME V&V 10, Guide for Verification and Validation in Computational Solid Mechanics).

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

Credibility: "The quality to elicit belief or trust in M&S results." (NASA-STD-7009)

De facto Standard: An M&S that has achieved a dominant market share, which includes commercial off-the-shelf (COTS) applications, open-source code, and in-house code, within the relevant community of practice, but has not been formally established or required by wide consensus, code, or law.

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[4] http://www.merriam-webster.com/dictionary/caveat. Retrieved April 22, 2013.
[5] https://modelingguru.nasa.gov/docs/DOC-1828. Retrieved April 22, 2013.

Design of Experiments (or Experimental Design): A series of tests in which purposeful changes are made to the input variables of a system or process and the effects on response variables are measured. It is applicable to both physical processes and computer simulation models.[6]

Deterministic: A term describing a system whose time evolution can be predicted exactly.

Environment of the System (or Real World System): The set of elements external to a system. The RWS and its environment may interact through the exchange of properties. 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 can be subjective, is reducible, and may be identified with model uncertainty.

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

Face Validation (or Validation by Review): The process of judgment by peers, Subject Matter Experts (SMEs), and other stakeholders to ascertain if an M&S is (or if M&S results are) consistent with perceived system behavior. The process should include an assessment of the model assumptions and specifications (and the conceptual model) and is often used in the early stages of M&S development.

Favorable Use: A phrase deeming the application of an M&S as meeting relevant acceptance criteria by the program/project in collaboration with the Technical Authority (Requirement 4.1.3 (a) of NASA-STD-7009).

Formal Peer Review: A review sanctioned by the program/project and conducted in accordance with rules explicitly established by the reviewed or reviewing organization.

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

Framework: A set of assumptions, concepts, values, and practices constituting a way of viewing reality. For M&S, this may be a computing environment that integrates multiple interacting components on a single computer or across a distributed network.[7]

Informal Peer Review: A technical assessment not conducted pursuant to a process established by the reviewed or reviewing organization.

Input Pedigree: A record of the traceability of data from its source through all aspects of its transmission, storage, and processing to its final form used in an M&S. Any changes from the

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[6] 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.
[7] A modification from http://www.answers.com/topic/framework#ixzz1CL7UTZYb. Retrieved April 22, 2013.

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.

Interface Definition Document/Interface Control Document (IDD/ICD): For all practical purposes, synonymous terms. In the M&S context, these are formal documents defining interfaces between models, elements of a model, or simulations. The documents are typically used to specify input/output (I/O) variables, units, coordinate systems, initial and boundary conditions, and other parameters necessary to link one M&S to another.

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

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.[8]

Limits of Operation: The boundary of the set of parameters for which an M&S result is acceptable based on the program-/project-required outcomes of verification, validation, and uncertainty quantification. (NASA-STD-7009)

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

Maximum Likelihood: A method of parameter estimation that produces the highest probability estimate from a particular data set, given the probability distribution model.[9]

Model: A description or representation of a system, entity, phenomena, or process.[10] 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. A model of a model (commonly called a metamodel), e.g., a response surface constructed from the results of M&S, is considered a model.

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.[11]

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

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[8] http://support.esri.com/en/knowledgebase/GISDictionary/term/kriging. Retrieved April 22, 2013.
[9] Adapted from NIST: http://www.itl.nist.gov/div898/handbook/apr/section4/apr412.htm. Retrieved April 22, 2013.
[10] Adapted from Banks, J., ed. (1998). *Handbook of Simulation*. New York: John Wiley & Sons
[11] 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 stochastic (non-deterministic) events, the outcome of which is described by a probability.[12]

Real World System: The actual system the model is representing for the analysis; refers to the real system operating in its real environment. The term RWS is used to differentiate between the "system under analysis" and the "modeling system used for the analysis." Synonyms used in this Handbook, for contextual reasons, are "real system" and "reality of interest." (NASA-STD-7009)

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-7009; adapted from ASME V&V 10). 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.

Regression Testing: Software testing that seeks to uncover errors after changes to the program, e.g., bug fixes or new functionality, have been made. The intent of regression testing is to assure a change did not introduce new errors.[13]

Risk: The combination of the probability that a program or project will experience an undesired event and the consequences, impact, or severity of the undesired event if it were to occur. The probability and consequences may have associated uncertainties. (NASA-STD-7009, adapted from NPR 7120.5).

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

Sensitivity Analysis: The study of how the variation in the output of a model can be apportioned to different sources of variation in the model input and parameters. The Results Robustness of an M&S-based analysis is obtained via sensitivity analysis (NASA-STD-7009, adapted from Saltelli, 2005).

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

Stochastic: Involving or containing a random variable or variables. Involving chance or probability.[14]

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[12] NASA/SP-2009-569, Bayesian Inference for NASA Probabilistic Risk and Reliability Analysis
[13] Myers, Glenford. (2004). *The Art of Software Testing*. Hoboken: John Wiley & Sons, Inc.

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Uncertainty: (a) The estimated amount or percentage by which an observed or calculated value may differ from the true value;[15] (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 (NASA-STD-7009, adapted from NPR 8715.3, NASA General Safety Program Requirements); (c) Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand.[16]

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. (NASA-STD-7009)

Unit Problem: A problem that captures one or more fundamental characteristics relevant to the current application required for accuracy in the M&S.

Unit Testing: Any type of software testing conducted on the smallest meaningful, testable fragments of code to ensure the code behaves exactly as intended under various conditions. For procedural programming languages, such code fragments are generally functions or subroutines.[17]

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 if a computational model accurately represents the underlying mathematical model and its solution from the perspective of the intended uses of M&S.

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[14] http://dictionary.reference.com/browse/stochastic. Retrieved April 22, 2013.
[15] *The American Heritage Dictionary of the English Language, 4th ed.* (2006). Boston: Houghton Mifflin Co.
[16] *International Vocabulary of Metrology (VIM) 3 -* Basic and General Concepts and Associated Terms. Bureau International des Poids et Mesures, Joint Committee for Guides in Metrology
[17] http://www.saravanansubramanian.com/Saravanan/Articles_On_Software/Entries/2010/1/19_Unit_Testing_101_For_Non-Programmers.html. Retrieved April 22, 2013.

4. INTRODUCTION

Note: The acronym M&S is used in a variety of ways in the literature: model and simulation, model or simulation, models and/or simulations, modeling and simulation, and modeling and/or 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-7009, the decision was to focus on the product of models and simulations rather than on the process of modeling and simulating. This is explicitly stated in the Foreword to NASA-STD-7009 and is used throughout the Standard in that sense. Shifting meanings in this Handbook would be inconsistent and confusing; therefore, the use of M&S in this Handbook, as in the Standard, refers to models and simulations. There are times when the singular or plural form is intended, which can be inferred from the context.

4.1 Background of NASA-STD-7009 and NASA-HDBK-7009 Development

NASA-STD-7009 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 development, though it is primarily focused on the results of an M&S-based analysis. Most M&S standards and recommended practices have 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, which have resulted in the slow adoption of NASA-STD-7009.

After formal approval in July 2008, NASA-STD-7009 was delegated to the individual program, project, or M&S practitioner to adopt. While existing programs/projects were not required to adopt it, new programs and projects are to adopt it, depending on their needs and M&S-based analysis criticality. Initially, the only guidance provided was in the form of rudimentary training materials on the NASA Standards website and the Office of Primary Responsibility (OPR) contact information. The first M&S document produced related to NASA-STD-7009 was a checklist by JPL to provide guidance specific to their M&S activities: Model Review Certification Record (MRCR)[18]. Through part of 2010, the Constellation Program included NASA-STD-7009 as an applicable document and was developing a Recommended Practices Guide (RPG) based on the document (Recommended Practices Guide for Modeling and Simulation Credibility Assessment (Constellation Program), Aegis Report No. VJ-NASA-09-RP002, Draft 2009[19]).

In the first 2 years of its existence as a voluntary Standard, many questions were generated during implementation of NASA-STD-7009, both general questions and those for specific engineering disciplines attempting to meet its requirements. NASA's Aerospace Safety Advisory Panel (ASAP) also maintained a continuing interest in the implementation of the Standard as indicated in its Annual Report for 2008 and Annual Report for 2009, as its development was a

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[18] For more information about the MRCR (an Excel file), contact W.J. Bertch at JPL.
[19] VJ-NASA-09-RP002 was in review in the Constellation Program but was never approved.

direct result of a safety-related accident. The interest and questions regarding the practical implementation of NASA-STD-7009 provided the impetus to develop this Handbook, which was sponsored by the NASA Engineering and Safety Center (NESC) in December 2009.

Initial efforts in the development of this Handbook included the review of related NASA documentation (software requirements, product data and lifecycle management requirements, and NESC procedures); other related U.S. Government documentation, including OMB Circular A-119, Voluntary Consensus Standards, 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 external M&S standards and guides, including ASME V&V 20, Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer; ASME V&V 10; IEEE 1597.1, IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations, and the Mission Assurance Improvement Workshop, "Guidance for Space Program Modeling and Simulation," (Baxter, 2010).

The development of the 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 are that it is good to:

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 Scale (CAS) 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 CAS Factors to NASA-STD-7009 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-7009 by M&S practitioners, the additional emphasis on risk by the ASAP, the details of various aspects of M&S provided by other Government and professional organizations, and the findings from NASA pathfinder projects provide the basis for the development of this Handbook. While implementation of NASA-STD-7009 is initially perceived as complex, this is only 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 its complexity. The following are examples of the varieties of M&S:

- M&S primarily based on differential equations and/or difference equations.
- A relative geometry model of various objects over time.
- Regression models from empirical data.
- Various system data relationship models.

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 and is complicated by M&S systems that are combined into larger and/or distributed analytical platforms. Therefore, one essential consideration in the development of the Handbook was to provide guidance and explanations about the requirements and recommendations included in NASA-STD-7009 and thus ease and broaden its use. A worksheet-centered approach provides a readily usable tool for an M&S effort to use throughout its lifecycle.

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."[20] Studies were also accomplished in the area of medical/surgical procedures showing 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 and/or critical implications to human life or mission success, the use of a checklist or worksheet to guide the development, use, and discussion of M&S-based results is appropriate. The Worksheet resulting from the development of this Handbook combines aspects of both worksheets and checklists.
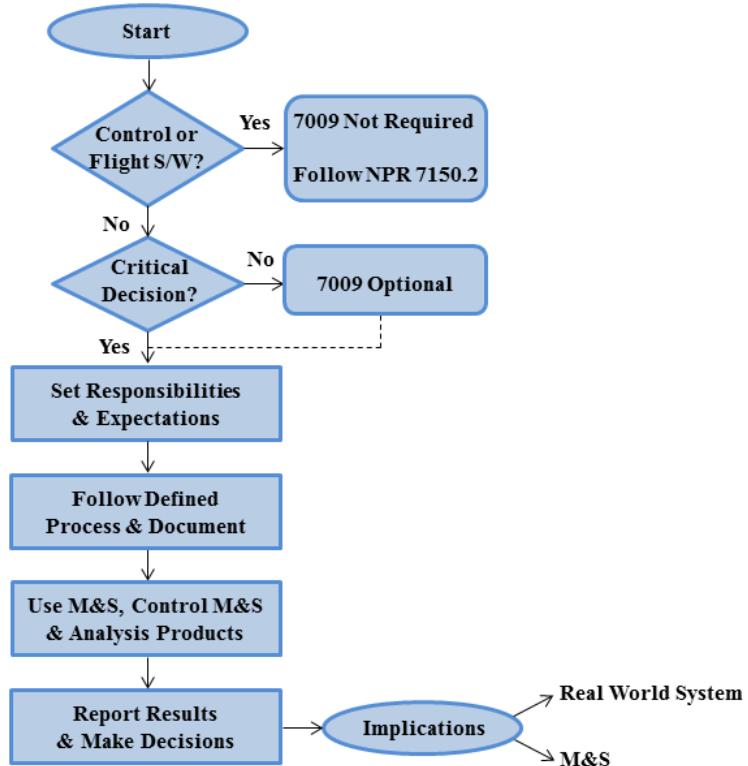
Note: This Handbook and Worksheet are not intended to be comprehensive or overly prescriptive. It is not possible to include everything needed for every type of M&S or leave enough room for full disclosure of everything requested. This Handbook primarily provides guidance to a more complete discussion of the details surrounding M&S-based analyses.

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

4.2 The Inferred NASA-STD-7009 Process

A process for using NASA-STD-7009 was not defined because of the variety of possible implementations; however, a generalized process is inferred (figure 1, NASA-STD-7009 Inferred Process).

Figure 1—NASA-STD-7009 Inferred Process

This process begins with potential exclusion gates based on the M&S being embedded in control or flight software and whether the use is intended as a significant part of critical decisions. This comes with the understanding that any project developing or using an M&S may wish to make use of the defined practices. Once use of NASA-STD-7009 is established, responsibilities are set, and expectations for achieving the requirements of the M&S project, including what and how to manage the artifacts of the project, are substantiated. During the development and use of the M&S, control of the M&S, data, and analysis products is accomplished. From the M&S-based analyses, results are reported that lead to decisions made with respect to the RWS or the M&S.

4.3   A Worksheet-Centered Approach

A key tool facilitating the use of the NASA-STD-7009 and this Handbook is a Worksheet developed as a guide to ensure the operations and processes for M&S are accomplished in an organized, consistent, and complete manner, thus improving both the safety and quality of the process.

4.3.1 Purpose of the Worksheet

This Handbook is designed to help the users of NASA-STD-7009 focus on concepts generally applicable to the discipline of modeling and simulation and, to that end, uses a Worksheet-centered approach. For example, M&S should be verified and validated distinctly, i.e., separately, and the results of an M&S-based analysis should include an understanding of the associated uncertainties. The other items in the Worksheet, which includes a results credibility assessment, can also be addressed by most M&S. However, some types or applications of M&S may have additional criteria for acceptance, which is the subject for discipline-specific recommended practices. Note:

     a.   The use of a worksheet does not guarantee an error-free system or process, especially if "checking off the boxes" is the only result. The Worksheet provides a structure for reaching a more complete understanding of an M&S-based analysis, i.e., one that is well developed, documented, maintained, and operated. From the information obtained in progressing through the Worksheet, the M&S practitioner, technical reviewer, and/or decision maker will have a better sense of the M&S and analysis credibility.

     b.   This Worksheet is not intended to capture all information relevant to a given M&S-based analysis. It is intended as a guide to a more complete understanding of the M&S and analysis results and allows the documentation of notes and other reference documentation.

     c.   The Worksheet solicits the results from the assessment of the M&S activity's compliance with the requirements of NASA-STD-7009 (in accordance with Appendix C of the Standard).

4.3.2 Organization of the Worksheet

The Worksheet is organized into a header and four sections, described in detail in section 5 of this Handbook.

     a.   The header contains basic information about the RWS, the M&S, the assessed analysis criticality, and the responsible parties for the RWS and M&S.

     b.   Each section includes key items and questions to elicit further details about the M&S and associated analysis and report summary information from those inquiries.

         (1)   The first section focuses on the RWS to which an analysis is directed, the M&S that provides the basis for the analysis, and how the M&S and RWS correlate.

         (2)   With this foundation, the second section documents the analysis results, the uncertainty contained in the results, and caveats that may detract from the acceptability of the analysis.

(3) The third section emphasizes the credibility assessment as a minimal set of factors providing a broad assessment of the M&S results, including the aspects of development, management, and use.

(4) The fourth section addresses compliance with the requirements of NASA-STD-7009 and the risk associated with accepting the analysis recommendations.

A key feature of this Worksheet is that it starts with an understanding of the context and criticality for a given situation and ends with an understanding of the risks involved with accepting the analysis recommendations derived.

4.4   Standardized Items for Reporting an M&S-Based Analysis

The following set of standardized items for reporting an M&S-based analysis was developed in NASA-STD-7009 and is explained in more detail in this Handbook:

a.   Understand the roles and responsibilities of the people involved, from the customers/stakeholders, i.e., the program/project managers and Technical Authorities, to the M&S practitioners and analysts. This responsibility chain follows current NASA governance.

b.   Plan and document the activities in the M&S process. A majority of the requirements of NASA-STD-7009 require documentation of what was accomplished.

c.   Perform a risk assessment in accordance with Appendix A of NASA-STD-7009 to determine the criticality of an impending analysis and the required use of the NASA-STD-7009.

d.   Understand the RWS and specific problem, the M&S, and how well they correlate.

e.   Report the following items with M&S-based analysis results. If these items or acceptability criteria for these items are not included, available, or accomplished, a clear statement of that situation is to be declared.

(1) The estimated results.

(2) A statement of uncertainty in the results.

(3) Caveats to the results. Placards of non-nominal conditions or events in an M&S-based analysis should accompany the results if:

　　　A. Established acceptance criteria are not achieved.
　　　B. Model assumptions are violated.
　　　C. Limits of model operation are violated.
　　　D. Warning and/or error messages occur during the execution of an M&S.

E. Intended use and setup/execution assessments are unfavorable.

F. Requirements of NASA-STD-7009 are waived.

(4) An understanding of results credibility. NASA-STD-7009 defines eight factors of credibility that contribute to the overall technical assessment of an M&S-based analysis. Depending on the criticality of an analysis, a technical review of an M&S activity may be prudent, using the following factors as a basis:

A. Verification.

B. Validation.

C. Input pedigree.

D. Results uncertainty.

E. Results robustness.

F. Use history.

G. M&S management.

H. People qualifications.

f. Understand the level of compliance with the requirements of NASA-STD-7009. Each M&S activity and program/project is unique, with a variety of expectations with respect to budget, schedule, requirements, and risk. These are to be balanced with the completeness with which an M&S activity complies with the requirements of NASA-STD-7009.

g. Assess the risk associated with basing a decision on the analysis. Methods of assessing risk depend on the set of scenarios in which the risk is manifest, the likelihood of those scenarios, and the consequences if they occur (NASA/SP-2010-576, NASA Risk-Informed Decision Making Handbook). Many factors contribute to how the M&S-based analysis influences the risk of a decision, e.g., the credibility factors listed in section 4.3.e.(4) above.

NASA-STD-7009 and this Handbook provide a basis for good practices in modeling and simulation. They are not expected to address the details of all types of M&S or all problem domains, but they do provide a standardized structure and foundation from which further understanding is possible.

4.5 Models – Key Concept

NASA-STD-7009 defines a model as a description or representation of a system, entity, phenomena, or process. Models are necessarily imperfect and/or incomplete for a variety of reasons:

a. It is not possible to make an exact representation because:

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

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

(3) It is not possible to include all possible variations of the subject RWS.

    b. It is not desirable to make an exact representation because:

        (1) Added fidelity (detail) adds cost and complexity.
        (2) Adding unnecessary details detracts from focus of the analysis.

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 do not produce exact or perfectly correct 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.

In addition, there are also references to terms such as sub-model, linked model, coupled model, integrated model, surrogate model, and metamodel. NASA-STD-7009 discusses some of these terms, stating, "A model may be constructed from multiple sub-models; the sub-models and the integrated sub-models are all considered models. Likewise, any data that goes into a model is considered part of the model. A model of a model (commonly called a metamodel), e.g., a response surface constructed from the results of M&S, is considered a model."

Surrogate models are 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, as described below. In effect, surrogate models are constructed in a manner parallel to empirical models where experimental data are used as the basis for I/O relationships between independent and dependent variables. In the case of surrogate models, the data come from the results of simulations rather than experiments.

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

The term linked models refers to cases in which two or more models interact through one-way coupling. A typical example is found in the case of telescopes and optical instruments, where the impact of temperature changes upon optical image quality must be limited by careful design. The linked analysis required in this case involves (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. 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-7009 to the individual M&S and also to the linked or

integrated M&S as a whole. The level definitions for the Input Pedigree factor in the CAS anticipate exactly this scenario.

4.5.1   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.

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.

4.5.2   The Modeling and Simulation Process

No discussion of modeling and simulation is complete without an understanding of the process involved from conception through application. Many such processes for an M&S activity are published with nuances to the particular discipline to which each is directed. For NASA M&S activities, the process followed would be part of the M&S Plan identified in Requirement 4.1.4 of NASA-STD-7009. A generalized process may be inferred from the original forays into M&S V&V. Some additional ideas inherent in this topic, along with the basic ideas of the RWS, conceptual model, and computational model, are that:

    a.   A referent may be used as an analog to the RWS that does not currently exist and may take a variety of forms, e.g., information from a similar system or a system specification. In this case, validation of the computational/simulation model is accomplished with respect to the referent, and the correlation of the referent to the RWS needs to be evaluated.

    b.   A model specification may be necessary along with a conceptual model, which may include the precise formalisms of mathematical notation or pseudo-code for complex constructs, i.e., a math model.

    c.   A simulation uses a computational model or simulation model to predict, mimic, emulate, or represent system behavior.

d.   M&S-based analysis results are often derived, i.e., post-processed, from raw M&S output data. Synonymous terms to an analysis based on the use of a model or simulation are model-based analysis, M&S-based analysis, and simulation analysis.

A generalized process for M&S development and use is shown in figure 2, Generalized M&S Process Including Model Use, in a left-to-right process flow. The process flow is described in table 1, Generalized M&S Processes, with the incumbent V&V feedback processes (shown in green).
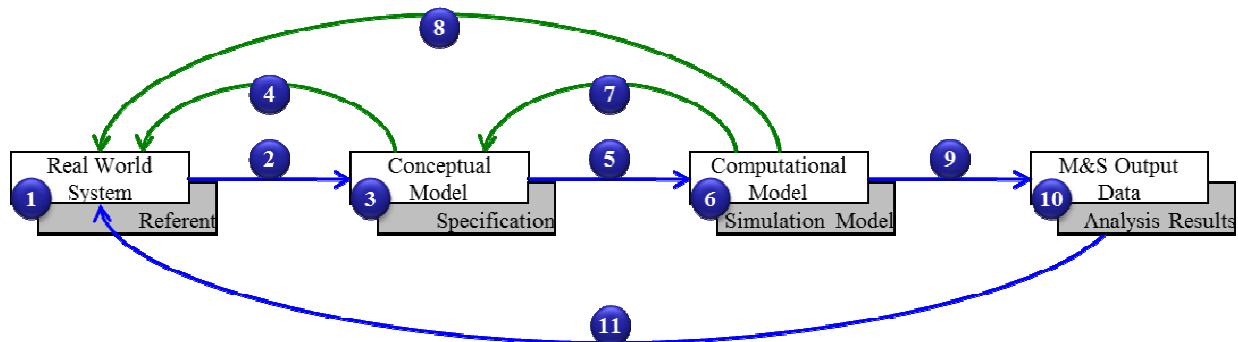
Figure 2—Generalized M&S Process Including Model Use

Table 1—Generalized M&S Processes

M&S Process Step	Description	Importance in M&S
1. RWS (and/or Analogous Referent)	The object/subject of the modeling/analysis	The RWS is the focus of the M&S, from which the model is developed and to which the analyses are directed.
2. Examine the System	Decomposition analysis of the subject to determine the relevant aspects to include in the model	Determines the abstractions, e.g., what to include and what to not include in the model, level of detail, assumptions, and model component interrelationships
3. Conceptual Model and Model Specification	The collection of abstractions, assumptions, and descriptions of physical processes representing the behavior of the reality of interest from which the mathematical model or validation experiments can be constructed (adapted from ASME V&V 10)	Provides narrative descriptions, block diagram, flow chart, equations, or pseudo-code, which, in turn, provide a static representation of the RWS, which is most likely complemented by a model specification
4. Validation of Conceptual Model	The process of determining the degree to which the conceptual model is an accurate representation of the real world from the perspective of the intended uses of the model or the simulation	Ensures the essential aspects of the RWS are captured for the impending analysis
5. Model Implementation	Constructing the models (for computer-based models, this means coding the algorithms) that will represent system behavior	The RWS model is built from the specifications.
6. Verification of Computational/Simulation Model with Conceptual Model	The process of determining if a computational model accurately represents the underlying conceptual and mathematical model and its solution from the perspective of the intended uses of M&S	Ensures the model is built to specification
7. Computational/Simulation Model	The computer-based code and logic, including the numerical representation of the mathematical model that imitates the characteristics of a system, entity, phenomena, or process	The Computational/Simulation Model is the basis for RWS analysis.

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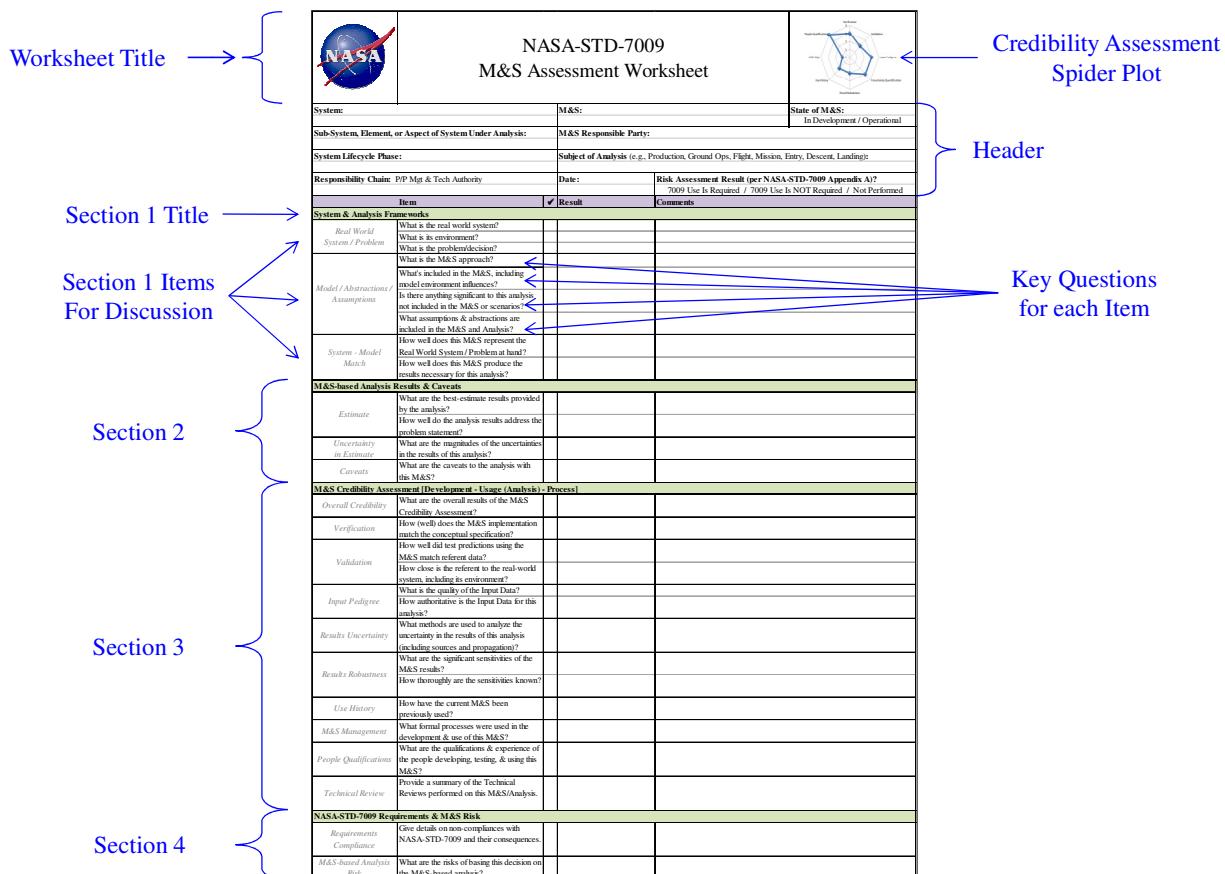
M&S Process Step	Description	Importance in M&S
8. Validation of Computational/Simulation Model with RWS or Analogous Referent	The process of determining the degree to which a Computational/Simulation Model is an accurate representation of the real world from the perspective of the intended uses of the M&S	Ensures the model adequately represents the intended RWS
9. Develop and Run Scenarios (Design of Experiments)	The description or definition of the relevant system and environmental assumptions, conditions, and/or parameters, i.e., M&S input, used to drive the course of events during the simulation	The set of scenarios to run determines the completeness of the analysis and can support the sensitivity analysis of scenario parameters.
10. M&S Output Data	The data produced by the M&S when running the scenarios	The raw output from running the M&S with the scenarios of interest; these data may be post-processed to produce results directly related to the analysis.
11. Results Analysis Applied to RWS	The M&S output data analysis producing direct recommendations applicable to the RWS	The M&S process comes full circle with implications to the RWS.

