Achieving Accreditation Utilizing Model Development Indices and Model Description Reports

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ABSTRACT

Simulation-based acquisitions strive to reduce program costs, schedule, and risk throughout the acquisition life-cycle while increasing the military utility and supportability of fielded systems. This is accomplished by developing representative models and simulations of systems and subsystems informed by referent data varying among subject matter expertise, benchtop experiments, test data, and/or first-principal physics. Pioneering a process in verification and validation of models, Branford McAllister developed a systematic process to assess the level of maturity using Model Maturity Levels. Evolving McAllister's approach, model description reports (MDRs) document model development indices (MDIs) as a consistent, universal framework while progressing through the verification, validation, and accreditation (VV&A) process. Taking a notional air launched weapon system, there can be hundreds of MDRs to describe systems and subsystems from the control system kinematics, rocket motor, and aerodynamics, to the avionics and sensors. A well-conceived VV&A plan with a sufficient number of MDRs focuses on the required criteria for each level of maturity and can optimize test events to gain knowledge points and fill significant gaps with field referent data. When test events illuminate model deficiencies, an iterative process can quickly correct a model, thereby restarting the MDI maturation process. This iterative and graduated approach to VV&A allows for MDRs to advance through VV&A phases to reach a given level of maturity with a similar cadence. Therefore, the system would be ready for accreditation provided all other criteria are met within the V&V plan. These events can be coordinated with acquisition program milestones such as Test, Flight, or Production Readiness Reviews or System Verification Reviews. The evolution of McAllister's process can yield increased confidence to the models within the simulation, which can lead to highly concentrated experiments to fill data gaps, and consequently, can lead to simulation accreditation and achievement of the goals of simulation-based acquisition.

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INTRODUCTION

Simulation-based acquisitions strive to reduce program costs, schedule, and risk throughout the acquisition life-cycle while increasing the military utility and supportability of fielded systems. This is accomplished by developing representative models and simulations of systems and subsystems informed by referent data varying from subject matter expertise, benchtop experiments, test data, and/or first-principal physics. When designing these simulations, developers and engineers must expand upon the traditional systems engineering approach that commonly leverages the existing real world for products by creating a world which embodies their products. For example, systems engineers building a missile can focus upon specific parts of their product like a guidance unit generating commands to the flight surfaces. The systems engineers will need to know the physical laws describing the atmosphere of which the missile flies through, but the systems engineer typically will not have to figure out how to simulate an atmosphere. Simulation developers need to start from scratch and build an artificial world, deciding the framework of how the simulated world works, then placing an item of interest in it to see how it responds. Henceforth, the development of a useful simulation begins with the construction of a blueprint or conceptual model to help stakeholders visualize the intended outcome as well as monitor progress toward the end goal, and it also functions as a bounding methodology to help scope the problem and its solution.

The concept of acquiring new systems for the Department of Defense based on *models* is not new. The concept of a flying object was based on a physical model, and with the onset of the Space Age, the demand for digital models increased. As budgets tighten, programs work through high-skill, low density personnel strains, and systems become more software intensive, the move to simulation-based acquisitions accelerates. As the use becomes more ubiquitous, more learning occurs. In 2017, the Scientific Advisory Board (SAB) reported on findings related to Test and Evaluation capability gaps where cyber, space, and electronic systems' technology were outpacing current performance metrics. The report goes on to identify how, "Modeling and Simulation (M&S) has become a key requirement for modern DoD system development. It is needed for initial concept development, requirements development, design, and test. For many systems, it is also an important element of the mission planning system used to predict performance and make battle decisions during operations. Thus, a rigorous M&S development process is critical…" (Scientific Advisory Board, 2017). The same report later discusses an example of a missile system, "where an integrated M&S strategy is used to develop a high-fidelity simulation of the weapon system (fire control radar, weapon control system, launcher, and missile). Ground test facilities are used to gain confidence in the hardware, operational software, and simulation. Depending on missile cost, there may also be relatively little opportunity to flight test the weapon system. High fidelity M&S tools provide a means to simulate many flight scenarios and thus, provide confidence needed for a fielding decision," This report culminates with several recommendations: including a detailed simulation validation plan; developing the highest fidelity possible model; and a rigorously planned Design of Experiments that minimizes the number of test points required. While the SAB makes these bold recommendations, it leaves the implementation of model development and model verification and validation open to interpretation.