4.5.3 Philosophy and Structure of this Handbook with a Worksheet

NASA-STD-7009 is structured toward the management and quality aspects of M&S activities. Since the focus of this Handbook is toward more effective use of NASA-STD-7009, its structure is necessarily different and follows the structure of the Worksheet[21]. A diagrammatic overview is shown in figure 3, Overview of the Worksheet, with a full page view in Appendix A of this Handbook. Each portion of the Worksheet is discussed generally and then in detail.

Figure 3—Overview of the Worksheet
(See Appendix A of this Handbook for a full-page view of the Worksheet.)

The top of the Worksheet includes a representational credibility assessment spider plot that is one of the key features of NASA-STD-7009. As the credibility of results is central to a more complete understanding of an M&S-based analysis, each credibility factor and its relative rating, e.g., on a spider plot or bar chart, are included.

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[21] A spreadsheet version of the M&S Assessment Worksheet can be downloaded from https://standards.nasa.gov/released/nasa/NASA-HDBK-7009_Worksheet.xlsx. Retrieved 5-14-2013.

4.5.4 General Structure of the Sections Supporting the Worksheet

The goal for these guidelines and for the use of the Worksheet is that they are ultimately useable/actionable, i.e., users know what they need to do. As such, instructions in section 5 of this Handbook follow the following outline:

    a.   An introductory paragraph defining the Worksheet item.

    b.   Succinct statements about what is needed to satisfy this item. People versed in NASA-STD-7009 and this Handbook would use these statements as a review of details to consider, while people new to M&S might use this as an overview with more detailed explanations and examples supporting these details in the following sections.

    c.   Explanations as to the type of information to enter in the Result and Comments columns for this item/question and what additional information should be considered.

    d.   Examples of what to include for this Worksheet item.

    e.   If the Worksheet item is a CAS factor, suggestions for achieving each defined level of credibility.
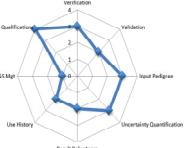
In the initial development phases of this Handbook, the Worksheet was simply a list of questions. While benchmarking against checklists and worksheets found in other industries, the ideas of grouping related items and providing an approximate flow emerged. Once this was attempted, the structure of the resulting Worksheet developed.

5. THE WORKSHEET

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 necessarily mandatory in all cases. These are recommended practices and suggested questions by which to glean more depth of understanding of the M&S-based analysis, while potentially working toward NASA-STD-7009 compliance.

5.1 Header

The Worksheet header (figure 4, Worksheet Header) addresses two areas of clarification for using any M&S-based analysis: linking the M&S used in the analysis to the RWS or sub-system to which the analysis is made and documenting the responsible parties for the RWS and the M&S. The clarification of the responsibility chain for the RWS and the M&S became apparent during some initial uses of NASA-STD-7009.

NASA	NASA-STD-7009 M&S Assessment Worksheet	
System:	**M&S:**	**State of M&S:** In Development / Operational
Sub-System, Element, or Aspect of System Under Analysis:	**M&S Responsible Party:**	
System Lifecycle Phase:	**Subject of Analysis** (e.g., Production, Ground Ops, Flight, Mission, Entry, Descent, Landing)**:**	
Responsibility Chain: P/P Mgt & Tech Authority	**Date:**	**Risk Assessment Result (per NASA-STD-7009 Appendix A)?** 7009 Use Is Required / 7009 Use Is NOT Required / Not Performed

Figure 4—Worksheet Header

5.1.1 Left Side of Header

The left side of the header addresses the system, sub-system, or aspect of the system relative to the analysis at hand, along with the current system lifecycle phase and the key responsible parties. Here, it is important to be specific in designating the real-world focus of the analysis. Simply stating a particular analysis relates to, for example, the Space Shuttle or the MSL, is too vague. Some details of the RWS worth noting are the current system lifecycle phase, the sub-system or component of the RWS under analysis, and the aspect (a particular part or feature) of the system under analysis as described below:

     a.   Current system lifecycle phase as designated by the project management phases defined in NPR 7120.5: The expectations of an analysis most likely change as a project matures. For example, the RWS operational performance analysis in the Concept and Technology Development Phase of a project is most likely much less accurate than the same analysis in the Operations and Sustainment Phase. The defined NASA project management phases are:
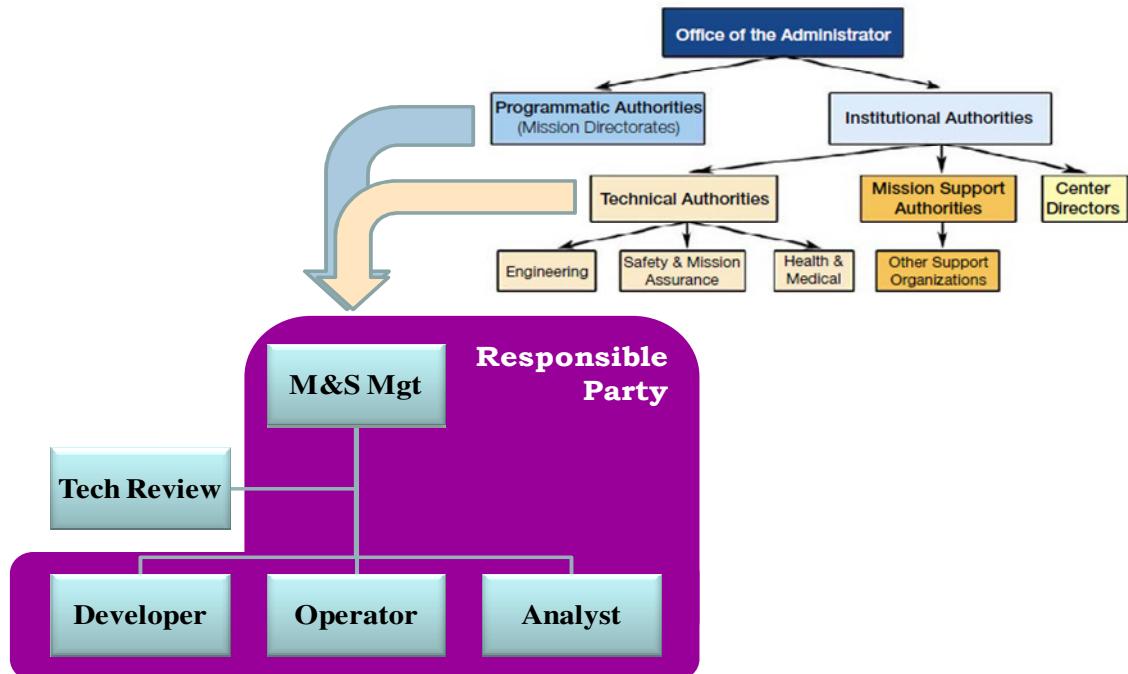
       (1) Pre-phase A – Concept Studies.
       (2) Phase A – Concept and Technology Development.

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(3) Phase B – Preliminary Design and Technology Completion.
(4) Phase C – Final Design and Fabrication.
(5) Phase D – System Assembly, Integration and Test, and Launch.
(6) Phase E – Operations and Sustainment.
(7) Phase F – Closeout.

b.   Sub-system, element, or aspect of system under analysis: One item very important to a more complete understanding of a problem and the associated analysis is its decomposition, which identifies the focus of the analysis, e.g., sub-system or component, in the context of the greater system of which it is a part. (See examples in section 5.2.1.2 of this Handbook.) Some typical examples of an engineering sub-system (element, portion, or aspect) of the system under analysis are:

(1) Structures.
(2) Mechanisms.
(3) Fluids.
(4) Thermal Management.
(5) Electrical Power.

c.   Responsibility Chain: Additionally, understanding the roles of program/project management and the Technical Authority for a program or project should be recognized and is discussed in NASA-STD-7009 and in NPR 7120.5. NPD 1000.0, Governance and Strategic Management Handbook, also addresses the check-and-balance structure in the NASA organization with the separation of Programmatic Authorities from the Technical Authorities. Specifically, section 4.1 of NASA-STD-7009 states:

"Program and project management have the responsibility to identify and document the parties responsible for complying with the requirements in this standard."

The Technical Authority, however, is largely responsible for accepting compliance with or deviations from the requirements of NASA-STD-7009. A depiction of these interrelationships and the required dual chain of responsibility are shown in figure 5, Relationships in the Responsibility Chain.

Figure 5—Relationships in the Responsibility Chain

5.1.2   Right Side of Header

On the right side of the header, information relative to the M&S used in the current analysis is documented, including the M&S (or M&S system) designation, the M&S responsible party, the subject phase of the analysis, the Worksheet completion date, and whether NASA-STD-7009 is required by the M&S Risk Assessment in Appendix A of the Standard.

Some nominal examples for the analysis phase by the M&S are:

    a.   Production (or Manufacturing).
    b.   Ground Operations.
    c.   Launch Count Down or Pre-Flight.
    d.   Ascent or Take-Off.
    e.   Mission Operations (may include "on orbit" for spacecraft or "en-route" for aircraft).
    f.   Entry (for spacecraft), Descent, and Landing.

Many alternatives, detailed sub-phases, or off-nominal conditions, such as aborts, are also possible. Additionally, the environment may be the subject of the analysis.

The M&S Risk Assessment in Appendix A of NASA-STD-7009 results in a categorization of the potential risk associated with an impending analysis. The result is a placement of potential risk on a matrix in critical (red), moderate (yellow), or relatively low risk (green) areas; however, the outcome of the assessment, in discussion with management, decision makers, and Technical Authorities, is a determination of whether NASA-STD-7009 is required. While the example shown in Appendix A of NASA-STD-7009 is a 4x5 matrix, the program/project determines the requisite dimensions or tool. Current formal NASA documentation does not specify the

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dimensions of a risk matrix, but a 5x5 matrix appears to be most common. (See figure 6, M&S Influence-Decision Consequence (5 x 5) Risk Matrix.) This is similar to the concept of Risk-Informed Safety Case (RISC) introduced in Volume 1 of the NASA System Safety Handbook (NASA/SP-2010-580), published in November 2011.

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

Figure 6—M&S Influence-Decision Consequence (5 x 5) Risk Matrix

For a technical decision where engineering judgment suffices, if M&S-based analysis results are used at all in supporting that decision, the influence of M&S-based analysis results may be considered minor or even negligible. In such a case, the M&S would be identified as non-critical. This Handbook and Appendix A in NASA-STD-7009 are used to help assess the criticality of M&S using a risk-based approach.

5.2 Section 1 – System and Analysis Frameworks

The purpose of the first section of the Worksheet is to provide the basis and context for the analysis results. The context for any decision or analysis result is the RWS; therefore, the portion of the RWS under analysis, including the boundaries, need to be understood first, along with the problem definition. Second, the basis for the M&S-based analysis results, which includes the basic structure of the M&S, the abstractions and assumptions, the analytical boundaries of the M&S system, and limits of operation, need to be understood. With this understanding of the analytical context of the RWS and the M&S, an assessment of the correspondence between them is possible. Only after this assessment is accomplished should the results of the analysis be considered (section 2 of the Worksheet).

5.2.1 RWS and Problem

The first and last consideration for any M&S is the RWS, either as it exists or as it is intended to exist. Without reference to the RWS, M&S reduces to an academic exercise. Therefore, a clear understanding of the analysis focus with the M&S is the starting point.

Clearly defining the RWS is the first step in the analysis of a problem, and it is from this definition that the context of the analysis is understood. The term system can be taken in many ways, and its use in the vernacular can take on various meanings in the same conversation, so a clear understanding of the context of its use is required. For the purposes of this document, the RWS is the system, or portion thereof, under analysis. Typically, the environmental influences on the RWS are also included in the definition of the model.

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This portion of the Worksheet (figure 7, Worksheet Item: Real World System/Problem) solicits key aspects of the RWS included in the analysis, along with significant external or environmental influences and the specific problem addressed.

Item	✓	Result	Comments
System & Analysis Frameworks			
Real World System / Problem — What is the real world system?			
What is its environment?			
What is the problem/decision?			

Figure 7—Worksheet Item: Real World System/Problem

The intention of this Worksheet item is to obtain a clear and complete understanding of the RWS under analysis:

    a.   The overall RWS and the focus area of the analysis should be annotated in the header portion of the Worksheet (figure 4).

    b.   The environmental realm, or operating domain, that is the focus of the analysis.

    c.   The problem of interest for this system, sub-system, or aspect of the system in the specific environment or during a specific operational phase that is the focus of the current analysis.

An architectural diagram of the RWS focus area, which should include the significant influences from interfacing or environmental elements, can be instructive.

5.2.1.1 Explanations

5.2.1.1.1 Defining the RWS

In understanding the real system and real environment, it is often useful to separate the RWS modeled from where, how, and under what conditions it is performing the operation. Classifying the system elements also helps visualize the modeled problem. System descriptions and details may include a variety of characteristics, e.g., statistics, properties, inherent variabilities, sensitivities, historical data, design maturity, and uncertainties.

Engineered systems can be modeled at any point in the design stage, while complex natural systems, e.g., non-engineered physical systems and human systems, can be modeled only to the degree that knowledge or appropriately representative hypotheses are available to represent their functional response. If design maturity or system knowledge is low, then sensitivities that take into account uncertainties and design choices need to be addressed and inventoried.

Note that low design maturity or idealized representations of the functional responses of complex natural systems may result in a low M&S-based analysis credibility rating. This underscores the fact that the credibility of analysis results may have little association with the model itself.

The RWS environment refers to external elements that affect it in a significant way, e.g., vacuum, temperature, dust, torque, or gravitational constant. A clear and complete understanding of the environment is a key part of understanding the RWS.

5.2.1.1.2   Problem Statement

A clear statement of problem, decision, or technical issue should be documented. It is often stated as a question or an issue description with the appropriate context but without any methodological prescription or inferred solution. This is the question to be answered using the model, and it should stem from the needs of the required decision. The model, simulation analysis, and information in the resulting recommendations should be tailored to this, not vice versa.

The problem statement and domain are best formulated at the time the modeling/analysis task is given, preferably through a negotiation between the modeler/analyst and key stakeholder(s).

Key questions to help in the problem statement formulation are:

    a.   What is the decision to be made?
    b.   What part of the decision will stand on the model and analysis?
    c.   What outputs and conclusions are necessary to support the decision?

5.2.1.2   Examples
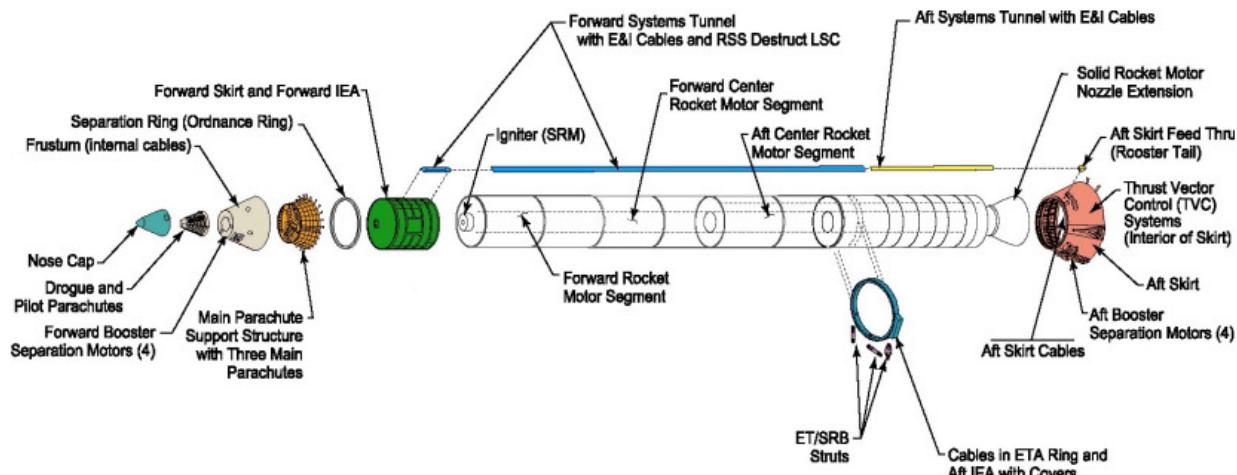
From any complete systems perspective, the following need to be known:

What Must be Known	Example
a. The overall RWS	a. The Space Shuttle – Orbiter
b. The problem focus area, e.g., the sub-system(s) involved	b. Orbiter Thermal Protection System, e.g., tile
c. The environmental realm or operating domain that is the focus of the analysis	c. Shuttle ascent from launch to T +9 minutes in clear and calm weather
d. The problem of interest for the system in the specific environment or during a specific operational phase	d. The induced stress or fractures on the Orbiter tile from impact
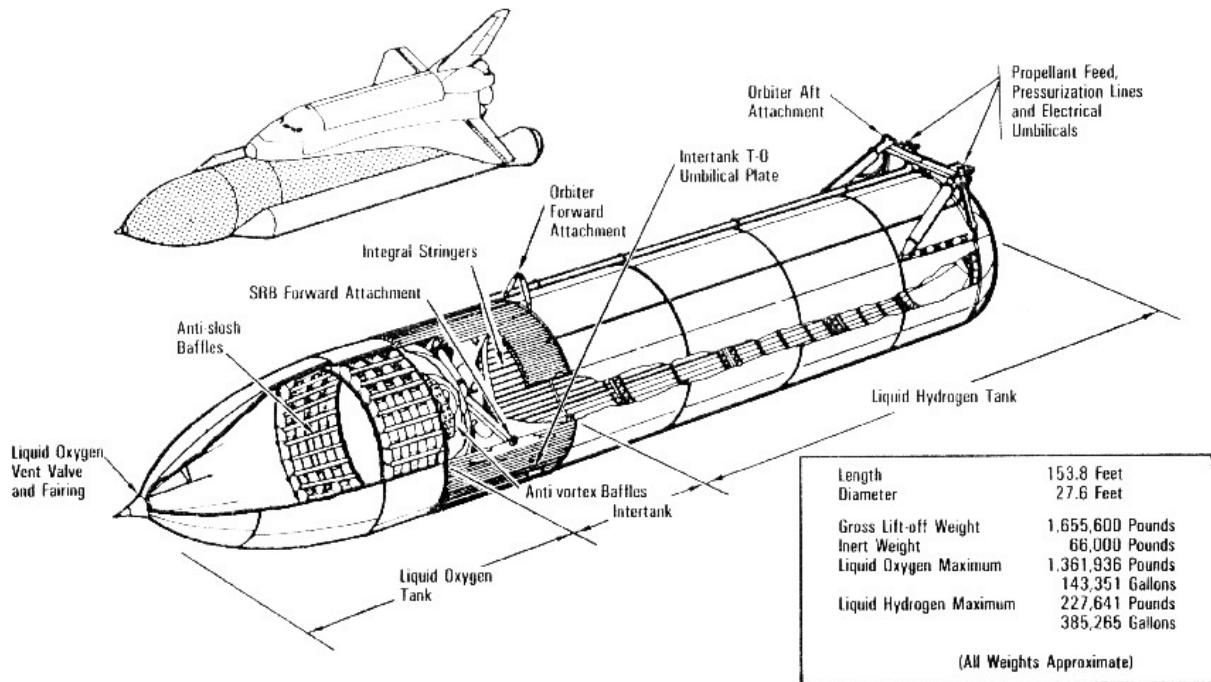
With this context, data from the analysis about the level of induced stress or potential of fractures on the Orbiter tiles from impact can be used to make decisions with regard to flight safety.

These basic descriptions of this particular real-world situation provide a clear understanding of the problem boundaries as basis for a recommended solution (decision).

There are many methods of depicting the RWS to better understand its relationship to the component parts. Architectural, exploded, and relationship diagrams are useful in pinpointing the specific area of an RWS that is modeled and analyzed (figure 8, Exploded Diagram of the Space Shuttle Solid Rocket Booster, and figure 9, Relational Diagram of the Space Shuttle External Tank).
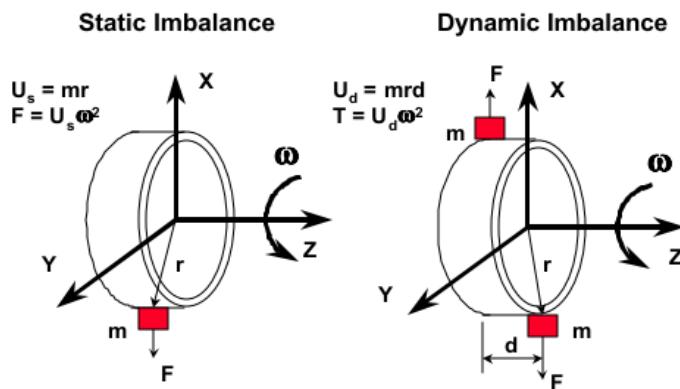
Figure 8—Exploded Diagram of the Space Shuttle Solid Rocket Booster

Figure 9—Relational Diagram of the Space Shuttle External Tank

A conceptual model (defined in section 3.2 of this Handbook) is useful in showing the functional relationship of a system's parts. For example, reaction wheels, momentum wheels, and control moment gyros are devices used to provide attitude control for remote sensing missions. When the rotors in these devices are spinning, inhomogeneity in mass distribution produces centrifugal forces and moments (similar to those in an unbalanced automobile tire or a load of laundry in a washing machine) that will affect pointing performance and result in blurred images. Arbitrary inhomogeneous mass distributions in the rotors may be modeled as discrete, lumped masses attached to ideal cylinders, as illustrated in figure 10, Conceptual Model – Free Body Design.
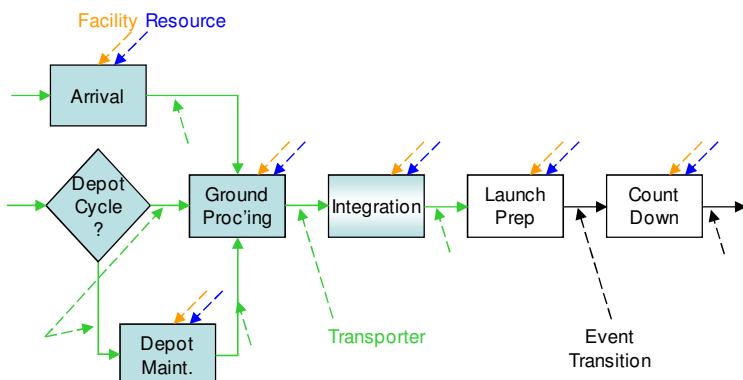
Figure 10—Conceptual Model – Free Body Diagram

A control system designer may need such a model to address many questions related to dynamic performance of a satellite. For example:

    a.   What imbalance specifications (coefficients U_s and U_d in the diagram) need to be levied on the reaction wheel supplier to meet satellite pointing requirements?

    b.   What is the effect upon satellite pointing performance for a given reaction wheel with measured imbalance coefficients?

If the analysis problem is more process-based, a conceptual flow diagram is useful in showing the relationships of a system's component processes and resources (figure 11, Conceptual Flow Diagram of a Process).

Figure 11—Conceptual Flow Diagram of a Process

With such a model, an operations planner can analyze a system's ability to meet launch rate expectations and make decisions with respect to component supplier arrival rates, resource (facility and transporter) quantities, or work shift and depot cycle policies in an attempt to improve the system's processing performance.

5.2.2   Model/Abstractions/Assumptions

This Worksheet item (figure 12, Worksheet Item: Model/Abstractions/Assumptions) is used to understand the M&S used in a given analysis. Models are developed from abstractions of an actual or proposed RWS implemented using the algorithmic logic of a conceptual model. (See section 4.2.2 of this Handbook.) Assumptions and abstractions focus model development for a particular purpose and should not have adverse influence on intended analysis outcomes. Logic and algorithms, which define implementation of the abstraction, including assumptions and limitations, are provided through the conceptual model. Items known to be missing from the M&S or solution and the modeling level of detail, i.e., fidelity, should be documented, e.g., the level of accuracy/precision in a geometric model and the time-step granularity in a process model. In addition, any limitation of the execution environment to represent the RWS fully, from the computational hardware, virtual machine, or software applications used to implement and run the model or simulation, should be understood and documented.

Item	✔	Result	Comments
System & Analysis Frameworks			
Model / Abstractions / Assumptions — What is the M&S approach?			
What's included in the M&S, including model environment influences?			
Is there anything significant to this analysis not included in the M&S or scenarios?			
What assumptions & abstractions are included in the M&S and Analysis?			

Figure 12—Worksheet Item: Model/Abstractions/Assumptions

This Worksheet item is characterized by four general issues:

    a. The M&S approach, methods, and architecture.
    b. What is included in the M&S, including model environment influences.
    c. Significant omissions to this M&S or scenarios for the analysis.
    d. Significant assumptions and abstractions for the M&S, scenarios, and analysis.

The following items illustrate the results and comments a reviewer might make in the Worksheet after review of a model or simulation:

    a. What are the M&S approach, methods, and architecture?

       Result: Acceptable.

       Comments: A finite element transient solution of launch dynamics. The simulation behavior is of sufficient granularity to address the analysis problem; a large set of conditions can be screened and problem areas noted for further detailed assessment.

    b. What is included in the M&S, including model environment influences?

       Result: Acceptable.

       Comments: Computational environment and model abstraction and conceptualization explained. All important aspects of the RWS are included with no shortcomings seen at this time.

    c. Is there anything significant to this analysis not included in the M&S or scenarios (definition in section 3.2 of the Handbook)?

       Result: Unacceptable.

       Comments: Model failed to capture significance of temperature-dependent material properties on deflection control.

d. What assumptions and abstractions are included in the M&S and analysis?

Result: Acceptable.

Comments: Physics of the situation in the model are adequately formulated. Conceptual model is sufficiently documented.

5.2.2.1 Explanations

The questions provided for this Worksheet item are provided to ensure a complete explanation of the M&S and should consider the following aspects:

a. M&S approach, methods, and architecture

(1) The modeling methods used, e.g., mathematical, stochastic/probabilistic, geometry, discrete event, relational, behavioral, physical, agent-based, human in the loop, and hardware in the loop).

(2) The level of fidelity/detail represented in the approach/model, as characterized by typical expected/desired results accuracy.

(3) The architecture (or diagram) of the M&S system, to include:

A. A high-level architectural diagram (or conceptual model) of the M&S system with major components and their respective interfaces, which provides an understanding of the solution objective. (See figure 13, Flow Diagram of Space Shuttle Launch Site Process; figure 14, Conceptual Model of Space Shuttle Launch Site Process; and figure 15, M&S Architectural Diagram, in section 5.2.2.2.1 of this Handbook.) There should be a relationship to the real-world problem with acceptable abstraction, including:

i.   Physical world environmental influences, e.g., pressure, thermal, electromagnetic.

ii. Data I/O requirements.

iii. Interoperability requirements with other M&S.

iv. Solution accuracy considerations.

B. If the model is computer-based, define and/or diagram the computational architecture with key hardware and software components, including dependencies or restrictions and stand-alone or distributed platform and related details or issues, e.g., machine run-time speed, capacity, bandwidth accuracy, computing centralization or distribution, and use of homogeneous or heterogeneous computational elements.

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(4) The types of problems the M&S is intended to support, e.g., training, force structure analysis, command and control, experimentation, component design, system analysis, or analysis of alternatives.

(5) Key data features (such as input data and output data) should be noted:

    A. For input data, identify the information required to populate and execute the M&S, including input data sets, hard-wired data, i.e., constants, environmental data, and operational data. Provide descriptive metadata, metrics, and authoritative or approved sources for all data.

    B. For output data, identify the results from an M&S run, including a definition, the unit of measure, and the range of values for each data item.

b. Inclusions in the M&S, including environment effects

(1) State how the model is abstracted into a problem of quantifiable solution.

(2) Identify model components in the conceptual model, and describe how the model solves the problem abstraction (MIL-STD-3022, Standard Practice Documentation of Verification, Validation, and Accreditation (VV&A) Models and Simulations). Abstraction provides a generalization of the problem, which reduces the information content to a more easily implemented solution, with focus toward a particular relevant purpose.

c. Significant omissions to the M&S or analysis, including scenario completeness.

Include limiting factors and constraints on the solution, along with known omissions of significant features of the RWS or characteristics of the problem.

d. Assumptions and abstractions of the M&S and analysis.

(1) Assumptions and abstractions should be noted along with (or in) the conceptual model and/or model specification.

(2) Analysis bounds and M&S limits of operation should be quantified and maintained.

5.2.2.2   Examples

5.2.2.2.1   Space Shuttle Processing Model Example

An example of a Space Shuttle process flow at the Kennedy Space Center (KSC) is shown in figure 13.
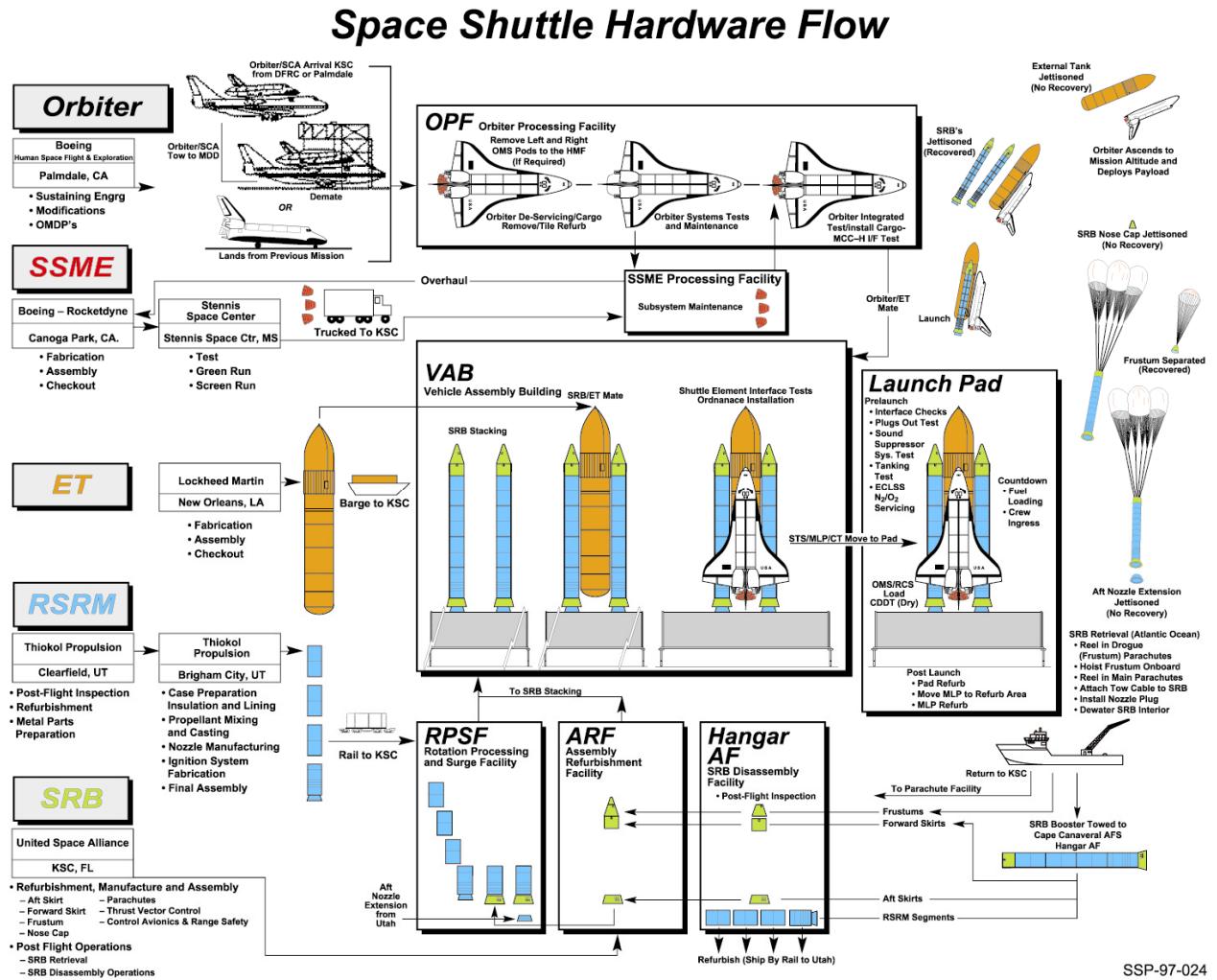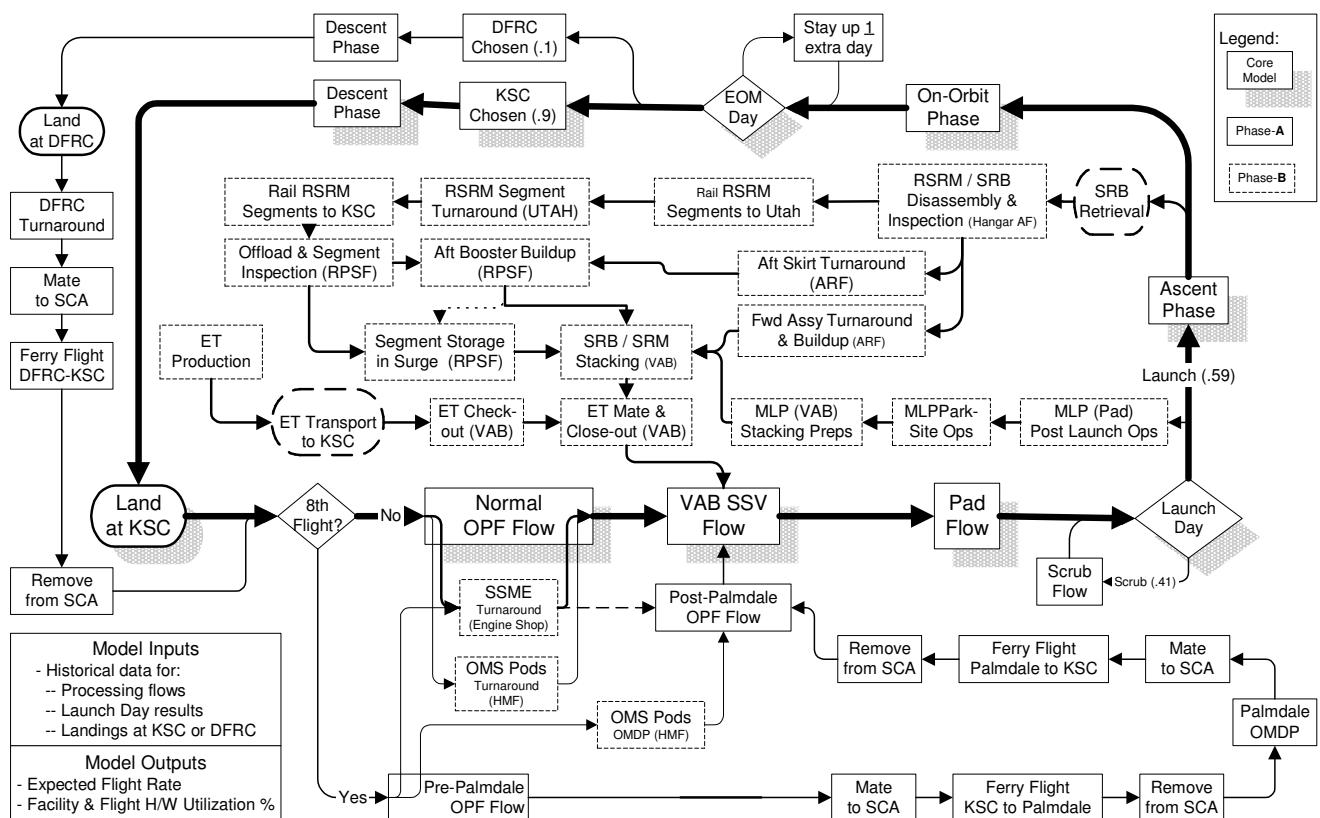
Figure 13—Flow Diagram of Space Shuttle Launch Site Process

From this diagram, discussions with SMEs and a review of program documentation, a more complete conceptual model was developed (figure 14).

Figure 14—Conceptual Model of Space Shuttle Launch Site Process

From the conceptual model, the computational model was developed using a single computer (Microsoft Windows®; no special requirements other than memory) and three separate software packages: a COTS discrete event simulation (DES) application, a custom-built user interface, and a COTS spreadsheet application. The user interface was used to define the set of scenarios with hundreds of parameters for system analysis, along with manifest definition data from the spreadsheet. The COTS DES application used these deterministic and stochastic inputs to run the model through a defined number of replications and produce statistical performance data of the RWS. In the architectural diagram (figure 15), the data flow between the three applications is seen.
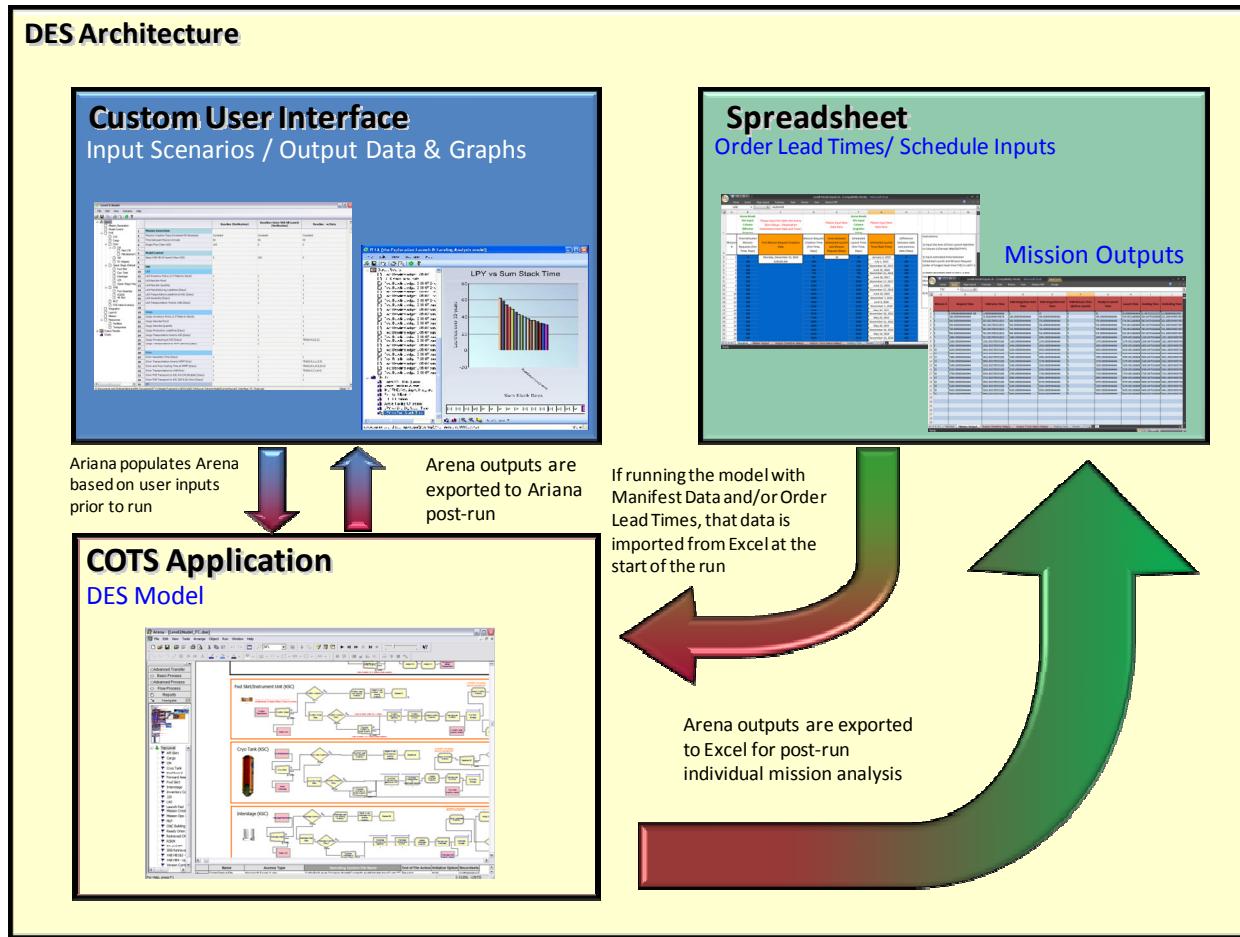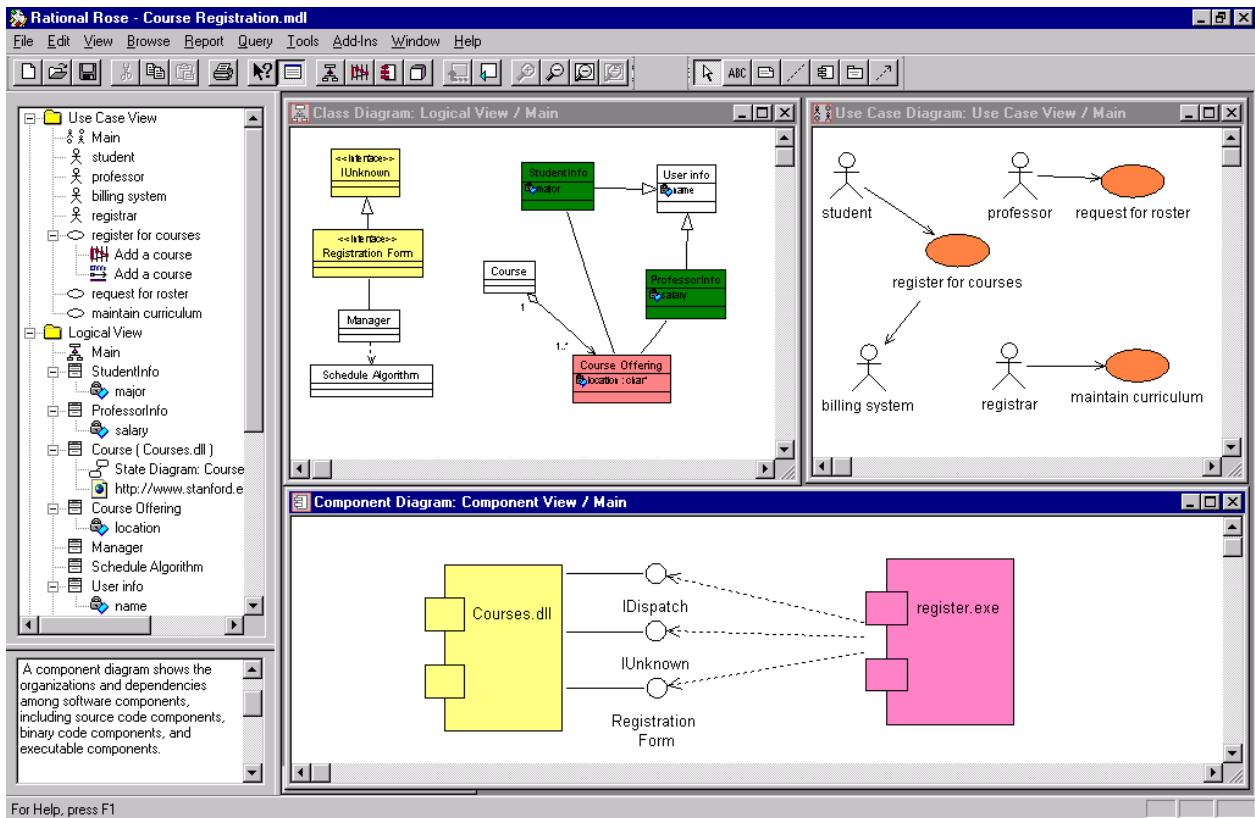
Figure 15—M&S Architectural Diagram

5.2.2.2.2 Object Definition Conceptual Model Example

Figure 16, Conceptual Modeling with COTS Software, shows the utility of conceptual model development using commercial software. (See DoD RPG Special Project Concept Model Development and Validation.) The multiple views shown provide a mechanism to define and interrogate conceptual model characteristics through multiple data and functionality representations. Hierarchical data trees and associated graphical views of class, component, and use case data are illustrated. Additional techniques for performing comparative analysis between the conceptual data model for new systems and the physical data models represented in applications, databases, and related systems are found in Hagan & Walker, 2009.

Figure 16—Conceptual Modeling with COTS Software

DoD documentation and directives (MIL-STD-3022 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.

5.2.3   System – Model Match

This Worksheet item flows naturally from sections 5.2.1 and 5.2.2 of this Handbook. With separate understandings of the RWS and the M&S, the intent now is to assess how well the M&S, as it is intended to be used, matches the RWS. It is understood that in novel cases, i.e., new or one-of-a-kind missions, the similarity between the RWS and the M&S may not be completely determinable before the first flight. At times, the appropriate data are not even collected during a given mission to validate an existing model. However, some basis, e.g., an analogous referent, should be available for accepting the model as appropriate to the analysis. In such cases, an understanding of what is known and unknown about the M&S and the RWS is used as a basis for acceptance.

a. What makes the M&S a good representation (or portion-of-interest) of the RWS?

(1) Relevant portions or aspects of the RWS are included in the model.

(2) The accuracy and fidelity of the M&S are to be adequate for representing the RWS.

(3) Model abstractions, assumptions, or functions different from the RWS are to be identified and assessed.

(4) The validated operating domain of the model is to be assessed with respect to the targeted operating domain of the RWS, including relevant environmental characteristics, with differences identified and assessed.

b. It is important to understand how the M&S directly produces the results necessary for the analysis.

(1) Is the intended use of the M&S directly applicable to the RWS problem?
(2) Are the M&S results a direct answer to the RWS problem?
(3) Is post-processing of the M&S output required?
(4) If M&S results post-processing is required, then:

A. Of what does it consist?
B. Is it part of V&V?
C. How is it documented?

The above information may be provided for this Worksheet item (figure 17, Worksheet Item: System – Model Match), with annotations, explanations, or references to other documentation given in the Comments field:

Item		✔	Result	Comments
System & Analysis Frameworks				
System - Model Match	How well does this M&S represent the Real World System / Problem at hand?			
	How well does this M&S produce the results necessary for this analysis?			

Figure 17—Worksheet Item: System – Model Match
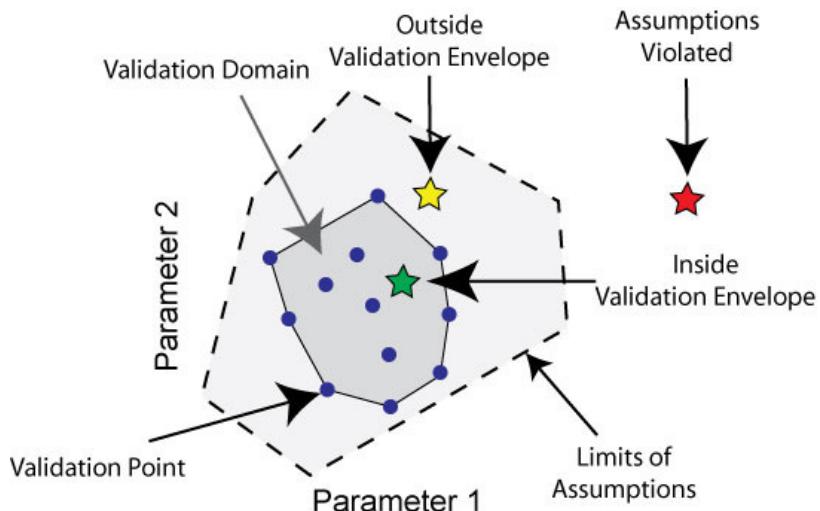
5.2.3.1   Explanations

5.2.3.1.1   What makes the M&S a Good Representation of the RWS (or Portion Thereof)?

All models are implicitly limited. What is inferred from this statement is that models only behave as designed and do not capture every behavior exactly like an RWS, act like all possible instances of an RWS, or encompass all aspects of an RWS. While the RWS may currently exist or may only be conceived, a model is a system representation. An understanding of how well the M&S matches the RWS is imperative to ensure the adequacy of system representation and the specific problem under consideration.

Validation is the primary activity during M&S development to understand analytically how well a model represents an RWS. A typical situation is illustrated in figure 18, Notional Illustration of a Validation Domain, for the case of two parameters of the system and/or the environment. The solid circles represent points in the two-dimensional (2-D) parameter space at which validation referent data are available. The solid line represents the envelope of the validation points, which encloses the validation domain, i.e., the region in which the M&S results have favorable agreement with the referent data. The dashed lines represent the boundary in which the key model assumptions hold, and reasonable results are expected. In many cases, the referent data do not cover the full region in which the limits of model assumptions are satisfied. The color symbols represent points for which the M&S results are inside the validation domain (green); outside the validation domain but still within the limits of assumptions (yellow); and outside the limits of assumptions (red). The validation activity should clearly define and document these boundaries.

Figure 18—Notional Illustration of a Validation Domain

Note that any point within the validation domain that does not exactly match a validation point is an interpolation. While interpolated results are generally considered acceptable, the nearness to exact validation points should be considered, as well as whether linear or curvilinear interpolation is warranted. On the other hand, any results outside the validation domain are considered extrapolations and much more caution is warranted. Again, the nearness to any exact point can be considered, but the behavior of the system anywhere outside the validation domain is really unknown.

When a model has been developed and validated for a particular RWS, then the validation boundaries are sufficient to determine the system-model match. However, when M&S are developed as a general solution to a class of RWSs, then the validation bounds need to be reassessed for each additional RWS to which the model is applied. Alternatively, systems are developed and accepted to operate within specified operational and environmental constraints. If an analysis is required with a model previously validated for a system but with the system operating outside previously specified margins, then a re-evaluation of the adequacy of the

model is necessary. If the re-evaluation shows the M&S to be inadequate, then model modifications and/or additional validation are required.

The preceding discussion focused on the validation bounds. Some of the same considerations apply to verification, although the model verification is not as strongly tied to a particular RWS as is its validation.

There are a few situations in which the adequacy of a model to represent the RWS comes into question:

a.   When a general-purpose model is applied to a particular system, situation, or problem. General-purpose models are created to address a wide range of problems. The intended use of such models should be considered carefully to ensure such a model is adequate to the situation to which it is applied, including the domain of validation, limitations of model assumptions, accuracy, precision, and producing results applicable to the problem it is addressing. In contrast, customized models are built to address a specific problem and should more directly comply with its needs.

b.   When an analysis is required of a system operating outside its normal limits. If an M&S is constructed to represent a specific system, the M&S is most likely validated only for the normal operating conditions for that system. Analyses of the system outside those normal limits of operations are extrapolations, which are not, by definition, within the bounds of validation. Therefore, the results of the analysis must be considered carefully and be accompanied with a placard. (Refer to the example in section 5.3.3.2 below).

c.   When an M&S is used to analyze a problem for which the limits of assumptions are exceeded. If the limits of assumptions are exceeded, great care must be taken with the suggested implications and with full knowledge of the risks involved.

Note: Both NASA-STD-7009 and this Handbook focus on M&S. The most credible use of any M&S is within the domain of V&V. Understanding the V&V domain in relation to the targeted operating domain of the RWS is crucial to understanding the M&S-based analysis. If the M&S use is extrapolated beyond the domain of V&V, then the analysis is to be accompanied by the appropriate caveat.

5.2.3.1.2   How Well Does the M&S Produce the Necessary Analysis Results?

An M&S is developed to address a particular system or problem type. If a model represents a system well but does not produce the required statistics or figures of merit on which to base a conclusion, then some adjustment or post-run manipulation of the data is required. Ideally, this is considered in the V&V phase of the M&S activity; however, tailoring of an established M&S to a specific purpose is also possible. In such cases, the M&S may not directly produce a needed result, but one may be derived. This process of derivation is to be carefully considered and documented.

5.2.3.2   Examples

Note: Examples will be developed and provided in a later revision.

5.3   Section 2 – M&S-based Analysis Results & Caveats

With the understanding of the RWS and the M&S and an acceptance of their correspondence, a look at the analysis results is appropriate, with the reminder that the M&S and the results produced are approximations with uncertainty. Any further qualifying statements surrounding the analysis should be included as a caveat to the analysis.

5.3.1   Best Estimate

The notion of a best estimate of results may be deceptively simple; however, it is critically important to remember that all M&S results are estimates and, therefore, contain uncertainty of a given system's response and not necessarily the exact response to expect from the RWS. It is also important to understand that, generally, the direct output of the M&S is itself not the final answer. A typical analysis requires multiple simulation runs, followed by some post-processing, possibly including statistical or non-statistical representation of output data. This can and often does involve the use of advanced statistical methods.

In at least some cases, the analyst may provide multiple answers to the problem; these answers are dependent on specific assumptions affecting the M&S from model form to model parameters to simulation run-time parameters. Each result is effectively a conditional best estimate.

The important questions to ask when presented with a best estimate include:

 a. What definition of best estimate was used by the analyst?

 (1) Mean, median, mode, maximum likelihood?
 (2) Were higher order statistical measures considered?
 (3) Were outliers removed?

 b. Is there agreement on the problem definition?

In question a(3) above, an outlier is simply defined as a data point in a set that lies outside the expected range of values. In practice, such a data point should be studied carefully and only removed if it is clearly an aberrant piece of data. It is also possible that a suspected outlier is a valid data point that happens to represent extreme values of the data set, which is detrimental if eliminated from an analysis. Additionally, in some studies with small data sets, eliminating any piece of data can significantly affect the representative statistics.

For this Worksheet item (figure 19, Worksheet Item: Estimate), the single valued result of an analysis may be put in the Result column, with qualifying statements, notes, or references to analysis documentation in the Comments column.

Item	✔	Result	Comments
M&S-based Analysis Results & Caveats			
Estimate — What are the best-estimate results provided by the analysis?			
How well do the analysis results address the problem statement?			

Figure 19—Worksheet Item: Estimate

5.3.1.1 Explanations

Possibly the most common statement of a measurement or prediction includes both the best estimate and the uncertainty and is expressed as:

Measurement or Prediction = Best Estimate ± Uncertainty

It is not always the case that the term best estimate is synonymous with commonly applied statistical measure, e.g., mean, median, maximum likelihood. The problem statement may be looking for extremes in expected outcome rather than a mid-point. In such cases, the results of a bounding analysis are driven to the extremes, i.e., are "no less than" or "no greater than" values, which provide neither two-sided error bars nor any kind of result distribution. A typical example involves predicting upper/lower temperature bounds for electronics. Many parameters in a thermal M&S are adjusted to provide hot or cold extreme predictions, which remove most or all of the aleatory uncertainties, i.e., naturally occurring randomness, in the estimate.

One consideration in the case of linked M&S, i.e., when the output from one M&S provides inputs to a second M&S, is that an M&S (or system of M&S) may serve multiple purposes. For example, the same M&S used to predict upper/lower bounds on temperatures may also be used to predict temperature changes over time that impact alignment stability of optics or other hardware. In the latter case, the desired best estimate may be the nominal value. It does no good for the structural M&S to be used with nominal parameters if the thermal M&S does not, as the end-to-end results will not reflect nominal performance. It is recommended to verify that the parameters of the thermal M&S were adjusted for each appropriate case, which is also considered under the CAS Input Pedigree factor.

5.3.1.2 Examples

The estimate for any given M&S-based analysis can take many forms. The following two examples will be further enhanced in sections 5.3.2.2 and 5.4.5.4 of this Handbook.

a. Example 1 – An analysis of the operations, integration, and launch processing of an operational launch vehicle in the middle of its design phase showed an average possibility of 3.96 launches per year with certain constraints.

b. Example 2 – The timeline analysis for a single process yielded the time-length of the process. From the 200 samples points obtained, the process average time was 2.00 days.

5.3.2   Uncertainty in Estimate

The Uncertainty in Estimate item is a high-level, aggregate view of uncertainty as it is manifested in the results of the M&S-based analysis. The details of the contributing sources of uncertainty in the M&S, the input to the M&S, and the propagation through a simulation analysis are discussed in the CAS – Results Uncertainty item (section 5.4.5 of this Handbook).

As the analysis results are based on a model of the real system and its environment with concomitant assumptions, approximations, estimates, and other uncertainties, it is inappropriate and possibly misleading to present the analysis outcome as a single definitive result without qualification.

Important questions to ask for this Worksheet item (figure 20, Worksheet Item: Uncertainty in Estimate) include:

   a. What are the magnitudes of the uncertainties in the analysis results?
   b. Are the uncertainties understandable and reasonable?
   c. How does the uncertainty influence the decision at hand?
   d. How does the uncertainty influence the risk associated with the decision at hand?

Item		✔	Result	Comments
M&S-based Analysis Results & Caveats				
Uncertainty in Estimate	What are the magnitudes of the uncertainties in the results of this analysis?			

Figure 20—Worksheet Item: Uncertainty in Estimate

The Result column can be used to document the magnitude of the aggregate or relative understanding of the results uncertainty, e.g., the percentage variation in the results, the standard deviation, half-width, statistical confidence interval, or other interval bound. The Comments column can be used for further clarifications or for references to supporting documentation.

5.3.2.1   Explanations

5.3.2.1.1   Reporting Results Uncertainty

The associated risk of accepting an analysis result increases if a discussion of uncertainty is not included. The topic of uncertainty is complex and difficult; however, the discussion helps to preclude misunderstandings, unjustified expectations, or conclusions that are either overly optimistic or overly pessimistic.

Uncertainty is most often described in statistical or probabilistic terms, e.g., the uncertainty of a measurement or the probability density function (pdf) of an inherently variable environmental parameter. However, other mathematical descriptions are also used, including interval bounds related to lack of knowledge, e.g., the reaction rate of a chemical reaction for which measurements are unavailable. (For a discussion of alternative uncertainty descriptions, see SAND2003-3769, Verification, Validation, and Predictive Capability in Computational Engineering and Physics.) For simplicity, the following discussion is confined to statistical or

probabilistic descriptions. When alternative descriptions are used, the suggestions described below should be adjusted accordingly.

The communication of uncertainty is accomplished in many ways. Common methods include a mean ± calculated error bands, e.g., a 5th and 95th percentile and/or confidence bands, and graphical methods, from box-plots to uncertainty distributions shown within a physical context. Graphical methods help visualize the span or range of the result from an analysis. The numerical uncertainty around an analytical result may be shown as follows.

- Estimate ± Standard Deviation.
- Estimate ± Half Width.
- Confidence Interval.

Raw sample standard deviations, histograms, and coefficients of variance relay incomplete information and are not recommended as full descriptions of uncertainty. Information on sample size and estimated distribution, e.g., normal, Weibull, nonparametric, skewed, or unknown, improve the utility of the spread information by giving information on the quality and quantitative bias of the estimate.

The following key points should be clearly understood and reasonable, i.e., make sense in the context of the RWS:

a. The best estimate from a given analysis is most likely a deterministic or single-valued answer, unless stated otherwise, e.g., the minimum/maximum probable value is or the best/worst case possibility is. It should be clear what type of result is given.

b. When the uncertainty for a given result is provided, it should be understandable and reasonable in the context of the RWS/problem. For instance:

(1) The uncertainty bounds should be physically possible, e.g., negative pressures or times are signals of incorrect calculation or assumptions. These estimates should be considered in context with the RWS.

(2) If the reported mean or median value is incorrect and the real system performs in a reasonably conservative part of the uncertainty bounds, then would this cause a problem?

(3) Does the resulting decision change when moving within the upper and lower bounds of the range of uncertainty?

c. When uncertainties are provided, does the decision risk change significantly with respect to the upper and lower bounds of that range of uncertainty?

d. Are the significant sources of uncertainty understood, as discussed in section 5.4.5 of this Handbook?

Qualitative estimates of uncertainty can be as useful as quantitative ones, though they may be more difficult to use to specify a resulting risk. The magnitude of the effect is most likely also qualitative.

5.3.2.1.2 Cautions

There are many ways of depicting uncertainty in data graphically, with possible adjustments to suit the needs of a particular situation. A box-plot (or box-and-whisker plot) is one such example for displaying the statistics of an associated data set. Key points on the statistical display of data should be clearly labeled and their meaning clearly conveyed.
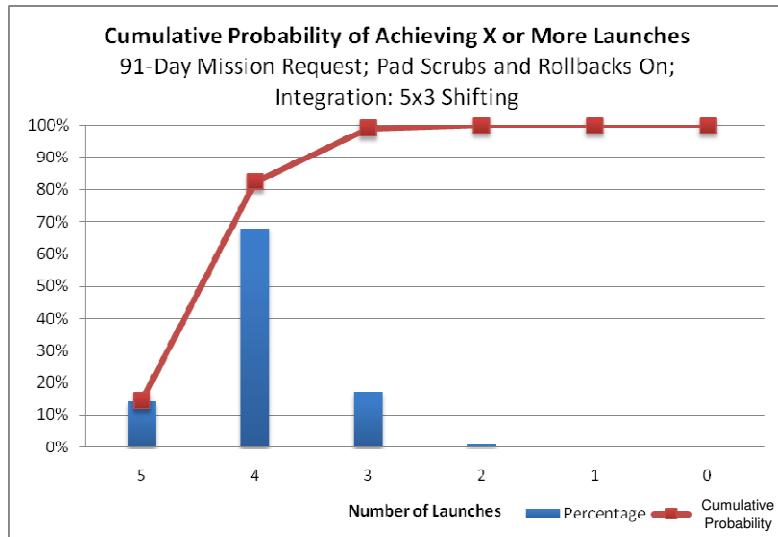
Uncertainty estimates that appear too optimistic, e.g., little to no variation or 3-σ estimates, or bounds drawn based on the range of data should be carefully questioned and may indicate an incomplete uncertainty assessment.

Uncertainty estimates that are more constricting than necessary may inappropriately drive program/project decisions.

When using a given confidence interval to inform decisions, be aware there is uncertainty about the confidence interval as well.

5.3.2.2 Examples

Further analysis from the first example in section 5.3.1.2 of this Handbook for launch vehicle operations, integration, and launch processing produced an understanding of the uncertainty around the estimate. Figure 21, Cumulative Probability Distribution of Analysis Results, shows there was an 82 percent probability of launching four or more times per year when trying to maximize the launch rate; however, there was also an 18 percent probability of launching only two or three times per year.

Figure 21—Cumulative Probability Distribution of Analysis Results

To answer questions a through d from section 5.3.2 (above) for this example:

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a. What are the magnitudes of the uncertainties in the analysis results?

The magnitude of the uncertainty for these results is essentially ±one launches per year with the specific probabilities shown in the graph and discussed previously.

b. Are the uncertainties understandable and reasonable?

Further understanding of the uncertainties requires a more detailed look at the M&S to determine why the number of launches is constrained. Either long process times or constrained resources are possible causes.

c. How does the uncertainty influence the decision at hand?

This uncertainty shows the inability of the modeled system to reliably maintain a constant launch rate greater than two. If program objectives require more than that, then changes to the operational system are required.

d. How does the uncertainty influence the risk associated with the decision at hand?

The uncertainties in the graph show more significant risk in reliably attaining more than three or four launches per year.

5.3.3 Caveats

For M&S-based analyses, the term caveat is defined as

> Modifying or cautionary information to consider when evaluating or interpreting the results of an M&S-based analysis.

In a given M&S-based analysis, a caveat is information pertinent to the results presented that should be documented and provided as a caution to the recipient, e.g., decision maker.

The reporting of caveats to an M&S-based analysis is initially stated in section 4.7 of NASA-STD-7009, with details called out in Requirement 4.8.1 of NASA-STD-7009.

NASA-STD-7009 includes requirements and recommendations for reporting results to decision makers. When describing the philosophy behind credibility assessment and its role in the decision-making process, the notion of caveats is introduced. The operational concept of the CAS requires that the presentation of M&S-based analysis results to a decision maker include:

- The best estimate of the results.
- A statement on the uncertainty in the results.
- The evaluation of the results on the CAS.
- Any explicit caveats that accompany the results.

Examples of possible caveats are:

a. Violations of M&S acceptance criteria, assumptions, or restrictions, e.g., limits of operation.

b. Exclusions from the model that significantly impact the results, the uncertainties in the results, and the conclusions derived from those results.

c. Errors and warnings that occur during an M&S-based analysis run.

d. Unfavorable outcomes from the intended use and setup/execution assessments.

e. Any waived requirements of NASA-STD-7009.

f. Analysis coverage space is inadequate or limited, e.g., as in a limited design of experiments.

g. Analysis focused on a specific design or vehicle configuration.

The types of information to include in this Worksheet item (figure 22, Worksheet Item: Caveats) are caveats that either should be considered or cause a rejection of the presented results.

Item		✔	Result	Comments
M&S-based Analysis Results & Caveats				
Caveats	What are the caveats to the analysis with this M&S?			

Figure 22—Worksheet Item: Caveats

5.3.3.1 Explanations

Each caveat should be assessed individually as to its impact on the analysis. Some details, events, cautions, or warnings to document as caveats may be:

a. Errors and warnings that occur during an M&S-based analysis run: Understanding the source of the errors/warnings and why they occurred

b. Violations of M&S acceptance criteria, assumptions, or restrictions: Not operating within the acceptance criteria for the M&S. A common practice is to identify qualitative and/or quantitative metrics, i.e., quality or goodness indicators for the M&S to be included in the acceptance criteria. An example from a structural finite element M&S (Bolognese, 2009) would be numerical tests (or flags) for indicators of an ill-conditioned stiffness matrix before the inversion of the matrix in a static analysis. Thresholds are set for a number of such scalar indicators. Analysis results may be accepted cautiously if one or more thresholds are exceeded slightly but generally are not in cases when any or all thresholds are exceeded to a significant degree.

c. Not adhering to the assumptions either built into the model or in the input to the model.

d. Violations of limits of operation: In instances where thresholds are exceeded but the analysis should be annotated with appropriate caveats and cautions.

e. Inadequate level of detail included in the model: Insufficient model detail discovered by the Worksheet items Model/Abstractions/Assumptions and System/Mode/Match should be listed in caveats.

f. Analysis coverage space is inappropriate or limited: Insufficient analysis coverage discovered, i.e., by Worksheet item Validation, should be listed in caveats.

g. Analysis focused on a specific design or vehicle configuration: Poor applicability of the analysis to the RWS as discovered by the Worksheet item System/Model/Match should be listed in caveats.

A good practice for reviewing M&S results would be the inclusion of a line-by-line examination of the documented assumptions and abstractions to:

- Determine if any of these were violated.
- Assess the consequences of such violations on the accuracy or interpretation of the results.

Furthermore, it is important to raise the same question about the possibility of undocumented or implicit assumptions. These situations might occur when off-the-shelf (OTS) M&S software is used for a variety of reasons, including:

- The (commercial) developers may not have documented their assumptions.
- The operators and analysts may not be totally familiar with the software.
- The operators and analysts may have used this code to the point where the underlying assumptions have effectively become implicit.

5.3.3.2 Examples

One method to ensure analysis caveats are noted adequately is to add placards to the results (figure 23, Example Placard).

CAUTION

**Analysis Performed
Outside the
Limits of Operation**
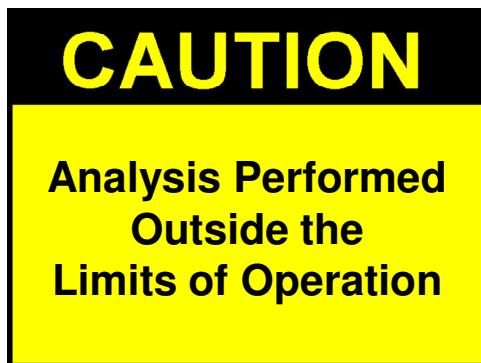
Figure 23—Example Placard

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

5.4 Section 3 – M&S Credibility Assessment

The first two worksheet sections form the basis for making a decision with respect to the RWS. However, there are details yet to consider as to the credibility of the results of an M&S-based analysis. These details are included in section 4.7 and Appendix B of NASA-STD-7009 and in the section 3 of the Worksheet, which addresses key development, usage, and process aspects of an M&S activity. One of the early applications of this credibility assessment method was accomplished by the Orion Project and documented in NASA TM-2011-215987, A Credibility Assessment Scoring (CAS) Process for Mission Risk Management.

 a.   There may be other key aspects to a particular type of M&S that are not included in this credibility assessment. Including them along with the credibility assessment defined in

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NASA-STD-7009 is acceptable and encouraged. The factors included in NASA-STD-7009'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 but only with the approval of the program/project Technical Authority. (See section 1.2.1 of NASA-STD-7009.)

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

5.4.1   Overall Credibility

The idea of M&S-based analysis credibility is necessarily complex and easily misconstrued, 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-7009 formalizes this assessment with a minimum set of criteria contributing to M&S-based analysis credibility.

The acceptable level for the overall credibility and contributing factors is determined by the program/project management in association with the Technical Authority, 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:

- The system development matures.
- Data become available from relevant phases of the program/project.
- The M&S matures and is used.

The assessment of overall credibility comes from a rollup of the credibility factor assessments for the M&S-based analysis and should include the following items:

- A tabular or graphical display for all of the CAS factors.

- The weighting used in calculating the each factor assessment, if the factor has a technical review sub-factor and the rationale for the weights.

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

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

Information entered on the Worksheet is a synopsis of more detailed information from an assessment of the M&S and the analysis performed with it. Figure 24, Worksheet Item: Overall Credibility, shows how the information would appear using the data in the example of Appendix B of NASA-STD-7009.

Item	✔	Result		Comments	
M&S Credibility Assessment [Development - Usage (Analysis) - Process]					
Overall Credibility	What are the overall results of the M&S Credibility Assessment?	Score:	1.7	Who assessed the analysis?	Jane Doe of the Assessment Team
		Weighting Used?	Yes	Rationale summary?	… (reference file name)

Figure 24—Worksheet Item: Overall Credibility

5.4.1.1   Explanations
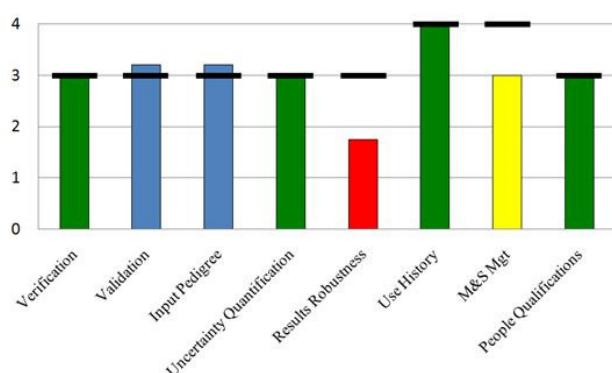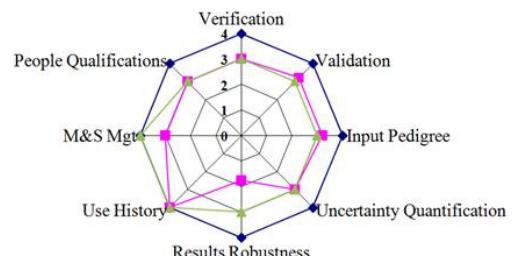
The overall credibility assessment of the M&S-based analysis is a synopsis of the individual factor ratings that follow in subsequent Worksheet items and CAS factor ratings. Reporting this information with an M&S-based analysis is required by Requirement 4.8.3 of NASA-STD-7009.

This overall credibility information provides the single-valued credibility assessment. However, this assessment is to be supported by information from the individual factor assessments. Improvement of the overall credibility assessment is only possible through improvement of the contributing CAS factors, which may also include an improvement in technical review. When weighting is used in the assessment of the five factors with sub-factors, the weights and rationale should be provided as part of this overall assessment. A table, bar chart, or spider plot (radar plot) of the CAS aids in understanding the overall assessment.

5.4.1.2   Examples

An example of CAS reporting in accordance with Appendix B of NASA-STD-7009 with target threshold values is shown in figure 25, Graphical Methods for Reporting M&S Results Credibility.

a. Bar Chart   b. Spider (Radar) Plot

Figure 25—Graphical Methods for Reporting M&S Results Credibility

Note: It is not possible for an M&S to achieve Level 4 credibility without considerable effort in M&S development and use and without 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 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 Technical Authority, to ascertain the acceptability of this information.

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5.4.2 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. The M&S can be considered verified when the following two conditions are satisfied:

- 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.

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

A review should examine the documented evidence relating to these two aspects of verification and address questions, including the following:

- What actions demonstrated the computational model functions exactly as intended, as specified by the conceptual model or other model requirements document? What were the results of these actions?

- What process was used to quantify numerical errors resulting from the software algorithms, and what were the results?

- 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?

The Results and Comments columns, shown in figure 26, Worksheet Item: Verification, could be used to note failures to satisfy all of the software specifications, the most significant potential sources of numerical error in the simulation, and at least a qualitative assessment as to the effects these differences may have upon predictions for the RWS.

Item		✓	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]				
Verification	How (well) does the M&S implementation match the conceptual specification?			

Figure 26—Worksheet Item: Verification

5.4.2.1 Explanations

The term "verification" is generally accepted to refer to two related processes: code verification and calculation verification (or solution verification). These processes are designed to demonstrate that the software implementation produces correct results.

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 the intended purpose (in accordance with the specifications). Verification of the structure and/or flow is by code tracing, unit testing, i.e., running the M&S through a series of low-level tests, and comparison of the coded model with the conceptual/mathematical models. Some, if not all, of the tests should be re-run any time the code is changed (a process known as regression testing) either to fix a software error or to add new functionality to ensure the changes do not introduce new errors. This topic also addresses the issue of code coverage, i.e., the percent of relevant logical branches within a code tested for proper numerical and logical execution.

b.   Calculation verification encompasses efforts to assess computational model correctness and numerical accuracy, independent of the physics being modeled. This requires consideration of numerous parameters associated with the numerical algorithms. These would include quantities such as solver tolerances and sampling intervals, with each having temporal characteristics, e.g., Runge-Kutta integration of differential equations, and spatial characteristics, e.g., type of mesh element and density of finite element meshes or density of ray bundles in thermal radiation models or in optical geometric ray-trace and physical diffraction models. Often, the choice of these values involves a trade between accuracy and run-time efficiency, and it is important that the effect on numerical accuracy be quantified and propagated to the overall uncertainties for the M&S results. Clearly, the best possible means to assess the correctness and accuracy of the numerical solution is by comparison to a closed-form solution, which may be possible, especially for simple, low-order problems. For example, eigenvalues and eigenvectors for three- or four-degrees of freedom (DOF) spring-mass systems can be found algebraically, and these solutions can then be used to test any numerical methods (eigensolvers) developed to support dynamics analysis of large-order finite element models (FEMs). Such results provide a rough estimate of the lower bound on achievable numerical errors. This topic should also address the statistical basis of any probabilistic analysis or confidence-based assertions.
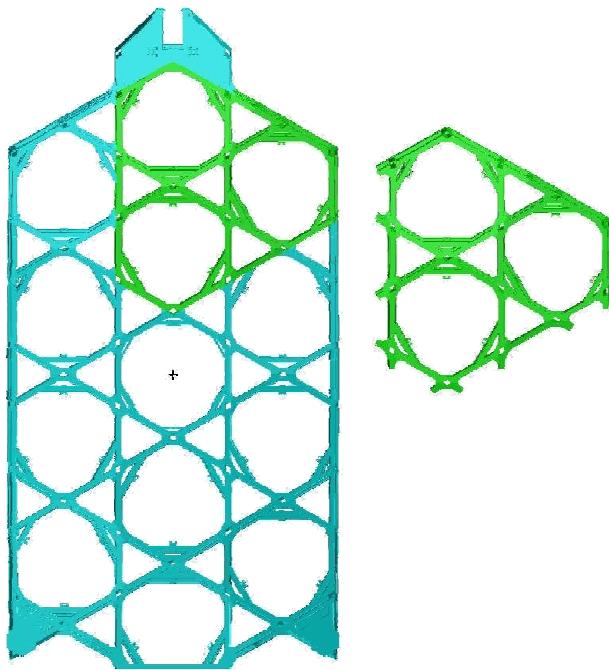
An additional context for verification is not associated with the development of the M&S but rather with its current use and is commonly called input verification. This process and its artifacts are used to detect human errors, e.g., typographical errors or other incorrect/inadvertent interactions with the software. 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 and/or other methods were employed is advisable when reviewing M&S results.

5.4.2.2　　Examples

Finite element codes such as the NASA structural analysis system (NASTRAN) compute conditioning and goodness numbers that provide implicit indications of numerical errors in the computational model. One example is the ratio of the diagonal terms of the stiffness matrix to the same diagonal term in the upper triangular factor computed during the static analysis procedure. A ratio higher than 10^8 could indicate possible model support problems or a high stiffness ratio in components at a grid point, and these areas should be investigated. A second example is a calculation of virtual work based on static displacements, which should be zero at force equilibrium. This number is known as epsilon, and the numerical results are generally deemed acceptable if $\leq 10^{-5}$; otherwise, the model should be examined for support problems (inappropriate constraints, boundary conditions, or grounding in a structural FEM) or the improper use of infinitely rigid elements. (The term "support problems" refers to inappropriate constraints, boundary conditions, or grounding in a structural FEM.)

Common examples in solution verification are ensuring the appropriate type of mesh element and mesh refinement for FEMs, such as those used to solve problems in structural mechanics and heat transfer. Some examples of the types of mesh elements are bars, plates, shells, or solids. The fundamental objective of mesh refinement is to increase the mesh density, i.e., reduce the spatial sampling between grid points, until no significant change is observed in the output quantities of interest. As is the case for analysis of thermal-elastic stability of the large cryogenic optical metering structure designed for the James Webb Space Telescope (JWST), the mesh density is a balance between predictive accuracy and computational efficiency and a non-optimal numerical error mesh density to achieve acceptable simulation run times.

To demonstrate the JWST composite design had achieved Technology Readiness Level- (TRL-) 6, experiments were performed on the backplane stability test article (BSTA), which is a small triad representative of a section of the full-scale (6.5-m (21.3-ft) diameter) structure that supports the 18 beryllium mirror segments. (See figure 27, JWST Backplane Stability Test Article (1/6th full-scale cutout of flight backplane).) These experiments were used to validate the model of the composite structure. Before validation, a study was performed to determine an acceptable mesh density, balancing numerical error with run time.
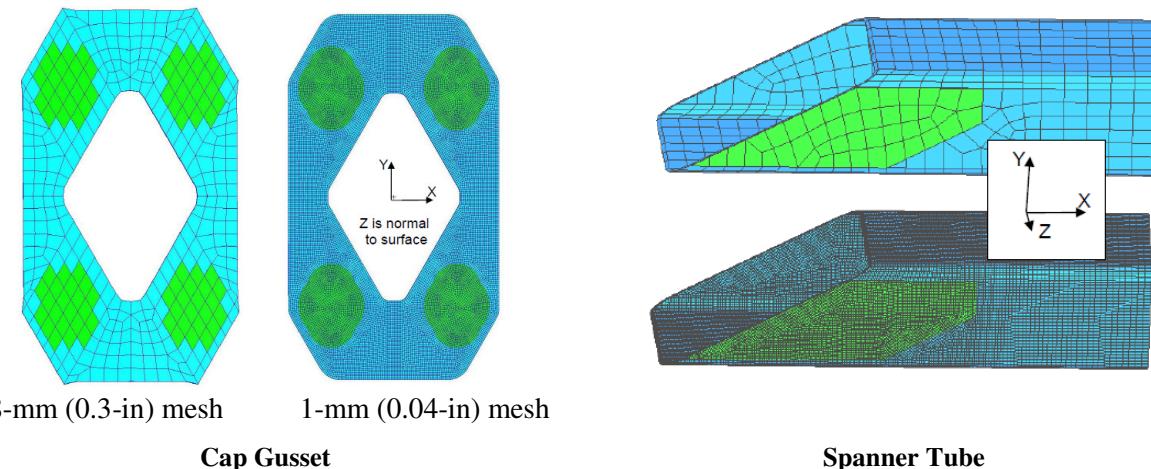
Figure 27—JWST Backplane Stability Test Article
(1/6th full-scale cutout of the flight backplane)

Based on extensive experience with precision composite structures, the structural analysts were confident that a highly refined mesh using 1-mm x 1-mm (0.04-in x 0.04-in) elements would have the desired accuracy for the intended use. Using a mesh this fine to model the entire BSTA would require on the order of 100 million DOF in the model and exceed the capabilities of the computer system, not only in the numerical sense but also with respect to visualization. For the full-scale structure, the situation would obviously be even worse.

The strategy employed was to model the various piece-parts that comprised BSTA, as well as JWST's primary mirror backplane. The meshes for these piece-parts were built using the 1-mm (0.04-in) mesh density (sometimes called the Gold Standard Mesh by the project team), and then a series of less refined models were systematically built, all the while being compared against the most refined mesh in terms of stiffness, distortion, and thermal forces.
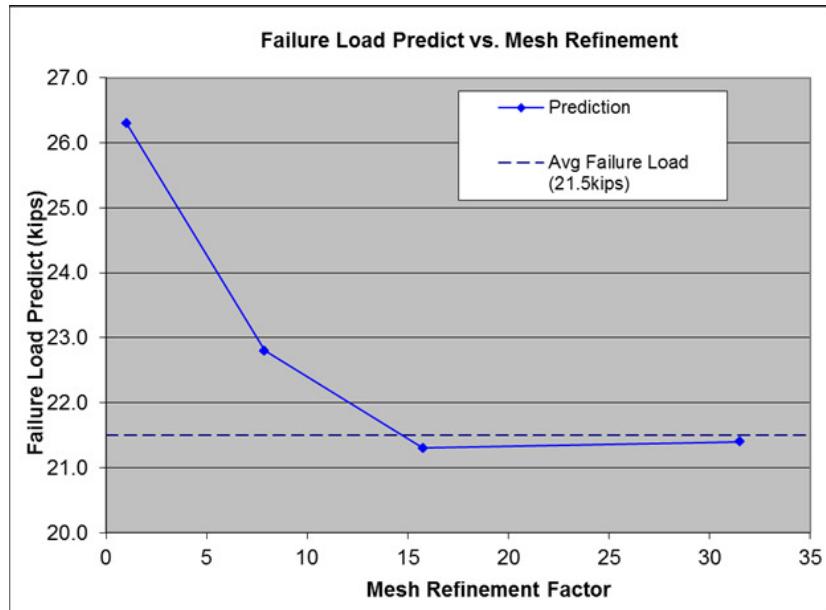
The goal was to stay within 10 percent of the highly refined mesh for all of these metrics. In the end, the so-called BSTA Standard Mesh met the accuracy requirement using 8-mm (0.3-in) elements. Applying this mesh density to the entire BSTA now required on the order of 1.2 million DOF, which was computationally tractable.

Visualizations of the two meshes are shown in figure 28, Nominal Analysis Mesh and Highly Refined Mesh, for two of the many piece-parts used to build BSTA and the JWST primary mirror backplane: the cap gusset and the spanner tube.

8-mm (0.3-in) mesh   1-mm (0.04-in) mesh

Cap Gusset   **Spanner Tube**
Figure 28—Nominal Analysis Mesh and Highly Refined Mesh

Figure 29, Failure Load Prediction versus Mesh Refinement, shows the typical results of a convergence study. The predicted static failure load for a component is plotted versus the refinement factor (1x, 8x, 16x, 32x) for four different models of varying mesh density and with the average failure load observed in testing.

Figure 29 – Failure Load Prediction versus Mesh Refinement

It is important that all possible uses of the model are considered when selecting the convergence metrics. In this case, the original intended use for the model was to predict thermal-elastic stability of the JWST backplane. Up to this point, dynamics (jitter) analysis had been done using a much simpler structural representation with only one- and two- dimensional (1-D and 2-D) elements, e.g., bars and plates, and not the 3-D solid elements used for thermal distortion analysis. The project decided that maintaining two models would be problematic; hence, the solid-element model became the single source for both analyses. If stiffness had not been selected as one of the convergence metrics during the mesh refinement study, the numerical

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errors in the dynamics model would not have been quantified, and the BSTA Standard Mesh might have produced unacceptably large errors for jitter predictions.

This example highlights a particular challenge with M&S built using COTS software. Because of its proprietary nature, COTS software typically does not provide evidence for verification Levels 1 and 2. However, by the fact that the software is widely used and accepted by the industry, it is assumed compliant with those levels. The model, which uses the NASTRAN software, was assessed at Level 4 for verification. The mesh refinement study (formal method) quantified the impact of mesh density on numerical error, and a density was chosen that satisfied the project-defined acceptance criteria (errors are small).

5.4.2.3 Improving Credibility in Verification

To successfully attain a given level of credibility for the verification factor, all lower level criteria have to be satisfied. Methods and suggestions to improve the credibility assessment for this factor are given in table 2, Achieving Verification CAS Factor Levels.

Table 2—Achieving Verification CAS Factor Levels

Level	Verification	Evidence	Needed to Achieve this Level
4	Numerical errors small for all important features	Reliable error estimation methods are used to quantitatively assess numerical errors. These estimates show the errors are small from test suites, which exercise all important algorithms, all important features and capabilities, and all important couplings (physics, modules, etc.) of the full computational model.	Determine the important features of the computation model using, for example, a sensitivity analysis approach. Apply formal numerical estimation, and demonstrate the errors associated with the important features satisfy requirements for the intended use, adjusting numerical parameters, e.g., sampling and tolerances, as required.
3	Formal numerical error estimation	Some formal method is used to assess numerical errors associated with unit testing with significant coverage of the code.	Quantify the effects of numerical errors, e.g., temporal sampling (time-domain simulation), spectral sampling (frequency response), and spatial sampling (finite element mesh, ray trace); tolerances used for iteration loops; finite machine precision.
2	Unit and regression testing of key features	Favorable results from unit and regression testing of key features of the computational model	Identify the key features of the computational model. Conduct unit tests to demonstrate correct behavior of the relevant parts of the code. Conduct regression tests when the code is updated (fixed or new functionality added) to demonstrate that no new errors were introduced as a result.
1	Conceptual and mathematical models verified	Favorable evidence of verification for conceptual and mathematical models	Show the M&S predictions agree with analytical solutions for simple systems.
0	Insufficient evidence	Insufficient evidence	

5.4.3   Validation

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. This is sometimes referred to as anchoring the model and is based on comparisons between the simulation (computational) results and some referent. Validation 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.

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Validation is typically an iterative process involving multiple attempts at tuning model parameters, including those representing the system, controlling numerical accuracy, and in some cases the M&S assumptions and framework. 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. Requirement 4.1.3a of NASA-STD-7009 identifies the conditions the program/project has to satisfy to achieve a favorable comparison between the M&S and the referent.

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 with respect to the RWS?

  c. 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?

  d. What model and/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 that 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. It is important to ensure the model not be overtuned so as to unnecessarily narrow the domain of validation.

When reviewing the validation activities for a given M&S, it is important to identify known differences between the referent and the RWS. A referent may be the RWS to which the analysis is directed, or it could be a similar or analogous system, whereby the closeness of the referent to the RWS becomes pertinent. The Worksheet Results and Comments columns (figure 30, Worksheet Items: Validation) could be used to note the most significant differences and at least a qualitative assessment as to the effects these differences may have upon predictions for the RWS. When subsequently reviewing the uncertainty quantification methods and results, the M&S practitioner should account quantitatively for each estimate of uncertainty introduced by these differences and note what was done for model calibration, and what parameters were adjusted and by how much from their nominal values.
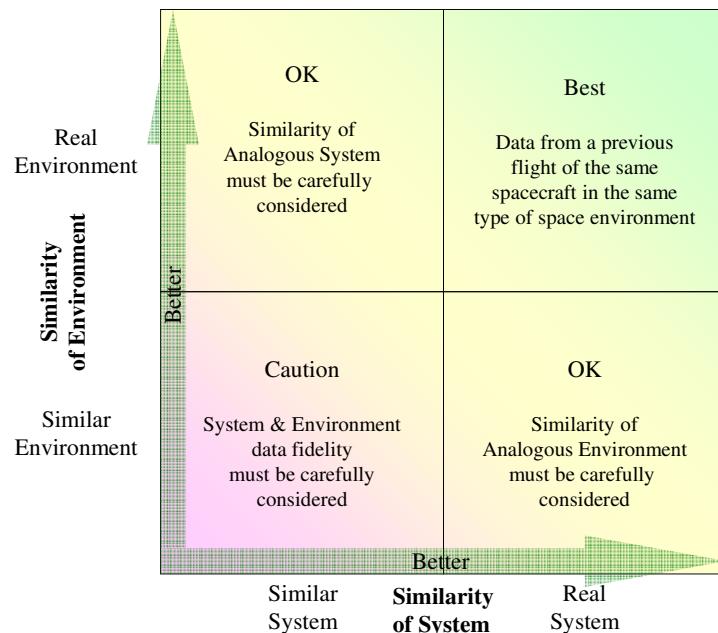
Item		✔	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]				
Validation	How well did test predictions using the M&S match referent data?			
	How close is the referent to the real-world system, including its environment?			

Figure 30—Worksheet Item: Validation

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5.4.3.1 Explanations

As previously stated, validation involves comparisons between results of the computational model and a referent. Generally, the referent is experimental data and, in ideal circumstances, these data come from the real system being modeled or analyzed. However, the RWS is not always forthcoming, particularly in the development of novel systems. In such cases, analysis models have to obtain data from some analogous system for validation purposes. Two aspects of a validation referent are important and notionally depicted in figure 31, Referent Similarity.

Figure 31—Referent Similarity

The bottom axis of figure 31 is used to indicate the quality of the referent system. As one moves from left to right in this depiction, the quality of the system data from the referent improves relative to the target system. If no equal system exists and the validation data are from similar systems, the quality of similarity is important to consider, and caution is warranted. In some cases, another M&S may be used as a referent for validation; in such cases, it is necessary to consider the similarity of the system being modeled with the referents used to validate the other M&S.

The use of another M&S as the referent is a debatable but still common practice. For many programs/projects, the opportunity to validate the M&S through experimental measurements comes only after flight hardware is built and tested. Accordingly, throughout the earlier lifecycle phases, the choices for validation are either by review (sometimes called face validation) or by independent M&S. It is desirable for independent M&S to make use of different assumptions, methods, and software. Getting the same or similar results by independent means boosts confidence in the original results by removing some of the epistemic uncertainty. Another situation where model-model validation is common involves the use of surrogate models (sometimes called metamodels). Surrogate models are typically created by exercising a high-

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fidelity model repeatedly, varying the inputs, and collecting the outputs to form response surfaces. The surrogate models, once validated, can then be used in place of the more complex model to achieve run-time efficiency.

As the similarity of the referent approaches that of the target RWS, analysis credibility correspondingly improves. However, the environment of the referent system is equally important. If the referent system is sufficiently similar to the target system but operates in a different environment, then judgment of the referent data suitability is important. The real-world environment analogy is indicated along the vertical axis in figure 31, showing improvement in referent quality while moving up the axis. Both axes depict a spectrum of possibilities, with full credibility achieved when an exactly matching referent system resides in the exact environment of the operational target system.

It is important to note that throughout a program/project lifecycle the intended use of a given M&S can change. In the most general case, the M&S is created to support the design of the RWS to understand how well the design meets mission requirements. Then, the M&S evolves to analyze how the system design meets its specifications, eventually showing the system can safely perform its mission. Throughout this process, the fidelity of the M&S will likely improve, along with the quality of the input and possibly referent data, requiring the reiteration of validation.

A typical process of referent data evolution might be:

- Similar historical system.
- Prototype, testbed, or alternative M&S for the new design.
- The new design but not in the real environment.
- The RWS in its real environment.

In such a case, as the quality of the referent improves, better assessments of M&S validity are possible. However, the adequacy of M&S validation must still be reconsidered with respect to the lifecycle maturity of the RWS and the criticality of the decisions influenced by analyses with the M&S.

The evolution in both the fidelity of the M&S and the quality of the referent used for validation should be considered, as these factors link to verification, uncertainty quantification, sensitivity analysis, and ultimately to predictive accuracy. In general, an M&S with less fidelity is a more cost-effective tool for exhaustively sweeping the parameter space in support of uncertainty and sensitivity analyses; however, it is typically only validated using lower quality referents. Yet, an M&S with higher fidelity, ostensibly validated using a higher quality referent, is typically the tool used for critical analyses. The combination of uncertainties from different M&S requires careful thought. Furthermore, lower quality referents, e.g., laboratory testbeds, may allow for a wider variety in range of experimental measurements than is possible with the RWS. Accordingly, the validation domain for the higher fidelity M&S may be smaller than that for the lower fidelity M&S; therefore, if the higher fidelity M&S is used for critical analyses, then there is a trade between greater validity and greater risk of operating outside the more narrow validation bounds.

5.4.3.2 Examples

The first of three examples involves a gravitational model and illustrates the use of a second model as the referent. Specifically, it involves the approach developed to validate the Gottlieb spherical harmonic gravity acceleration and torque algorithms as implemented in the Johnson Space Center Engineering Orbital Dynamics (JEOD) simulation software.

To model the orbital motion of a spacecraft realistically, the acceleration caused by gravity has to be computed accurately. Gravitational torque acting on the spacecraft has to be accurately computed for high-precision attitude modeling. The gravitational potential of a large, massive body, i.e., planet, is commonly modeled as a spherical harmonic series from which acceleration and torque can be computed. Most acceleration and torque algorithms are complex and involve mathematical recursions to compute high-order Legendre and trigonometric functions efficiently. Validation techniques exist for simple spherical and oblate planet models. A technique for validating general, higher order gravity algorithms was required. The technique described below validates gravity algorithms, not the specific coefficients of any gravitational body, and is therefore not limited to Earth models.

A fictitious system of point masses was developed to represent a large gravitational body. For familiarity, this point mass planet was scaled to approximate the mass of Earth. Low-degree normalized spherical harmonic gravity coefficients were computed to represent the total gravitational potential of the point mass planet. The point masses were configured such that all gravity coefficients above degree two were non-zero and that coefficients of degree five (and higher) were at least several orders of magnitude smaller than the approximate limit of double-precision floating point arithmetic (15 significant figures). The assumption was that algorithm recursions that worked correctly to degree and order four also worked correctly for higher degrees and orders. However, to mitigate errors caused by truncation of the infinite spherical harmonic series, gravity coefficients through degree five were included in the model. The coefficients were used as data for the JEOD algorithms to compute acceleration and torque at various test locations external to the point mass system, including points over the north and south poles where mathematical singularities could present numerical problems. Simultaneously, the acceleration and torque vectors related to each point mass were computed directly from basic gravity principles and summed to give the total acceleration and torque acting at each test location. The total acceleration and torque were compared to those quantities computed using the JEOD algorithms for validation purposes.
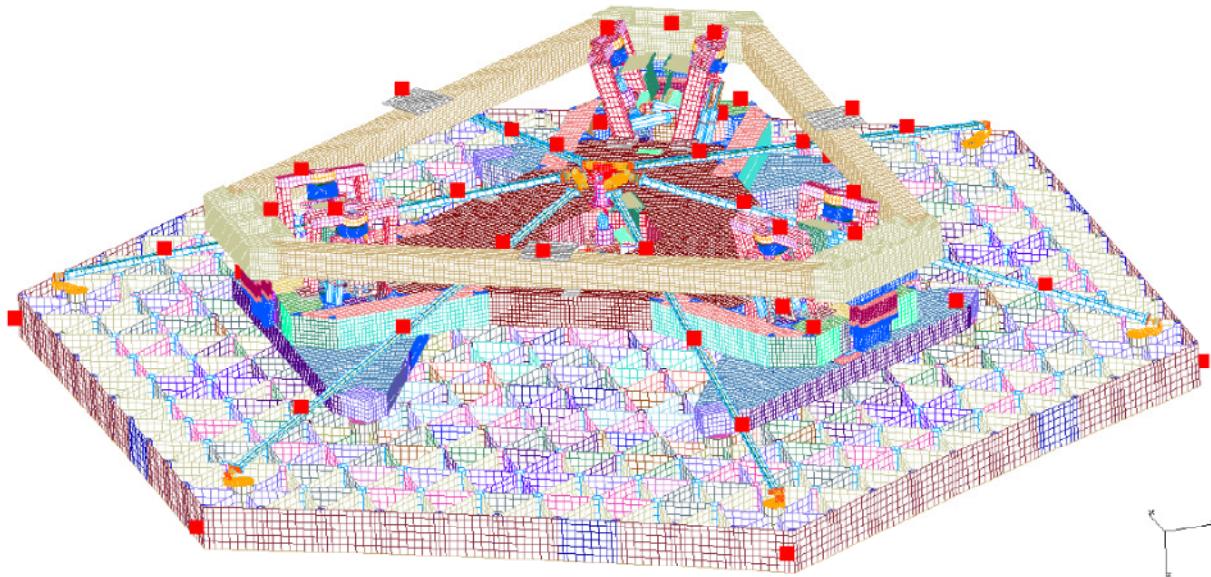
Level 2 for Validation was assessed, as M&S results compare favorably for unit problems at validation points by comparison of M&S results to an acceptable referent, which in this case are higher fidelity M&S results. The predictions from lower order harmonic series representation of a gravity model were compared to predictions from a higher order representation and found to be acceptably close for the intended use.

The second example, also from the JWST project, illustrates a common situation wherein validation leads directly to calibration or tuning of the model. Ideally, one or more experiments are conducted, with predictions made for each. When the results are compared, uncertainties in the predictions should account for all known unknowns, including numerical errors, i.e.,

quantified via the verification process, and model parameter variability. Many times, however, only the latter is considered and only implicitly through the use of an automated process in which model parameters are randomly or systematically adjusted, post-test, until some best match to the measurements is produced.

Figure 32, Mesh for Prototype of Primary Mirror Segment Assembly, shows the mesh for a prototype of a Primary Mirror Segment Assembly (PMSA).

Figure 32—Mesh for Prototype of Primary Mirror Segment Assembly

To validate the PMSA model for several different dynamics analyses, a modal survey test was conducted. The PMSA was suspended by bungees to achieve free-free boundary conditions and was instrumented with 49 accelerometers at 25 locations (12 triaxial and 13 uniaxial). Data were acquired using impact excitation at three locations on the mirror. The frequency content of the data was recorded to 2000 Hz with 14 modes extracted.

The PMSA FEM was correlated using the following iterative procedure:
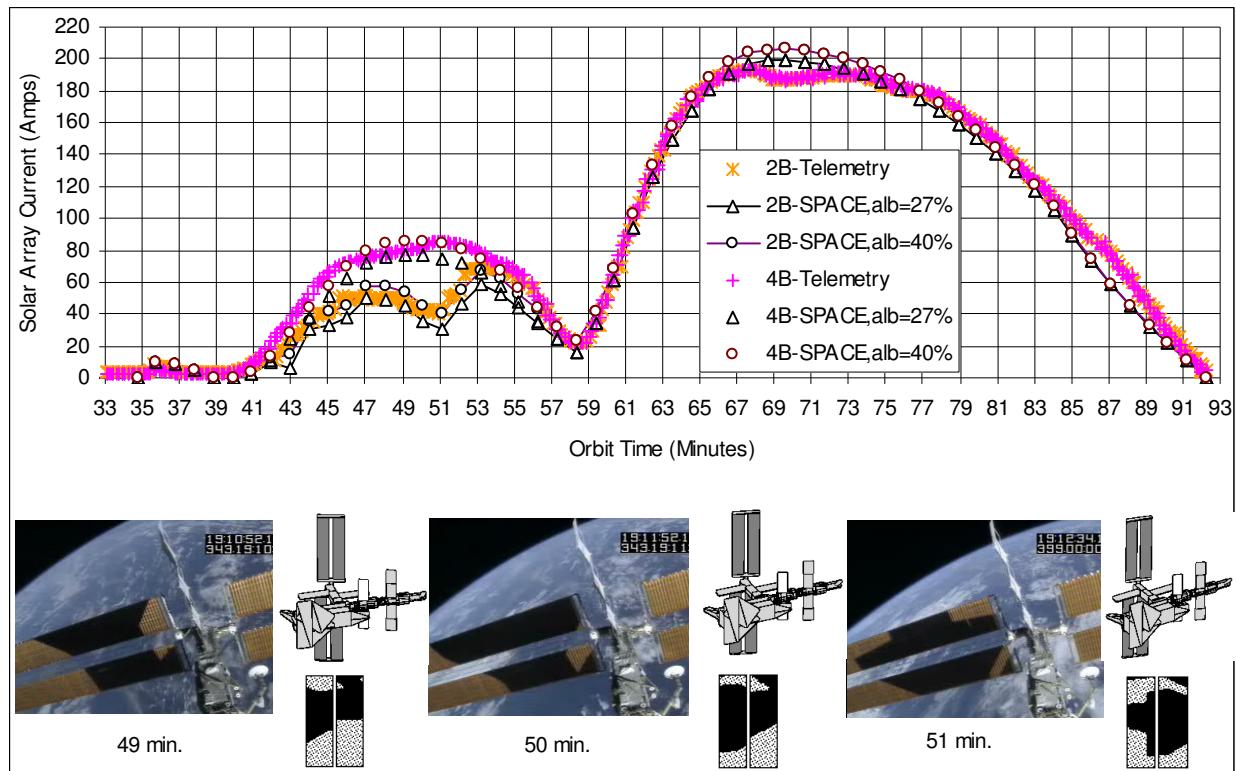
     a.   Modal sensitivities were found for the design variables, i.e., model properties, using NASTRAN.

     b.   The NASTRAN output, i.e., modal sensitivities and mass matrix, was input into the model correlation software Attune™, which runs in MATLAB®. Attune™ examines the design space to find a minimum correlation root mean square (RMS) error, including the frequency and modal orthogonality errors. The design variables are revised with the best correlation.

     c.   NASTRAN was run iteratively with the revised design variables. Then, Attune™ was used to find a new best correlation around the revised design variables. The design variables were revised and the process repeated until the correlation could no longer be improved.

Correlation was based on minimizing the difference in the predicted versus measured frequencies for the important resonant modes of this structure. Before correlation, the differences for the key modes ranged from 4 percent to 9 percent; however, post-tuning the largest difference was less than 3 percent, which met the goal of 5 percent set by project staff and documented in JWST-REF-002290, James Webb Space Telescope Math Models Guidelines Document, Rev. C. Key resonant modes are those associated with DOF for the mirror assembly that result in significant impact on optical performance of the telescope. For example, rotations about two orthogonal axes in the plane of the mirror surface (tip and tilt) shift the position of the image on the focal plane. Compared to an ideal model validation process, neither the numerical errors in the predictions nor the measurement errors were accounted for in this process. Furthermore, after tuning, the modal test could have been repeated with some combination of different force input levels, impact locations, and measurement locations. If predictions using the calibrated FEM matched all the new measurements to within 5 percent, then the validation goals would be satisfied. If not, this would be a good indication the test failed to control temperature and the temperature-dependent material properties were not accounted for in the predictions, i.e., the model form was not correct.

Level 3 for Validation was assessed, as M&S results compare favorably for problems of interest at validation points by comparison of M&S results to an acceptable referent, which are experimental measurements on problems of interest. This model does not achieve a higher score, even though these are the flight mirrors, because they are tested in a non-flight-like environment, i.e., at room temperature, under gravity load, and with non-representative boundary conditions.

As a final example, 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 33, ISS Power Prediction).

Figure 33—ISS Power Prediction

Level 4 for Validation was assessed, as M&S results compare favorably for the RWS at validation points by comparison of M&S results to an acceptable referent, which are measurements on the RWS. The model predictions are a good match to measurements from ISS in operation.

5.4.3.3   Improving Credibility in Validation
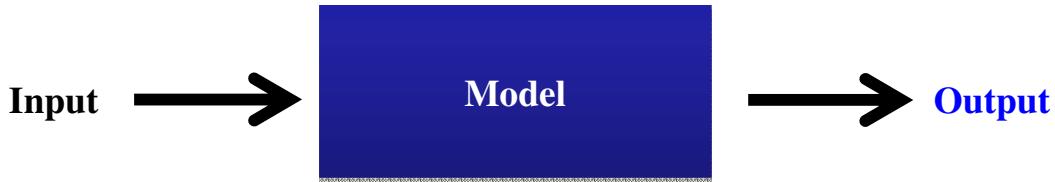
To successfully attain a given credibility level for the validation factor, all lower level criteria also have to be satisfied. Methods and suggestions to improve this credibility assessment are given in table 3, Achieving Validation CAS Factor Levels.

Table 3—Achieving Validation CAS Factor Levels

Level	Validation	Evidence	Needed to Achieve this Level
4	Results agree with real-world data.	M&S results compare favorably for the RWS at validation points by comparison of M&S results to an acceptable referent, which is measurements on the RWS.	Compare M&S predictions to the RWS.
3	Results agree with experimental data for problems of interest.	M&S results compare favorably for problems of interest at validation points by comparison of M&S results to an acceptable referent, which is an experimental measurement on problems of interest.	Compare M&S predictions to experimental data from systems or problems more complex than unit problems and reasonably similar to the RWS.
2	Results agree with experimental data or other M&S on unit problems.	M&S results compare favorably for unit problems at validation points by comparison of M&S results to an acceptable referent, which is either an experimental measurement or a higher fidelity M&S result.	Compare M&S predictions with either experimental measurements for unit problems or predictions from another higher fidelity M&S, i.e., one with a validation factor score of 2 or higher. Predictions have to meet program-/project-specified requirements.
1	Conceptual and mathematical models agree with simple referents.	M&S conceptual and mathematical models compare favorably with general problem and textbook referents.	The M&S specification agrees with the observed or assumed system behaviors. The M&S passes a set of necessary and sufficient sanity tests.
0	Insufficient evidence	Insufficient evidence	

5.4.4   Input Pedigree

The input pedigree factor strives to address the adequacy and/or quality of the inputs to the model, 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 (figure 34, General Model Diagram) 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.

Figure 34—General Model Diagram

Even an imperfect input can be used in a critical analysis but only if the associated uncertainty is identified. The central idea is to communicate clearly the credibility of the input used in the analysis based on various attributes of the data used.

The following factors should be considered for each input to 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, but not always, better.

        (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 the source data.

        (1) A single value.
        (2) A set of values.

e. Form of the input used.

(1) Deterministic.
(2) Deterministic with spread.
(3) Probability distribution or stochastic data.

For this Worksheet item (figure 35, Worksheet Item: Input Pedigree), the Result column should include the value of the credibility assessment. Other things to include are the following:

- Total number of inputs to the model: percentage of inputs pedigreed.
- The overall assessment of the quality and level of authority for the model input.

Item	✔	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]			
Input Pedigree — What is the quality of the Input Data?			
How authoritative is the Input Data for this analysis?			

Figure 35—Worksheet Item: Input Pedigree

The Comments column can contain information on the qualifications for the input assessment. Further notes with regard to the high-level questions for this item and references to supporting documentation are also appropriate.

5.4.4.1 Explanations

a. Source of the Data.

The goal for the source data used in any analysis is that it originates from an authoritative source, which could be an SME, a credible document, e.g., project documents, journal articles, test or operational results, spreadsheet, database, or another model.

b. Quality of Data Source.

The input to an M&S may have a variety of quality characteristics:

(1) Notional – an uninformed estimate.

(2) Informed – an educated or experienced estimate (minimum, most likely, or maximum).

(3) Specified – from system requirements.

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

(5) Measured – from direct knowledge (empirical readings) or calculation from the actual RWS.

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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 understand clearly 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. 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 lifecycle phase of the RWS and the availability of historical and/or analogous data. Early in a project's lifecycle, notional data are sometimes used for initial analyses. Whenever notional data are used, these data should be clearly noted. (This may also be noted in the M&S Results & Caveats item discussed in section 5.3.3 of this Handbook). 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. (See section 5.4.3.1 of this Handbook concerning the assessment of validation referents.)

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. Appendix B.3.2 of NASA-STD-7009 discusses this dependency on data obtained from other models for input. In such cases, the input pedigree credibility level is limited to the credibility level of the model from which the data are obtained.

c. Diversity and Quantity of Data Source

The basic idea of diversity of source data is that data are increasingly and statistically more acceptable coming from more than one instance, item, and/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, or a maximum, or a set 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 Space Shuttle Orbiter in the Orbiter Processing Facility, then the input will be more representative of the population if data are obtained from multiple orbiters 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: the more data the better the resulting pdf discussed in section 5.4.4.1.d

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below. 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.

  d. 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. The value of a parameter used in an analysis may be obtained in a variety of ways.

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 one or two standard deviations of the mean.

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 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.

5.4.4.2   Examples

For a system process analysis, one example of an input is the processing time at one location. Several choices are possible for this input. This is obtained from a data set of 200 observations, as described below:

  a. Average: 2.00 days.

  b. Uniform distribution of the range of possible values: [1.87 : 2.37] days.

  c. Triangular distribution using minimum, mean, maximum: [1.87 : 2.00 : 2.37] days.

d. Statistically fit probability density function:
    1.870625 + GAMM(1., 2.607787)/GAMM(1., 20.666568).

5.4.4.3 Improving Credibility in Input Pedigree

Determining the credibility level for the input to an M&S is interdependent on the factors discussed above. These details of input pedigree are to be considered in determining the overall input pedigree credibility level.

Table 4, Input Pedigree CAS 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 input pedigree are not strictly ordered and should be considered as part of the discussion in the overall assessment of input pedigree.

Table 4 —Input Pedigree CAS 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 Input: Form, correct units, and appropriateness to scenario.

Table 5, Achieving Input Pedigree CAS Factor Levels, provides guidance for improving the input pedigree.

Table 5—Achieving Input Pedigree CAS Factor Levels

Levels	Input Pedigree	Evidence	How this Level is Achieved
4	Input data agree with real-world data.	The input data compare favorably with measured data from the RWS, or the input data came from M&S with a summary credibility rating above 3.5. Uncertainty associated with the input data is known.	All input data are of the most representative form and obtained from an adequate amount of diverse, historical data from formally documented and authoritative sources for the RWS.
3	Input data agree with experimental data for problems of interest.	The input data compare favorably with acceptable measured referent data from problems of interest, or the input data came from M&S with a summary credibility rating above 3.0. Uncertainty associated with the input data is known.	Key input data are of a representative form and obtained from diverse, historical data traceable to formally documented and authoritative sources for the RWS or a close referent.
2	Input data are traceable to formal documentation	The input data are traceable to formal documentation, or the input data came from M&S with a summary credibility rating above 2.0.	Input data are traceable to formal documentation. Notional data are documented.
1	Input data are traceable to informal documentation.	The input data are traceable to informal documentation, or the input data came from M&S with a summary credibility rating above 1.0.	Input data are from informally documented sources, i.e., level of authority is not established, or an analogous system or M&S with a summary credibility rating above 1.0. The attributes of the input data, e.g., forms, values, and units, are correct relative to the intended use.
0	Insufficient evidence	Insufficient evidence	

5.4.5 CAS - Results Uncertainty
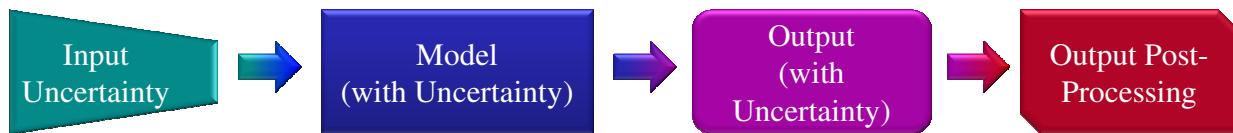
The Results Uncertainty Worksheet item is complementary to the Uncertainty in the Estimate item in the M&S-based Analysis Results & Caveats section, which focuses on the overall uncertainty manifest in the results of an M&S-based analysis. (For further information, see sections 4.4 and 5.3.2 of this Handbook.) This section and item provide a more detailed and complete exposition on the topic, though by no means is it a complete coverage of the topic.

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.

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In the latter case, if the decision stakes are high enough, it may be appropriate to invest in additional analysis or testing to reduce the uncertainty. Refer to the discussion of the decision robustness in section 1.5 of NASA/SP-2010-576 and sections 6.4.2.3 and 6.8.2.8, including discussion of figure 6.4-6, in NASA/SP-2007-6105, NASA Systems Engineering Handbook, for additional information.

The basic premise is that models are abstractions of actual or proposed RWSs, which necessarily induces 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 misleading, if not incorrect, results. Uncertainty presents itself in most aspects of modeling and, therefore, has its roots in system understanding, model building, input development, running models, and output analysis and thus spans the whole scope of the M&S process (figure 2). Figure 36, Locations for Contributing Factors Affecting Uncertainty, is an extension of figure 34 with general areas of uncertainty identified.

Figure 36—Locations for Contributing Factors Affecting Uncertainty

Uncertainty comes in many forms and may present itself in a variety of places relevant to the analysis, including the following:
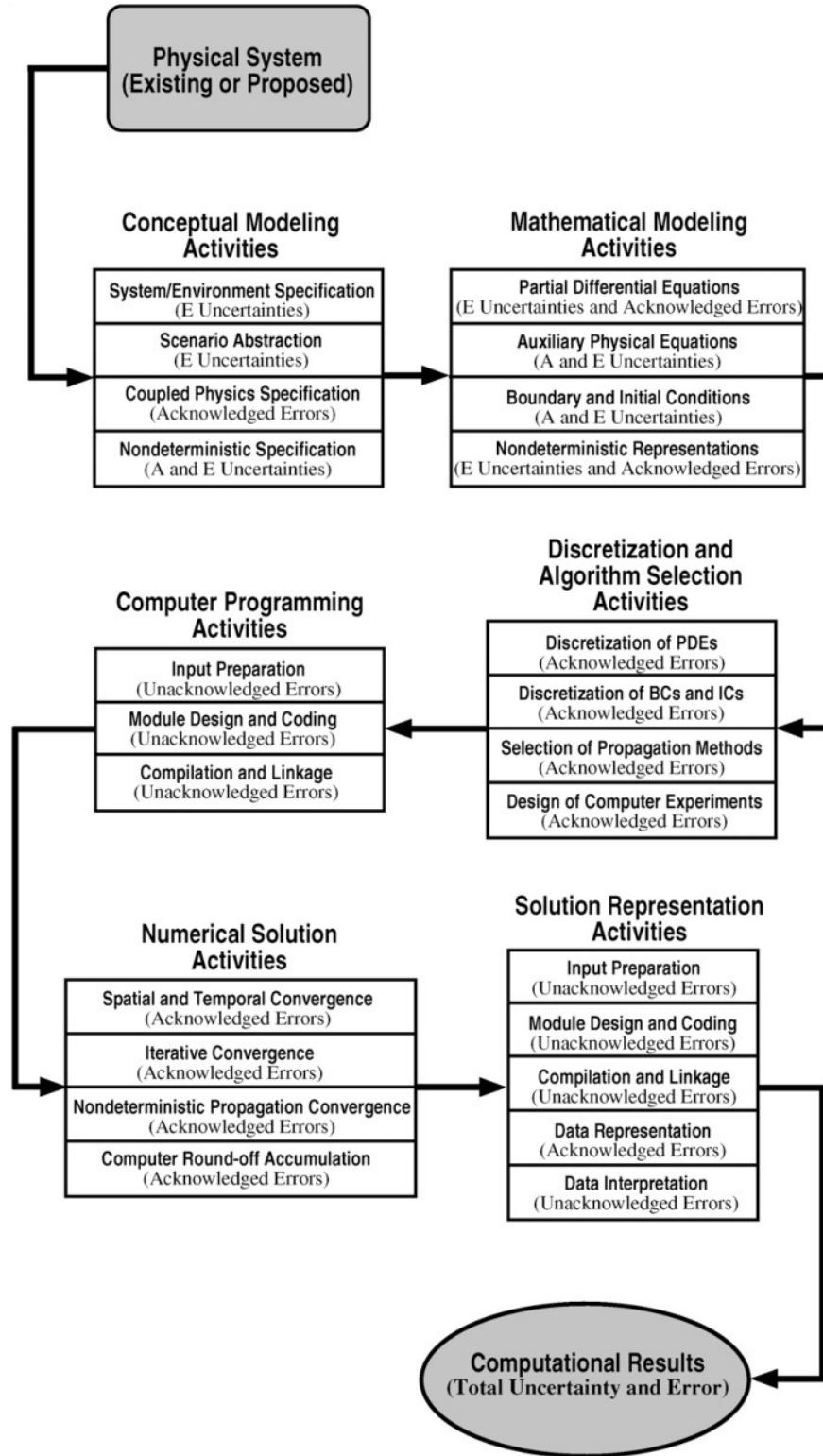
- System understanding: how well the system is known.

- Model building: what is and is not included in the model.

- Input: the amount of good, i.e., attributable or authoritative, data available and the form the data take. (See section 5.4.4 of this Handbook.)

- 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?

- Output analysis: does the form of the output portray the breadth of the results obtained?

Uncertainties are often classified into two separate types:

- 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

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- 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 basis.

There are many potential sources of uncertainty in a model, with typical sources listed in figure 37, Sources of Model Uncertainty, (Oberkampf, et al., 2002). This figure was made from the perspective of models based on partial differential equations; 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 37 refer to whether the uncertainty source is aleatory or epistemic. Furthermore, this figure distinguishes between epistemic uncertainties, aleatory uncertainties, and errors. For purposes of NASA-STD-7009, errors are considered uncertainties since they influence how well the model represents an RWS.

Figure 37—Sources of Model Uncertainty

The following information should be considered for the Results Uncertainty item. For large models, it may become necessary to focus on key sources of uncertainty. If this is the case,

additional caveats may be necessary, e.g., all sources of uncertainty are not documented or characterized. This may influence the risk associated with accepting the results of the M&S-based analysis.

    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) Excluded from the model that induces uncertainty?
        (4) In the data for, the parameters of, and the input to the model?
        (5) 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 obtained using design-of-experiments principles, or Kriging-model-based survey data,, including how uncertainty propagates through the model to the results?

    f.   Were the types of uncertainty documented?

        (1) Epistemic.
        (2) Aleatory.
        (3) Error.

    g.   How well is the uncertainty known?

    h.   What is the magnitude of the uncertainty?

    i.   Is there an Uncertainty Mitigation Plan?.

The Result column for this item, shown in figure 38, Worksheet Item: Results Uncertainty, should include the value of the credibility assessment and whether all sources, locations, types, and magnitudes of uncertainty are listed.

Item		✓	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]				
Results Uncertainty	What methods are used to analyze the uncertainty in the results of this analysis (including sources and propagation)?			

Figure 38—Worksheet Item: Results Uncertainty

The Comments column can include qualifications of information in the Result column, along with items pertaining to the actions and plans to reduce the uncertainty.

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5.4.5.1 Explanations

This section discusses details associated with types of information needed to more fully understand uncertainty in M&S:

  a. 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.

  b. 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.

  c. 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.

  d. 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.

  e. Uncertainty Mitigation Plan: For critical parameters with uncertainty, it may be useful to develop a plan for reducing that uncertainty

One method for tracking and qualifying the uncertainties in an M&S is by using a table similar to table 6, Sample Table for the Uncertainties of a Process.

Table 6—Sample Table for the Uncertainties of a Process

Name	Source	Location	Included in M&S?	Type	Well Known	Magnitude	Mitigation Plan

5.4.5.2   Examples

    a. Process Time Example

For the second example in section 5.3.1.2 of this Handbook (the timeline analysis for a single process), uncertainty analysis yields a broader understanding of the results presented (table 7, Example Table: For the Uncertainties of a Process).

Table 7—Example Table: For the Uncertainties of a Process

Name	Source	Location	Included in M&S?	Type	Well Known	Magnitude	Mitigation Plan
Prep Time Process	Historical Data	Launch Vehicle Stacking Facility Process	Yes	Aleatory	Yes: 200 data points	+0.13 or -0.37 days (for the estimated value of 2.00 days)	No: uncertainty well known

To represent the Prep Time Process (table 7) in the model, several types of data can be used:

    (1) Deterministic Representation: to represent the process time without uncertainty, one of three values are typically chosen:

        A. 2.00 days to represent the average case.
        B. 1.87 days to represent the best (optimistic) case.
        C. 2.37 days to represent the worst (pessimistic) case.

    (2) Stochastic Representation: to represent the process time with uncertainty, a probability distribution may be chosen or statistically determined, based on available data:

        A. Uniform distribution – U(1.87 : 2.37).

            If little else is known about the process time other than the extremes (minimum and maximum values), a uniform distribution allows random values to be generated during the simulation run from this mathematical model with equal probability.

        B. Triangular distribution – T(1.87 : 2.00 : 2.37).
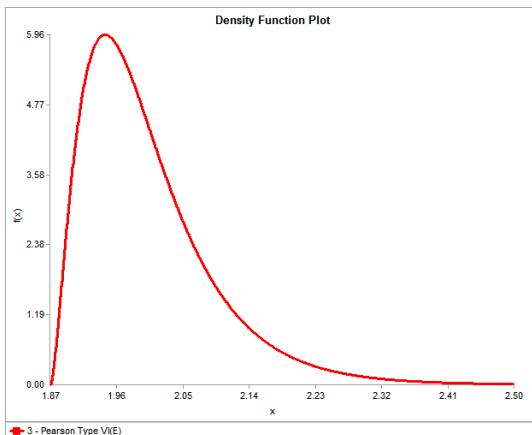
            When the extremes and most likely value of the process time are known, a triangular distribution allows random values to be generated during the simulation run from this mathematical model with the highest probability of values coming closer to the most likely value.

        C. pdf – Pearson VI(E).

When a set of values is available from the RWS process, a pdf may be statistically determined, from which random values are generated during the simulation run that statistically match the available data from the system.

i. Represented as 1.870625 + GAMM(1., 2.607787)/GAMM(1., 20.666568).

ii. Graphically represented in figure 39, Example of a Right Skewed Distribution.
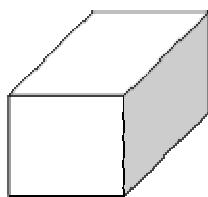
Figure 39—Example of a Right Skewed Distribution

b. Box Example

A simple example in evaluating uncertainty is the determination of the volume of a box from a picture (figure 40, 3-D Box Example). The volume is represented as a deterministic model. Assuming a box of dimensions width (W), depth (D), and height (H), the volume (V) is:

$$V = W * D * H$$

Figure 40—3-D Box Example

The two dimensions, H and W, can be directly measured, e.g., with a ruler. Uncertainties in these two dimensions are related to variations in image replication, accuracy in the ruler, ability of the ruler user, process for measurement, e.g., if a measurement outside, inside, or in the middle of a line, errors, e.g., recording the wrong value, and other variations. The type of uncertainty from these various sources falls into two categories: aleatory and epistemic. An example of an aleatory uncertainty is the variation in image replication, since this is a stochastic process that does not change as additional information is gathered. Alternatively, an example of epistemic

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uncertainty is the recorded measurement, since this could change as additional measurements are taken, improved-accuracy methods are used, or the measurer becomes better with practice.

The third dimension, D, requires inference, since this distance may be arbitrarily to make the 2-D picture look more realistic. The inference process could assume that D is the same as W and H (if they are identical) on the presumption that the figure is a symmetrical box. Alternatively, the parameter D could simply be measured with the ruler and taken at face value, or a guess could be made based upon the values of W and H and the projected third dimension. This uncertainty from the degree of knowledge of D is classified as epistemic.

These measures, the associated uncertainty, and other factors are included in table 8, Example Table: For the Uncertainties in the Analytical Volume of a Box.

Table 8—Example Table: For the Uncertainties in the Analytical Volume of a Box

Name	Source	Location	Included in M&S?	Type	Well Known	Magnitude	Mitigation Plan
Height	Ruler measurement	Picture height	No	Aleatory	Yes	±1.6 mm (±1/16 in)	No
Width	Ruler measurement	Picture width	No	Aleatory	Yes	±1.6 mm (±1/16 in)	No
Depth	Ruler measurement and	Picture depth	No	Aleatory	Yes	±1.6 mm (±1/16 in)	No
	Unknown scale factor		Somewhat	Epistemic	No	Unknown	Yes

5.4.5.3   Improving Credibility in Results Uncertainty

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 CAS factors, this is accomplished on a case-by-case basis. Ideas for improving the uncertainty assessment are shown in table 9, Achieving Results Uncertainty CAS Factor Levels.

Table 9—Achieving Results Uncertainty CAS Factor Levels

Levels	Results Uncertainty	Evidence	How this Level is Achieved
4	Non-deterministic and numerical analysis	Uncertainty estimates are quantitative and based upon nondeterministic and numerical analysis.	Full probabilistic/stochastic analysis performed from model construction, to data input, running the M&S, and analysis of output, with a complete understanding of uncertainty propagation through the model. Uncertainties for all results are provided quantitatively.
3	Non-deterministic analysis	Uncertainty estimates are quantitative and based upon nondeterministic analysis.	Uncertainties for key results are provided quantitatively through non-deterministic analysis.
2	Deterministic analysis or expert opinion	Uncertainty estimates are quantitative and based upon deterministic analysis or expert opinion.	Uncertainties expressed quantitatively from SME opinions and/or as notional spreads of deterministic values. Propagation of the uncertainties into the results should be addressed.
1	Qualitative estimates	Uncertainty estimates are qualitative.	Sources of uncertainty identified and qualitatively addressed
0	Insufficient evidence	Insufficient evidence	

5.4.6 Results Robustness

Results Robustness is attributed to 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 impact the RWS, the sensitivities of the model should be similar to the sensitivities of the RWS. The robustness of the model results is one of the factors to assess the credibility of the analysis (Requirement 4.7.1 in NASA-STD-7009). The justification for the evaluation and any technical review of Results Robustness needs to be documented (Requirements 4.7.2 and 4.1.5 in NASA-STD-7009).

Notes:

(1) NASA-STD-7009 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 robustness are opposites. If a

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system is sensitive to relatively small changes in operating parameters or conditions, then it is not considered robust. On the other hand, if the system is found to be insensitive to relatively small changes in operating parameters or conditions, then the system is considered robust. Sensitivity analysis is the technique 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 CAS 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-7009 is met.

(3) Sensitivity analysis can also be used early in the RWS lifecycle, 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.

This Worksheet item is shown in figure 41, Worksheet Item: Results Robustness.

Item	✔	Result		Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]				
Results Robustness	What are the significant sensitivities of the M&S results?		CAS Value: 1.7	Note significant sensitivities -
			Weighting Used? Yes	% of parameters for which sensitivities were explored -
	How thoroughly are the sensitivities known?			
				How much testing was performed to characterize the results sensitivity?

Figure 41—Worksheet Item: Results Robustness

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?

The overall assessment of this factor should be noted in the Results column. Significant sensitivities in model results as compared to the RWS should be noted in the Comments column, along with any statements concerning the quantity or percentage of model parameters to which the model results show sensitivity and lead to different decisions.

5.4.6.1　Explanations

Results Robustness is concerned with how the results of an M&S-based analysis change as a result of changes in the parameters, variables, and conditions. For this factor, the CAS score is determined using the guidance provided in table 3 of NASA-STD-7009, along with the additional guidance provided in section 5.4.6 of this Handbook. Model and RWS sensitivities should be compared and documented.

Note: Sensitivity can vary throughout a time-dependent model and, unless only the end state is the output metric of interest, these sensitivities over the course of the simulation should be identified. Additionally, sensitivities can be linear or non-linear. In some systems analyses, solved over large temporal and/or spatial extents, non-linear sensitivity analysis may be appropriate.

For the situation in which an M&S and its sensitivities are validated and acceptable for use in analyzing an RWS and the analysis results show sensitivity to relatively small changes in operating parameters, the RWS should be operated close to those parameters. On the other hand, in the case of a novel RWS, i.e., where no validation data exist, and the M&S of the system indicates sensitivity to relatively small changes in key operational parameters, additional efforts, e.g., testing the RWS or data gathered from an analogous system, should be undertaken to better understand system behavior in the region of operation.

There are cases where a robustness assessment or sensitivity analysis can provide valuable qualifying information to an M&S-based analysis.

    a. In the two cases listed below, M&S-based results are most likely acceptable:

        (1) The RWS is robust, and the M&S response is validated as similarly robust.

        (2) The RWS is sensitive (not robust), and the M&S response is similarly validated as sensitive.

b. In the next two cases, caution is warranted and is a validation issue:

(1) The RWS is robust, but the M&S response shows sensitivity to relatively small changes in variables or parameters.

(2) The RWS is sensitive (not robust) to changes in operating parameters, but the M&S response indicates insensitivity to such changes.

5.4.6.2   Examples

Examples will be developed and provided in a later revision.

5.4.6.3   Improving Credibility in Results Robustness

Table 10, Achieving Results Robustness CAS Factor Levels, provides guidance for improving the assessment of Results Robustness.

Table 10—Achieving Results Robustness CAS Factor Levels

Levels	Results Robustness	Evidence	How this Level is Achieved
4	Sensitivity known for most parameters; key sensitivities identified	Sensitivity of the M&S results for the RWS is quantitatively known for most of the variables and parameters, including all of the most sensitive variables and parameters.	All key sensitivities that would drive model results are identified. Sensitivity of the results to most (>50%) of the model parameters has been quantified through sensitivity analysis.
3	Sensitivity known for many parameters	Sensitivity of the M&S results for the RWS is quantitatively known for many variables and parameters.	Sensitivity of the results to many (20-50%) of the model parameters has been quantified through sensitivity analysis.
2	Sensitivity known for a few parameters	Sensitivity of the M&S results for the RWS is quantitatively known for a few variables and parameters.	Sensitivity of the results to some (<20%) of the model parameters has been quantified through sensitivity analysis.
1	Qualitative estimates	Sensitivity of M&S results for the RWS is estimated by analogy with the quantified sensitivity of similar problems of interest.	Sensitivity of the M&S results is assumed by comparison to the quantified sensitivity of a similar problem.
0	Insufficient evidence	Insufficient evidence	

5.4.7   Use History

The Use History factor in the CAS describes the extent of prior favorable uses of the particular M&S in similar situations. Favorable means the M&S satisfied relevant acceptance criteria deemed sufficient by the program/project management in collaboration with the Technical Authority (NASA-STD-7009, Requirement 4.1.3(a)). The two dimensions to consider for a specific M&S result are the time of successful M&S use and the types of problems for which it was used. The central idea for Use History with regard to credibility is the longer a given M&S is used and the closer the historical use is to the current use, the more credible the results. While this is not a guarantee of good results, it is an indicator of the past successful trials of the M&S and, therefore, a point of discussion.

This item (figure 42, Worksheet Item: Use History) includes a single general probing question, which can be further understood with the following details:

- The time length of use for the M&S.
- The number of analyses accomplished with the M&S.
- The similarity of the previous analyses with the current use.
- When the model was most recently changed.
- The favorable comparison, e.g., accuracy, of M&S results with the data.

Item	✔	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]			
Use History	How have the current M&S been previously used?		

Figure 42—Worksheet Item: Use History

These suggested details can give a sense of the historical use of the M&S (how long it has been used; how much it has been used; for what has it been used; how accurate analysis results have been). However, when an M&S is changed, it may also change its domain of intended use. Additional scrutiny may be required of an M&S that has recently changed to understand its intended use, V&V status, and relevancy for current use.

The Results column should note the CAS factor assessment and list significant cases of prior use. In the Comments column, supporting details and documentation regarding those instances, along with the similarity of analyses performed, should be recorded. Major departures from primary uses of the M&S should be annotated, if relevant to the current analysis.

5.4.7.1   Explanations

When using COTS M&S software, insight into verification software testing can be limited. In some cases, source code, test suites, and data are available or may be made available with appropriate non-disclosure agreements. The goal is to obtain past-use information supporting the use of the COTS M&S software for an analysis.

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Exercise caution when using a particular M&S with a history of application to similar problems, as it is possible the current application uses a new version and runs on a different platform (central processing unit, operating system, compiler) or has added features, e.g., supports certain detailed physics previously unmodeled, used for the first time.

It is recommended to examine carefully simple, qualitative arguments about the closeness of historical use of the M&S to the current use.

5.4.7.2   Examples

5.4.7.2.1   Example 1: Choice of optical modeling, e.g., geometric ray trace and physical diffraction, code for the Laser Interferometer Space Antenna (LISA) mission.

The following past uses of the Code V or Zemax modeling platforms argued in favor of developing a custom code:

   a.   For optical systems modeling, does the Use History of an existing model show that the issue of scale (wavelength versus system dimensions versus M&S precision) is adequate to the needs of the current analysis?

   b.   For a system designed to operate at very short wavelengths or at longer wavelengths over large scales, which may require quad precision so numerical errors are insignificant, e.g., collector apertures sited on individual spacecraft flying in formation to realize a very long baseline interferometer), does the Use History of an M&S show that it supports the required level of quad precision?

5.4.7.2.2   Example 2: Choice of thermal modeling, e.g., conduction, convection, and radiation heat exchange, code by the JWST mission.

What are the comparative Use Histories of the previously used Thermal Synthesizer System (TSS) and Systems Improved Numerical Differencing Analyzer (SINDA) models compared to the alternate Thermal Desktop® and Thermal Model Generation (TMG) codes? What are the details requested in section 5.4.7 (above)? Detailed questions such as the following should be addressed when comparing historical and current usage:

   a.   How long have these modeling codes been used and qualitatively for how many analyses: a few? many?

   b.   Was the ray-trace solver used to compute radiation heat exchange factors? Was that similar to how the current application will use it?

      (1) Was past use of the scattering model similar to what is needed for the current analysis?

      (2) Were the types of surfaces analyzed previously using these models similar to the current system?

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(3) Are different coatings, materials, or fabrication processes used for the RWS such that the fine details of the surface invalidate the scattering model used?

c.   How well does this code integrate with other discipline codes, e.g., Mechanical Computer-Aided Design, structural FEM, and stray light, with which it must exchange information? Are there pitfalls?

5.4.7.3   Improving Credibility in Use History

To attain a given credibility level for the Use History factor successfully, all lower level criteria are to be satisfied. Table 11, Achieving Use History CAS Factor Levels, provides guidance for improving the assessment of this factor.

Table 11—Achieving Use History CAS Factor Levels

Level	Use History	Evidence	How to Achieve Each Level
4	De facto standard	De facto standard	Use an M&S that is used extensively or exclusively within the relevant community of practice.
3	Previous predictions were later validated by mission data.	Post-decision real world events have been represented accurately in results, e.g., validated by mission data.	Provide evidence the M&S satisfies the criteria for Validation Level 4 for one or more prior applications.
2	Used before for critical decisions	Used previously to perform analysis upon which critical decisions have been made	Provide evidence the M&S was used for critical decisions. Identify the mission and the instance(s) in which the M&S was used.
1	Passes simple tests	Specific scenarios have been created to test application, or results compare favorably with outputs from other similar tools.	Document the successful completion of development (including V&V) of this M&S for the revision used in the current analysis.
0	Insufficient evidence	Insufficient evidence	

5.4.8   M&S Management

The M&S Management factor provides supporting evidence of M&S credibility by describing the extent to which an M&S activity defines, follows, and documents a formalized planning and implementation process, which is similar to the Capability Maturity Model® Integration[SM] (CMMI[SM])[22] level developed by the Software Engineering Institute at the Carnegie Mellon University, including:

- Work product management.
- Process definition.
- Process measurement.
- Process control.
- Process change.
- Continuous improvement.
- Configuration Management (CM).
- Support and maintenance.

This item, shown in figure 43, Worksheet Item: M&S Management, indicates a single general question about the administration of the M&S process.

Item	✓	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]			
M&S Management — What formal processes were used in the development & use of this M&S?			

Figure 43—Worksheet Item: M&S Management

Additional key issues for assessing the M&S Management CAS sub-factor include the following:

a.   Was there a defined formal process for M&S development and use, i.e., was there a project plan?

b.   How CM was accomplished for the M&S and data?

(1)   Is there an M&S and data repository system?
(2)   What versions of M&S and data were used for the current analysis?

c.   If the analysis system is comprised of a set of coupled models, was there an ICD?

The Results column can be used to document the assessed credibility level with notes, e.g., no evidence of formal M&S management process. The Comments column could be used to record additional details or identify reference documents.

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[22] http://www.sei.cmu.edu/reports/02tr012.pdf. Retrieved April 23, 2013.

5.4.8.1 Explanations
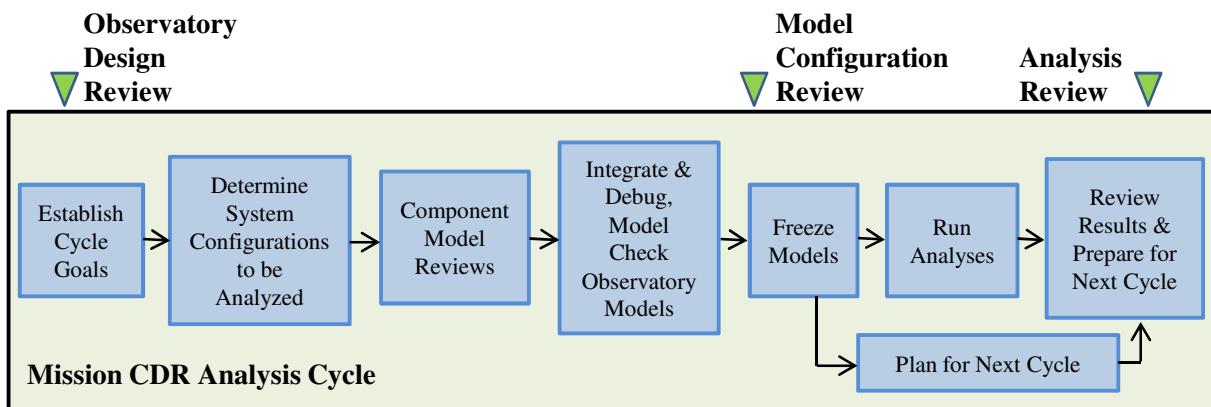
There are a variety of processes potentially associated with a given M&S. Each needs to be understood and the details probed to identify and assess aspects that may lead to credibility issues. These processes often are repeated over a program's/project's lifecycle, although they are likely to evolve to support the immediate objectives.

It is insufficient to ask the question "Were formal processes defined and implemented?" Proof they were followed is essential to adding to the overall credibility of the M&S through supporting evidence of good planning and use of best practices and providing information for the reviewers or decision makers to examine the processes and identify potential areas of concern.

5.4.8.2 Examples

An example of a higher level process is the JWST Program shown in figure 44, JWST Integrated Modeling Cycle. Multiple cycles supported requirements development, trade studies, and preliminary and detailed design. This process involved the following progression from:

   a. Defining the system/problem.
   b. Defining the M&S approach.
   c. Developing, inspecting, and reviewing component-level models.
   d. Assembling, inspecting, and reviewing system-level models.
   e. Executing simulations, and conducting analyses.
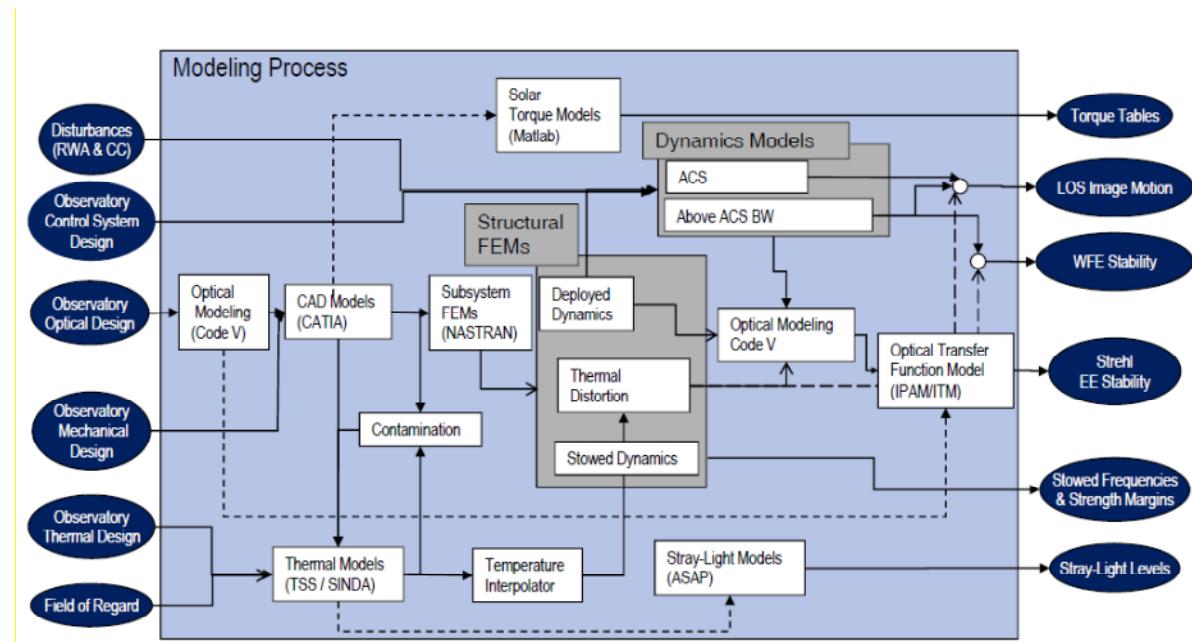
Figure 44—JWST Integrated Modeling Cycle

Nested within this process were multiple sub-processes. The development/inspection/review processes conducted at the component and system levels involved performing sets of sanity checks or verifications to ensure model workmanship, i.e., the models were built to specification, the acceptance criteria were met, or when not met, the impact was understood. The associated activities involved handoffs between models, with verifications repeated on both sides of the interface, similar to hardware integration activities. System model integration within individual disciplines or domains was accomplished using ICDs to ensure compatibility of coordinates, units, and geometries, including FEM meshes. Reviewers of such M&S processes should

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examine model interfaces, especially when component and system models are developed by different organizations or when models are translated between applications. For an integrated set of models used in analyses, examine how model/data interface control was formally established, e.g., in a Model-to-Model IDD/ICD.

The JWST simulations and analyses involve a complex process, shown in figure 45, JWST Interdisciplinary M&S Workflow[23], linking multiple M&S both in series and parallel. This ensemble of M&S is used to evaluate system-level performance under specified operational and environmental conditions, relative to a set of technical performance metrics. As with discipline/domain model integration, this process is rife with interfaces between organizations and different software tools and should be examined closely.

Figure 45—JWST Interdisciplinary M&S Workflow

It is important to balance the depth and breadth of the various aspects of M&S management against the scope of the M&S effort. It is possible to impose M&S management to the detriment of M&S quality. In a JWST case, with the M&S activity comprising numerous programmatic and technical interfaces, significant investment in infrastructure and process was essential. On simpler or less critical M&S efforts, complex controls may not be warranted.

The M&S management factor for credibility (like V&V) has to meet all lower level criteria to attain a particular assessment level. The JWST M&S management factor was assessed at Level 3, as follows:

- Meets Level 1: The roles and responsibilities for the M&S team were defined by JWST Project Management (NASA), Mission Systems Engineering (NASA), and Observatory Systems Engineering (Northrop Grumman).

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[23] http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1200449. Retrieved April 24, 2013.

- Meets Level 2: The M&S was developed, operated, and configuration controlled according to formal procedures defined in two documents: JWST-REF-002290 and JSWT-PLAN-006165, James Webb Space Telescope (JWST) System Modeling and Analysis and JWST Models Validation, Verification and Calibration Plan.

- Meets Level 3: Independent review performed by NASA Goddard Space Flight Center (GFSC). The M&S team periodically demonstrated repeatability of the M&S results.

There are many possible choices for M&S management strategies and their implementations. It is recommended the party responsible for M&S management (sections 1.1 and 5.1 of this Handbook) document the key elements and status of the chosen strategy. One example for documenting the M&S management effort is shown in table 12, Elements of M&S Management. Suitable M&S management plans should be coordinated with the software management plans required by NPR 7150.2, NASA Software Engineering Requirements.

Table 12—Elements of M&S Management

Sample Elements of M&S Management	Example Disposition/Status Notes
Project Plan	Project plan was documented and is current with the M&S.
Production Repository System	Repository system is used for the M&S development products and documentation, test scenarios and results, and analysis products.
Version Control	Model versions are controlled.
Data (relevant, current, authoritative)	Data are traceable to Preliminary Design Review baseline configuration Rev X (dated dd/mm/yyyy) obtained from _____ (source, individual, or program/project design data repository).
Interfaces	Model/data interfaces are documented and controlled via XX-ICD-xxxx dated (dd/mm/yyyy).

5.4.8.3   Improving Credibility in M&S Management

Table 13, Achieving M&S Management CAS Factor Levels, provides guidance for improving the assessment of M&S Management.

Table 13—Achieving M&S Management CAS Factor Levels

Level	M&S Management	Evidence	How to Achieve Each Level
4	Continuing Process Improvement	The M&S effort is using measurements on M&S processes to improve the repeatability of the M&S results.	Defined M&S metrics and processes are used to correct the models, simulations, and overall M&S processes and measure repeatability of M&S results.
3	Predictable Process	The M&S effort is measuring repeatability of the M&S results generated by the M&S	Define the metrics and processes needed to measure repeatability of the M&S results. Document repeatability measurements

Level	M&S Management	Evidence	How to Achieve Each Level
		processes.	outcomes.
2	Established Process	The M&S effort has established a documented process for M&S development and operations.	Formally document the processes for M&S development, operations, and compliance.
1	Managed Process	The M&S roles and responsibilities have been defined.	Identify M&S process management roles and responsible parties. The process for managing M&S products is informally documented.
0	Insufficient evidence	Insufficient evidence	

5.4.9   People Qualifications

The People Qualification factor is used to assess and understand the qualifications, e.g., education, training, and experience, of the personnel involved in the M&S activities. The inclusion of this factor is an important aspect to the overall consideration of results credibility. These qualifications should be related to the specific M&S and its underlying discipline, e.g., science, math, and engineering. Additional details are discussed in Appendix B.3.3.3 of NASA-STD-7009.

Note: The desired level for the assessed value and the contributing factors should be accepted by the project/program management in association with the Technical Authority, as appropriate for the current state of the system, M&S development, and the analysis/decision.

Figure 46, Worksheet Item: People Qualifications, indicates a single general question about the qualifications of the M&S practitioners.

Item	✔	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]			
People Qualifications What are the qualifications & experience of the people developing, testing, & using this M&S?			

Figure 46—Worksheet Item: People Qualifications

Additional points to consider are:

- The qualifications and experiences of the developer, operator, and analyst.
- Who performed the credibility assessment?
- Evidence supporting the People Qualifications assessment.

The overall assessed level of the qualifications for the people involved with the M&S can be annotated in the Results column (table 14, People Qualifications and Experience Example Table). The Comments column may include any additional information or notes needed to satisfy or better understand the People Qualifications information and/or any technical review results for this item.

Table 14—People Qualifications Example Table

	M&S Developer	**M&S Operator**	**M&S Analyst**
Educational Background			
Experience in M&S Discipline			
Training for the Specific M&S			
Experience with the Specific M&S			

5.4.9.1 Explanations

The primary information to convey is the qualifications of the people developing, testing, and using this M&S. Depending on the size and complexity of the M&S activity, the developer, operator, and analyst roles may be accomplished by one person or by a team of people for each role. The qualifications example in table 14 can assist in organizing this information. This table is only an example and may be tailored to the specific project.

5.4.9.2 Examples

Table 15, Example 1: The M&S Developer, Operator, and Analyst are the Same Person, and table 16, Example 2: The M&S Developer, Operator, and Analyst are Different People, show examples for documenting People Qualifications.

Table 15—Example 1: The M&S Developer, Operator, and Analyst are the Same Person

	M&S Developer	M&S Operator	M&S Analyst	CAS Factor
Educational Background	BS in Aerospace Engineering	BS in Aerospace Engineering	BS in Aerospace Engineering	2
Experience in M&S Discipline	4 years	4 years	4 years	
Training for the Specific M&S	Two 40-hour classes in MATLAB®	Two 40-hour classes in MATLAB®	Two 40-hour classes in MATLAB®	
Experience with the Specific M&S	2 years	2 years	2 years	

In the above example, the developer, operator, and analyst columns could be collapsed into a single column.

Table 16—Example 2: The M&S Developer, Operator, and Analyst are Different People

	M&S Developer	M&S Operator	M&S Analyst	CAS Factor
Educational Background	BS in Computer Science	BS in Aerospace Engineering	MS in Mechanical Engineering	3
Experience in M&S Discipline	5 years	5 years	10 years	
Training for the Specific M&S	Five 40-hour classes in MATLAB®	One 40-hour class in MATLAB®	None	
Experience with the Specific M&S	5 years	5 years	5 years	

5.4.9.3   Improving Credibility in People Qualifications

Table 17, Achieving People Qualifications CAS Factor Levels, includes information from NASA-STD-7009 as to the aspects and evidence for achieving each credibility level for People Qualifications, along with suggested methods of how to attain each assessed level. The extensive work experience for Credibility Levels 3 and 4 is defined as follows:

     a. Level 4: The individual or team lead has sufficient experience to mentor new and experienced practitioners on the specific technical and M&S disciplines without further technical oversight.

     b. Level 3: The individual or team lead has sufficient experience to mentor newcomers on the subject discipline (not necessarily the M&S) without technical oversight.

Table 17—Achieving People Qualifications CAS Factor Levels

Levels	People Qualification	Evidence	How Each Level is Achieved
4	Extensive experience in and use of recommended practices for this particular M&S	Possesses an advanced engineering or science degree or extensive work experience in M&S, has extensive experience with the development and use of the M&S being reviewed, and has employed specific recommended practices relevant to current application	Relevant to the specific technical M&S discipline: SME; extensive work experience in development and use; experience in the development and use of recommended practices
3	Advanced degree or extensive M&S experience and recommended practice knowledge	Possesses an advanced engineering or science degree or extensive work experience, has general M&S training, has specific experience with the M&S being reviewed, and has been trained on specific recommended practices relevant to the current application	Advanced degree Advanced M&S training Relevant to the specific technical M&S discipline: work experience in development and use; formal training and experience with the recommended practices
2	Formal M&S training and experience and recommended practice training	Possesses an engineering or science degree, has received formal training in formulation of M&S and generic training in recommended practices for M&S, and has developed M&S products	Formal technical education, training, and experience in the discipline relevant to the specific M&S and analysis Knowledge of discipline-specific recommended practices M&S development experience
1	Engineering or science degree	Possesses an engineering or science degree, has been introduced to the topic of M&S, and has been exposed to generic recommended practices in M&S	Basic technical education, training, and experience are documented for the practitioners involved in the M&S and analysis.
0	Insufficient evidence	Insufficient evidence	

5.4.10 Technical Review

A Technical Review of an M&S is commonly referred to as a peer review, i.e., a thorough review of technical content by peers. In NASA-STD-7009, Technical Review is not a separate factor in the overall M&S credibility assessment process but is a sub-factor for Verification, Validation, Input Pedigree, Results Uncertainty, and Results Robustness.

Figure 47, Worksheet Item: Technical Review, indicates a single general question about the qualifications of the M&S practitioners.

Item	✔	Result	Comments
M&S Credibility Assessment [Development - Usage (Analysis) - Process]			
Technical Review	Provide a summary of the Technical Reviews performed on this M&S/Analysis.		

Figure 47—Worksheet Item: Technical Review

Additional details to consider in the assessment of this sub-factor include the following:

    a.   The list of the technical reviewers and their qualifications.

    b.   The technical diversity in the review panel.

    c.   The independence of the peer reviewers from the project.

    d.   The formality of the Technical Review process, i.e., how it is planned, followed, and documented.

    e.   The currency of the Technical Review with the current revision of the M&S.

    f.   The comprehensiveness of the review for the M&S activity for all phases of the project, including independent technical activity, e.g., independent modeling, simulation, verification, validation, analysis.

A summary of all Technical Review information should be included in the Results column, with details, explanatory notes, or pointers to other documentation annotated in the Comments column.

5.4.10.1 Explanations

The level definitions of the Technical Review sub-factor focus on the degree of formality, technical expertise, and independence of the review undertaken. The formality and rigor of a review is characterized by the planning, process followed, and level of documentation. A formal Technical Review is well planned, followed, and documented. Reviewer qualifications and independence from the program/project should be considered. The independence of a review (internal to external) is characterized by how closely the panel members are to the program/project the M&S supports. In addition, the technical diversity of the reviewers is valuable in providing alternative perspectives to the problem domain. The comprehensiveness of the review entails how much of the M&S lifecycle was covered and to what level of detail. Finally, the completion date of each Technical Review should be documented. The date of the latest Technical Review, in conjunction with the change history of an M&S, indicates the currency of the review with respect to the current revision of the M&S.

This repetition across these CAS factors is beneficial in that numerous reviews are generally constituted throughout the program/project lifecycle, with each review focusing on particular topics. It would not be uncommon for different SMEs to be involved in the various reviews, depending upon their availability, areas of expertise, and focus of a particular review.

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Note: The Technical Reviews for M&S need not be constrained to the Development & Operations CAS factors (Verification, Validation, Input Pedigree, Results Uncertainty, and Results Robustness.) These five factors address the most technical aspects of an M&S; however, a complete M&S review could examine the additional factors under the Supporting Evidence heading, i.e., Use History, M&S Management, and People Qualifications.

5.4.10.2 Examples

Examples will be developed and provided in a later revision.

5.4.10.3 Improving Technical Review Credibility Assessment

The method of assessing the quality and completeness of a Technical Review can vary, depending on the aspects of a project. While the assessment result may fall anywhere in that spectrum, the best and worst conditions may be anchored as shown in table 18, Aspects of Technical Review Assessments.

Table 18—Aspects of Technical Review Assessments

	No Evidence	Assessment Spectrum	Best Possible
Technical Expertise	No relevant expertise documented	↔	Reviewers are all educated, trained, and experienced with this type of M&S.
Diversity in Expertise	Technical diversity in review members not documented	↔	Expertise in Technical Review is a good mix within and outside the M&S domain.
Level of Independence	No independence from M&S project	↔	Fully independent review panel, external to Agency with no ties to implementing organization
Level of Formality	No formal process documented	↔	Planning, execution, and closure of review formally documented
Phases of the M&S Lifecycle Covered	No Technical Reviews documented	↔	All phases of M&S project reviewed
Level of Detail	Detail level of Technical Review not documented	↔	All details of M&S reviewed
Currency with Revision of M&S	M&S revision not documented for the review	↔	Review current to latest revision of M&S

The best possible Technical Review in all respects is rarely practical and depends on the criticality, budget, schedule, and reviewer availability. The purpose of the assessment of Technical Review is only to understand how well it was accomplished.

Table 19, Achieving Technical Review CAS Factor Levels, shows the increasing gradation of Technical Review, with the highest level (4) reserved for reviews that include an independent evaluation of the individual factor. A formal review is documented and rigorous. An informal review is more ad hoc. NASA-STD-7009 assumes any external review is formal.

Table 19—Achieving Technical Review CAS Factor Levels

Level	Technical Review	How to Achieve Each Level
4	Favorable external peer review accompanied by independent factor evaluation	In general, better reviews are more independent, highly qualified with more technical diversity, more formal (planned and documented), encompass the full M&S lifecycle, cover more detail, current with the latest (or used) revision of the M&S.
3	Favorable external peer review	
2	Favorable formal internal peer review	
1	Favorable informal internal peer review	
0	Insufficient evidence	No technical review

An unfavorable review at any one level does not allow one to achieve that particular level. For example, if an external peer review for Level 3 is unfavorable, a favorable formal internal peer review still achieves Level 2.

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5.5 Section 4 – NASA-STD-7009 Requirements & M&S Risk

This last section includes two items for consideration of a complete NASA-STD-7009 based M&S assessment. First, it can be instructive to see how a given M&S activity has complied with each of the requirements in NASA-STD-7009, which relates to the requirements compliance matrix (Appendix C of NASA-STD-7009). Second, the M&S-based Analysis Risk item is a reminder of the two-fold role of risk in M&S-based analyses: the required use of NASA-STD-7009, based on the level of influence of the M&S on the consequences of the impending decision (in accordance with Appendix A of NASA-STD-7009) and an understanding and acceptance of the risk associated with the decision when the results from the M&S-based analysis are presented. The answer to the question "Is NASA-STD-7009 required?" is documented as an item in the Worksheet header. Tracking the program/project decision risks stemming from M&S-based analysis is captured in the M&S-based Analysis Risk item.

5.5.1 NASA-STD-7009 Requirements Compliance

The intent of NASA-STD-7009 is to establish routine and disciplined M&S processes. Section 4 of NASA-STD-7009 enumerates the minimum set of requirements to that end, along with an additional set of recommendations in each sub-section. Understanding the requirements that are and are not satisfied offers additional supporting evidence to the amount of rigor associated with the development of the M&S and its use in analysis. This associated Worksheet item establishes the importance of recording the level of compliance with these requirements and recommendations.

An understanding of the extent of compliance with the requirements of NASA-STD-7009 is needed. This is intended to be a high-level perspective supported by the Compliance Matrix in Appendix C of NASA-STD-7009. Consideration should be given to whether and how well the requirements were satisfied. Waivers to the requirements in NASA-STD-7009 should be documented.

While it is desirable that all requirements and recommendations are satisfied, program/project constraints can limit full compliance. Therefore, a view of adherence is not the best way to report this compliance. It is more important for an M&S activity to provide information directly related to the analysis than to have satisfied all of the check-the-box requirements. The Results column can be used to record an indication of compliance, e.g., percent completed, and then the Comments column can be used to note significant exceptions or accomplishments (figure 48, Worksheet Item: Requirements Compliance).

Item	✔	Result	Comments
NASA-STD-7009 Requirements & M&S Risk			
Requirements Compliance	Give details on non-compliances with NASA-STD-7009 and their consequences.		

Figure 48—Worksheet Item: Requirements Compliance

5.5.1.1 Explanations

Appendix C of NASA-STD-7009 provides a template for assessing requirements compliance. The first column lists the requirements; the second column is for recording the compliance status (C–compliant, NC–not compliant, N/A–not applicable); and the third and fourth columns can be used to record the method of verifying compliance and the evidence of compliance, respectively.

In practice, such a discrete view of compliance may not be the best approach. Critical decisions sometimes are made independent of the schedule governing the development of models, execution of simulations, final analysis, and documentation. Accordingly, degrees of partial compliance could be considered. For example, the technical work with respect to a particular CAS factor (and its associated group of requirements) may be accomplished and documented in presentation format, while the formal documentation necessary to satisfy all the requirements is still in progress. Also, the uncertainty and sensitivity analyses may involve a large number of parameters, only some of which had been evaluated at that point. In cases like these, it may be acceptable to make a judgment call and choose either "Compliant" or "Not Compliant" or use modifiers, e.g., essentially or partially, as long as they are defined. The other columns can then be used to record the status of the M&S effort relative to achieving full compliance.

5.5.1.2 Examples

Table 20, NASA-STD-7009 Compliance Matrix Partial Sample, shows example entries in the Compliance Matrix from Appendix C of NASA-STD-7009.

Table 20—NASA-STD-7009 Compliance Matrix Partial Sample

Requirements	Compliance Status (C, NC, N/A)	Method	Evidence
Requirement 4.1.1 – Shall document the risk assessment for any M&S used in critical decisions	NC	N/A	Risk Assessment not accomplished
Requirement 4.1.2 – Shall identify and document those M&S that are in scope	C	Set of M&S used and architecture documented in the XYZ M&S Plan	XYZ M&S Plan – Appendix A: Analysis Architecture

NASA-STD-7009 also includes a number of recommendations that are not listed in the Compliance Matrix. Using the format from Appendix D of this Handbook, compliance with these recommendations and other information could be captured.

5.5.2 M&S-based Analysis Risk

One of the basic challenges faced when presented with any analysis from which a decision is required is to understand the risks involved. These risks culminate in the end-state resulting from the decision and the subsequent actions or operations proceeding from that decision. These risks may be rooted in the modeling, simulation, and/or analyses producing the results on which to

base a decision. The presentation of the M&S-based analysis risks for a decision with respect to the consequences of the impending decision is necessary. This Worksheet item addresses the risks of basing the decision on the M&S-based analysis and use of the program's/project's risk assessment and decision-making process to track specific M&S-based analysis risks.

Note: The intent of this Worksheet item is different from the M&S Risk Assessment defined in Appendix A of NASA-STD-7009, which determines what M&S are required to use NASA-STD-7009. That requirement is based on the influence the M&S will have in the decision process and the severity of the decision consequence and is annotated in the header portion of the Worksheet.

The essence of this item is thus captured in the question included in this Worksheet item (figure 49, Worksheet Item: M&S-based Analysis Risk): "What are the risks of basing this decision on the M&S-based analysis?"

Item	✔	Result	Comments
NASA-STD-7009 Requirements & M&S Risk			
M&S-based Analysis Risk	What are the risks of basing this decision on the M&S-based analysis?			

Figure 49—Worksheet Item: M&S-based Analysis Risk

Program/project risks are often quantified through an M&S process. An understanding of how the M&S-based analysis quantifies program/project risk and of what risks are inherent in the M&S techniques is needed to ensure a complete understanding of a given decision. Two key ideas to keep in mind are:

- Application of M&S practices to quantify program/project documented risks.
- Tracking of risks inherent in the M&S implementation.

Potential entries in the Worksheet for this item are:

- Whether the risks associated with the results are presented.
- Whether the risks are acceptable for this project.

5.5.2.1 Explanations

A program/project may accept various levels of risk, depending on the mission type and criticality. NPR 8000.4, Agency Risk Management Procedural Requirements, evolves NASA's risk management to entail two complementary processes: Risk-Informed Decision Making (RIDM) and Continuous Risk Management (CRM). RIDM is intended to inform systems engineering decisions through better use of risk and uncertainty information in selecting alternatives and establishing baseline performance requirements. CRM is used to manage risks over the course of the development and implementation phases of the lifecycle to assure that requirements related to safety, technical, cost, and schedule are met. NASA provides guidelines for the RIDM process in NASA SP-2010-576. The guidelines for the entirety of the NASA risk management approach, including both RIDM and CRM, are provided in NASA/SP-2011-3422, NASA Risk Management Handbook. In programs/projects where a Risk Management Plan (RMP) is in place, the risk addressed by an M&S process is most likely posed in the RMP

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implementation. M&S is one analysis process by which RIDM-/CRM-enumerated performance measures of a risk may be probabilistically quantified. M&S activities can provide analysis and justification for risk acceptance and mitigating actions against program/project risks. This process assumes adherence to sound M&S practices, e.g., V&V and M&S integrity by CM, and the appropriate M&S applicability with regard to quantifying a risk's performance measure. The RIDM/CRM process helps assure the M&S results are correctly integrated into the program/project decision-making process.

5.5.2.2   Examples

**5.5.2.2.1**   Example 1: Application of M&S practices to quantify program/project documented risks
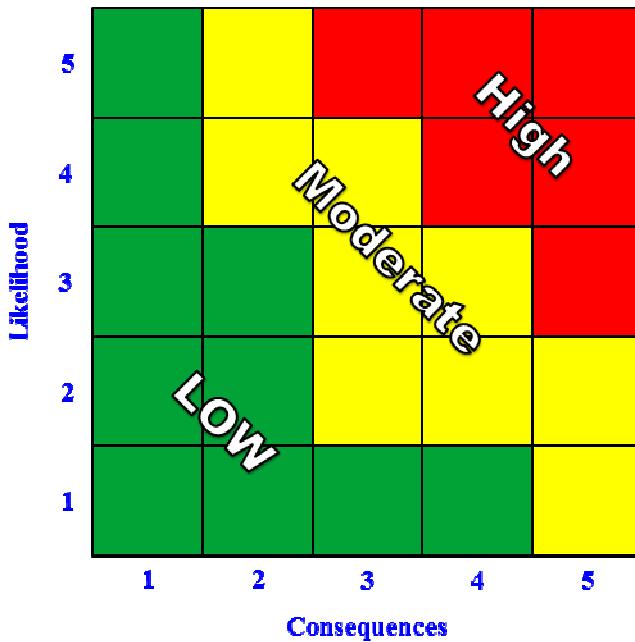
An example of a tracked program/project risk could be: Ice formed on the Space Shuttle's External Tank on the launch pad can dislodge and impact the Orbiter during ascent. There is a probability the resulting structural damage could result in the loss of the Orbiter and crew.

Questions to ask during a typical review meeting are:

- How was M&S used to assess program/project risk performance measures?

- What are the risks associated with this decision?

- How were the performance measures for this risk integrated into the program/project decision-making process?

- Has the M&S-based analysis adequately addressed the risks associated with the decision?

To answer these questions, the risks and associated performance measures should be assessed, possibly by using the M&S and associated analyses. In the previous example, the ice impact on an Orbiter's leading edge may be one of several risks quantified by an M&S approach that needs to be discussed in the program/project reviews. Answering these questions gives an indication about how comprehensive the M&S implementation and analysis were with regard to program/project needs. The results of the assessment should then be traceable to the risk-informed decision.

Insight into the communication of the risk of using the results of an M&S-based analysis can be provided by the CRM process's risk management matrix. NASA/SP-2007-6105 discusses CRM and RIDM in context with use of a typical risk management matrix (figure 50, Example Risk Matrix). This type of matrix is often used to assess a risk's ranking in the program/project risk posture.

Figure 50—Example Risk Matrix

5.5.2.2.2 Example 2: Tracking of risks inherent in the M&S

If the M&S process is seen to have its own risks, a statement defining those risks should be documented in the program/project risk management process.

As an example, lack of validation data for the tolerances in the Shuttle Orbiter wing leading edge damage model could lead to inadequate predictions in the severity of damage from the full range of known input boundary conditions.

This prompts review questions such as:

- Were the risks inherent to an M&S implementation added to the program/project risk management process?

- What modifications to the M&S validation process could be performed to increase confidence of the M&S assessment?

- What was the outcome of the risk mitigation process?

6. SUMMARY

While NASA-STD-7009 and this Handbook are provided to encourage good practices in M&S, not all M&S activities have to adhere to them. The required use of NASA-STD-7009 is determined by a risk assessment in accordance with Appendix A of NASA-STD-7009. The completeness or degree of compliance and expectations in credibility assessment are chosen by

program/project management in collaboration with the Technical Authority in accordance with current NASA governance.

The Worksheet introduced in this Handbook is an aid to implementing a rigorous M&S process and a more complete and standardized reporting of M&S-based analyses. This reporting includes:

a. Background and contextual information about the RWS.
b. The basis for the use of the M&S for the analysis.
c. The reporting of results with a statement of uncertainty and caveats to the analysis.
d. An understanding of results credibility as defined by NASA-STD-7009.
e. The level of compliance with the requirements of NASA-STD-7009.
f. An assessment of the risk associated with basing a decision on the analysis.

This information is intended to guide a more complete discussion of an M&S-based analysis, though is not expected to cover every aspect of all types of M&S. Each type of M&S, engineering discipline, system, and project has a uniqueness that may not be included. Discipline-specific M&S guides and program/project management requirements and practices should also be consulted.
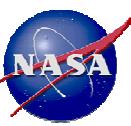
APPENDIX A

THE WORKSHEET

A.1   Purpose and/or Scope

This appendix provides guidance in the form of a full-page version of the M&S Assessment Worksheet (figure 51, NASA-STD-7009 M&S Assessment Worksheet), as discussed in section 5 of this Handbook. A spreadsheet version of the M&S Assessment Worksheet can be downloaded from https://standards.nasa.gov/released/nasa/NASA-HDBK-7009_Worksheet.xlsx.

A.2 NASA-STD-7009 M&S Assessment Worksheet

	NASA-STD-7009 M&S Assessment Worksheet	

System:	M&S:	State of M&S: In Development / Operational
Sub-System, Element, or Aspect of System Under Analysis:	**M&S Responsible Party:**	
System Lifecycle Phase:	**Subject of Analysis** (e.g., Production, Ground Ops, Flight, Mission, Entry, Descent, Landing)**:**	
Responsibility Chain: P/P Mgt & Tech Authority	**Date:**	**Risk Assessment Result (per NASA-STD-7009 Appendix A)?** 7009 Use Is Required / 7009 Use Is NOT Required / Not Performed

Item		✔	Result	Comments
System & Analysis Frameworks				
Real World System / Problem	What is the real world system?			
	What is its environment?			
	What is the problem/decision?			
Model / Abstractions / Assumptions	What is the M&S approach?			
	What's included in the M&S, including model environment influences?			
	Is there anything significant to this analysis not included in the M&S or scenarios?			
	What assumptions & abstractions are included in the M&S and Analysis?			
System - Model Match	How well does this M&S represent the Real World System / Problem at hand?			
	How well does this M&S produce the results necessary for this analysis?			
M&S-based Analysis Results & Caveats				
Estimate	What are the best-estimate results provided by the analysis?			
	How well do the analysis results address the problem statement?			
Uncertainty in Estimate	What are the magnitudes of the uncertainties in the results of this analysis?			
Caveats	What are the caveats to the analysis with this M&S?			
M&S Credibility Assessment [Development - Usage (Analysis) - Process]				
Overall Credibility	What are the overall results of the M&S Credibility Assessment?			
Verification	How (well) does the M&S implementation match the conceptual specification?			
Validation	How well did test predictions using the M&S match referent data?			
	How close is the referent to the real-world system, including its environment?			
Input Pedigree	What is the quality of the Input Data?			
	How authoritative is the Input Data for this analysis?			
Results Uncertainty	What methods are used to analyze the uncertainty in the results of this analysis (including sources and propagation)?			
Results Robustness	What are the significant sensitivities of the M&S results?			
	How thoroughly are the sensitivities known?			
Use History	How have the current M&S been previously used?			
M&S Management	What formal processes were used in the development & use of this M&S?			
People Qualifications	What are the qualifications & experience of the people developing, testing, & using this M&S?			
Technical Review	Provide a summary of the Technical Reviews performed on this M&S/Analysis.			
NASA-STD-7009 Requirements & M&S Risk				
Requirements Compliance	Give details on non-compliances with NASA-STD-7009 and their consequences.			
M&S-based Analysis Risk	What are the risks of basing this decision on the M&S-based analysis?			

Figure 51—NASA-STD-7009 M&S Assessment Worksheet

APPENDIX B

REFERENCES

B.1 Purpose and/or Scope

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.

B.2 Reference Documents

B.2.1 Government Documents

DoD

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NASA

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APPENDIX C

RELATIONSHIP OF NASA-STD-7009 TO NPR 7150.2

C.1 Purpose and/or Scope

Models are usually implemented in software. This appendix provides guidance in the form of a discussion of the relationship between the requirements and guidance for NASA-STD-7009 and the requirements and implementation plans for NPR 7150.2.

C.2 Embedded Models and Simulations

The relevant guidance is from section 1.2 of NASA-STD-7009: "This standard does not apply to M&S that are embedded in control software, emulation software, and stimulation environments. However, Center implementation plans for NPR 7150.2 should specifically cover embedded M&S, and address such M&S-specific issues as numerical accuracy, uncertainty analysis, sensitivity analysis, M&S verification, and M&S validation."

NASA-STD-7009 is mentioned in section 3.4.6 of NPR 7150.2, which reads, "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]." In NPR 7150.2, a software engineering (SWE) number designates a requirement.

Note that Center processes address issues such as verification, validation, numerical accuracy, uncertainty analysis, and sensitivity analysis for software implementations of M&S. Information regarding V&V techniques and the analysis of M&S can be found in NASA-STD-7009.

This note is meant to refer to all germane requirements in NPR 7150.2, not just to V&V of M&S for qualification of flight software or flight equipment. Accordingly, the implementation plans for NPR 7150.2 should address the verification, validation, numerical accuracy, uncertainty analysis, and sensitivity analysis of embedded M&S.

The relevant requirements from NASA-STD-7009 are 4.2.6 and 4.4.1 to 4.4.9. Each of these requirements begins with the phrase "Shall document." None of them requires that any specific activity be performed other than the relevant documentation. As NASA-STD-7009 states in section 4.1: "*…whatever was done is to be documented, and if nothing was done a clear statement to that effect is to be documented.*"

Since Center implementation plans for NPR 7150.2 vary in format and content, a specific prescription for dealing with embedded M&S in such a plan cannot be given; rather, the recommendation is for each implementation plan to mention the special documentation required for embedded M&S, in accordance with requirements 4.2.6 and 4.4.1 to 4.4.9 of NASA-STD-7009.

C.3   Other Models and Simulations

For all other M&S deemed by the risk assessment to be in scope of NASA-STD-7009, the requirements of both documents must be satisfied. From the perspective of NASA-STD-7009, some requirements in NPR 7150.2 are not applicable to M&S, while some are supplemental to or subsets of the requirements in NASA-STD-7009.

Table 21, Relationship of NPR 7150.2 to NASA-STD-7009, indicates the specific relationship of each requirement in NPR 7150.2 to NASA-STD-7009. The following key is to the remarks in the fourth column of table 21:

a.   NA: The NPR requirement is not germane to M&S per se. It may, for example, be a requirement on the NASA Centers. (See SWE-005 of NPR 7150.2: "Each Center shall establish, document, execute, and maintain software processes.")

b.   Supplemental: The NPR requirement is relevant to software for M&S but exceeds any requirement in NASA-STD-7009. For example, "The project shall implement, maintain, and execute the software plan(s)" (SWE-014 of NPR 7150.2) has no counterpart in NASA-STD-7009, which just requires a plan (albeit for the M&S as a whole and not just the software) (Requirement 4.1.4) but has no requirement for this plan be implemented, maintained, or executed.

c.   Subset of Requirement X: The NPR 7150.2 requirement is part of a requirement in NASA-STD-7009: Requirement 4.1.4 requires a plan for the M&S that includes such software aspects as verification and configuration management but has additional requirements on M&S-specific aspects with no counterpart in NPR 7150.2.

Table 21—Relationship of NPR 7150.2 to NASA-STD-7009

Section of NPR 7150.2	Requirement Descriptor	SWE #	NASA-STD-7009 Relationship
Preface	Effective date	1	Scope statement implicitly includes M&S implemented in software.
Organizational Capability	Agency software initiative	2	NA
	Center plan	3	NA
	Benchmark	4	NA
	Software processes	5	The Note in 3.4.6 of NPR 7150.2 means the topics in the Note are to be addressed in Center processes.
	List of Agency's programs and projects containing software	6	NA
SW Lifecycle Planning	Software plans	13	Subset of Requirement 4.1.4
	Execute planning	14	Supplemental
	Cost estimation	15	Supplemental
	Schedule	16	Supplemental
	Training	17	Supplemental to Requirement 4.6.2(a)
	Reviews	18	Supplemental
	Software development	19	Supplemental

Section of NPR 7150.2	Requirement Descriptor	SWE #	NASA-STD-7009 Relationship
	lifecycle or model		
	Software classification	20	Supplemental
	Software classification changes	21	Supplemental
	Software assurance	22	Supplemental
	Software safety	23	Supplemental
	Plan tracking	24	Supplemental
	Corrective action	25	Supplemental
	Changes	26	Supplemental
OTS SW	COTS, GOTS, MOTS	27	Supplemental
V&V	Verification planning	28	Subset of Requirement 4.1.3(e)
	Validation planning	29	Subset of Requirement 4.1.3(e)
	Verification results	30	Subset of Requirements 4.4.1 – 4.4.3
	Validation results	31	Subset of Requirements 4.4.4 – 4.4.6
Project Formulation	CMMI^{SM} levels for classes A, B, and C software	32	Supplemental
	Acquisition assessment	33	Supplemental
	Acceptance criteria	34	Subset of Requirement 4.1.3(a)
	Supplier selection	35	Subset of Requirement 4.1.4
	Software processes	36	Supplemental
	Milestone	37	Supplemental
	Acquisition planning	38	Supplemental
Government Insight	Insight into software activities	39	Supplemental
	Access to software products	40	Supplemental
	Open source notification	41	Supplemental
	Electronic access to source code	42	Supplemental
Supplier Monitoring	Track change request	43	Supplemental
	Software measurement data	44	Supplemental
	Joint audits	45	Supplemental
	Software schedule	46	Supplemental
	Traceability data	47	Supplemental
	Solicitation	48	Supplemental
Software Requirements Development	Document	49	Subset of Requirement 4.1.3
	Software requirements	50	Supplemental
	Flow-down and derived requirements	51	Supplemental
	Bi-directional traceability	52	Supplemental
Software Requirements Management	Manage requirements change	53	Supplemental
	Corrective action	54	Supplemental
	Requirements validation	55	Supplemental
Software Design	Document design	56	Supplemental
	Software architecture	57	Supplemental
	Detailed design	58	Supplemental
	Bi-directional traceability	59	Supplemental
Software Implementation	Design into code	60	Supplemental
	Coding standards	61	Supplemental
	Unit test	62	Supplemental

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Section of NPR 7150.2	Requirement Descriptor	SWE #	NASA-STD-7009 Relationship
	Version description	63	Subset of Requirement 4.2.9
	Bi-directional traceability	64	Supplemental
Software Testing	Plan, procedures, reports	65	Supplemental
	Perform testing	66	Supplemental
	Verify implementation	67	Supplemental
	Evaluate test results	68	Subset of Requirements 4.4.1 – 4.4.6
	Document and track defects	69	Supplemental
	Models, simulations, tools	70	Supplemental
	Update plans and procedures	71	Supplemental
	Bi-directional traceability	72	Supplemental
	Platform or hi-fidelity simulations	73	NA to M&S in scope
Software Operations, Maintenance, and Retirement	Document maintenance plans	74	Subset of Requirement 4.1.4
	Plan operations, maintenance, and retirement	75	Subset of Requirement 4.1.4
	Implement plans	76	Supplemental
	Deliver software products	77	Supplemental
	As-built documentation	78	Supplemental
Software Configuration Management	Develop configuration management plan	79	Supplemental
	Track and evaluate changes	80	Supplemental
	Identify software configuration items	81	Supplemental
	Authorizing changes	82	Supplemental
	Maintain records	83	Supplemental
	Configuration audits	84	Supplemental
	Implement procedures	85	Supplemental
Risk Management	Continuous risk management	86	Supplemental
Peer Reviews/ Inspections	Requirements, test plans, design, and code	87	Supplemental
	Checklist, criteria, and tracking	88	Supplemental
	Basic measurements	89	Supplemental
Software Measurement	Objectives	90	Supplemental
	Software measurement areas	91	Supplemental
	Collection and storage	92	Supplemental
	Analyze data	93	Supplemental
	Report analysis	94	Supplemental
	Software measurement system	95	NA
	Objectives and procedures	96	NA
Best Practices	Agency process asset library	98	NA
	Identify applicable practices	99	NA
Training	Software engineering	100	NA

Section of NPR 7150.2	Requirement Descriptor	SWE #	NASA-STD-7009 Relationship
	training		
	Software training plan	101	NA
Software Documentation Requirements	Software development/ management plan	102	Supplemental
	Software configuration management plan	103	Supplemental
	Software test plan	104	Supplemental
	Software maintenance plan	105	Supplemental
	Software assurance plan	106	Supplemental
	Center software training plan	107	NA
	Center software engineering improvement plan	108	NA
	Software requirements specification	109	Supplemental
	Software data dictionary	110	NA to M&S in scope
	Software design description	111	Supplemental
	Interface design description	112	NA to M&S in scope
	Software change request/problem report	113	Supplemental
	Software test procedures	114	Supplemental
	Software users manual	115	Supplemental
	Software version description	116	Supplemental
	Software metrics report	117	Supplemental
	Software test report	118	Supplemental
	Software inspection/ peer review/inspections	119	Supplemental
Tailoring of Requirements	Submit generic waiver request	120	Supplemental
	Document approved alternate requirements	121	Supplemental
Designation of Engineering Technical Authority	Center-level Engineering Technical Authority approval	122	NA
Compliance	Direction for Technical Authority	124	NA
	Compliance matrix	125	Supplemental
	Considerations for waivers	126	NA
	Review of "P (Center)"	127	NA
	Compliance records	128	NA
	Check compliance	129	NA
Software Lifecycle Planning	Software safety plan	130	Supplemental
	IV&V Plan	131	Supplemental
	Classification assessment	132	NA
	Software safety determination	133	Supplemental
	Safety-critical software requirements	134	Supplemental
Software	Static analysis	135	Supplemental

Section of NPR 7150.2	Requirement Descriptor	SWE #	NASA-STD-7009 Relationship
Implementation	Validation of software development tools	136	Supplemental
Software Peer Reviews/ Inspections	Peer review/ inspections of software plans	137	Supplemental
Software Documentation Requirements	Software safety plan contents	138	Supplemental
Compliance	"Shall": statements in NPR 7150.2	139	Supplemental
	"P (Center)"	140	Supplemental

APPENDIX D

RECOMMENDATIONS COMPLIANCE MATRIX
(NOT INCLUDED IN NASA-STD-7009)

D.1   Purpose and/or Scope

This appendix provides guidance in the form of table 22, Recommendations Compliance Matrix.

D.2   Recommendations Compliance Matrix

Recommendations from NASA-STD-7009 include the following:

Table 22—Recommendations Compliance Matrix

Recommendations	Compliance Status (C, NC, N/A)	Method	Evidence
Rec. 4.3a: The relevant characteristics of the system that is modeled should be documented.			
Rec. 4.3b: CM records should contain test cases that span the limits of operation for the M&S defined by the program or project. Test cases are defined as benchmark I/O sets used to verify proper execution of the M&S.			
Rec. 4.3c: The simulation should fail in a manner that prevents misuse and misleading results. 1. The simulation should provide messages that detail the failure mode and point of failure. 2. The analyst should document and explain all failure modes, points of failure, and messages indicating such failures.			
Rec. 4.4: The responsible party should document:			
a: Any aspects of M&S that have not been verified.			
b: Any aspects of M&S that have not been validated.			
c: If any significant physical processes, effects, scenarios, or environments have not been considered in the uncertainty quantification analysis.			
Rec. 4.5: Recommended Practices should be identified for:			
a: Input data and V&V			

Recommendations	Compliance Status (C, NC, N/A)	Method	Evidence
b: A quantified method of tracking adherence to Recommended Practices			
c: The purposes and objectives for the M&S and their pedigrees			
d: V&V processes for the M&S			
e: Uncertainty quantification methods for the M&S			
f: Understanding the disciplines incorporated in the M&S			
g: Analyzing and interpreting the M&S results, including documentation of inference guidelines and statistical processes used			
h: Recognizing and capturing the need for any changes or improvements in the M&S			
i: Reporting procedures for results			
j: Identifying best practices for user interface design to constrain the operation of the simulation to within its limits of operations			
Rec. 4.6: Recommended training topics for developers, operators, and analysts of M&S include:			
a: The intended use of limits of operation for models			
b: CM requirements			
c: Documentation requirements as specified in sections 4.2, 4.3, and 4.4 of NASA-STD-7009			
d: How to recognize unrealistic results from simulations			
e: Feedback processes to improve M&S processes and results, including providing feedback for results that are not credible, are unrealistic, or defy explanation			
f: Sensitivity analysis			
g: Uncertainty quantification			
h: V&V			
i: How to report simulation results to decision makers			
j: Statistics and probability			
k: Discipline-specific recommended practices, other applicable Agency policy, procedural requirements, and Standards			
l: Basic structures, mathematics, assumptions, and abstractions			
Rec. 4.7: Obtain additional insight into the credibility of M&S results by applying the			

Recommendations	Compliance Status (C, NC, N/A)	Method	Evidence
process in Appendix B.5 of NASA-STD-7009 to calculate and report any gaps between the achieved scores and the program-/project-defined threshold scores for each of the factors.			
Rec. 4.8: Reports to decision makers should:			
a: Include concluding remarks stating whether the M&S results are credible enough for the intended use			
b: Identify how to access more detailed backup material, including high-level descriptions of the models used and key assumptions for limits of validity			
c: Be placed in the CM system			
d: Summarize deviations from established recommended practices			
e: Include dissenting technical opinions regarding the credibility of the results or any recommended actions			
f: Convey serious concerns of the developers and analysts about M&S to project managers (and decision makers, if appropriate) as soon as they are known			

APPENDIX E

TECHNICAL WORKING GROUP

E.1   Purpose and/or Scope

This appendix provides guidance in a list of the individuals in the TechnicalWorking Group who drafted this Handbook.

E.2   Technical Working Group

Name	Center
Martin Steele (Office of Primary Responsibility Designee)	Kennedy Space Center
Tim Barth	NASA Engineering and Safety Center (Kennedy Space Center)
Mike Carney	Kennedy Space Center
Jeff Cerro	Langley Research Center
Howard Conyers	Stennis Space Center
Steve Cornford	Jet Propulsion Laboratory
Zack Crues	Johnson Space Center
Tim Crumbley	Marshall Space Flight Center
Ken Johnson	NASA Engineering and Safety Center (Marshall Space Flight Center)
Mary Livingston	Ames Research Center
Barbara McKissock	Glenn Research Center
Gary Mosier	Goddard Space Flight Center
Keith Niehuss	Marshall Space Flight Center
Bill Othon	Johnson Space Center
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For further questions or guidance in the use of this Standard, contact the Office of Primary Responsibility or other Center representatives listed above.