Pioneering a process in verification and validation of models, Branford McAllister developed a systematic process to assess level of maturity using Model Maturity Levels. McAllister leverages model description reports (MDRs) based on work by Turner et al. (2018) to document model development indices (MDIs) as a consistent, universal framework while progressing through the verification, validation, and accreditation (VV&A) process. Taking a notional air launched weapon system, there can be hundreds of MDRs to describe systems and subsystems from the control system, kinematics, rocket motor, and aerodynamics, to the avionics and sensors. A well-conceived VV&A plan with a sufficient number of MDRs focuses on the criteria and documentation required for each level of maturity and can optimize test events to gain knowledge points and fill significant gaps with field referent data. When test events illuminate model deficiencies, an iterative process can quickly correct a model, thereby restarting the MDI assessment process. This iterative and graduated approach to VV&A allows for MDRs to advance a model through VV&A phases to reach a given level of maturity with a similar cadence. Therefore, the model would be ready for accreditation provided all other criteria are met within the V&V plan. These events can be synchronized with acquisition program milestones such as Test, Flight, or Production Readiness Reviews or System Verification Reviews. The evolution of McAllister's process can yield increased confidence in models, which can lead to highly focused experiments to fill data gaps, and consequently, can lead to model accreditation and achievement of the goals of simulation-based acquisition.

The goal of this paper is to present a background for Modeling and Simulation (M&S), to expound on the theoretical framework of MDIs, and to discuss the application of such framework as a documentation tool and as artifacts for accreditation for simulation-based acquisition using an example of a notional air launched missile.

BACKGROUND

Jeff Rothenburg, while researching military simulations at RAND in the early 1980's wrote, "modeling in its broadest sense is the cost-effective use of something in place of something else for some purpose. Every model refers to some real-world entity (its referent) of which it is a model; it has some purpose with respect to this referent, and it must be cost-effective (in some relevant coin) to use the model for this purpose than to use the referent itself. Modeling thereby makes it possible to study phenomena that are too difficult, too dangerous, or impossible to observe directly" (Rothenburg, 1991). The "cost effective use of something in place of something else for some purpose" is an important, fundamental distinction of simulation development. Models are built as representations for a definitive purpose, which has been established. The purpose for which the model has been constructed is established in the simulation development process and can be graded using MDI levels; however, without proper buy-in, this can be a point where simulation development efforts potentially go astray. Systems engineers and software designers often view the end product as a replication of the real world whereas simulation developers, or simulationists, view the end product as a suitable imitation of the real world (Borah, 2002).

Law and Kelton (1991) suggested that, "A simulation practitioner must determine what aspects of a complex real-world system actually need to be incorporated into the simulation model, and what aspects can safely be ignored. It is generally not necessary to have a one-to-one correspondence between each element of the system and each element of the model. Modeling each aspect of the system will seldom be required to make effective decisions, and will also be infeasible due to time, money, or computer restraints." Widman, Loparo, and Nelson (1989) noted, "that the model cannot represent the real system completely. It always represents an idealized approximation. The simulationist must ensure that the approximation is adequate for the desired simulations." The M&S community should always remember what Shannon wrote, "The art of modeling can be mastered by those who possess the necessary skills of ingenuity, insight, and resourcefulness, as well as an extensive exposure to the systems and physical phenomena they are trying to model. There is no hard and fast rule about how the problem is originally formulated, i.e., how one looks at it in the first place. There are no magic formulas for deciding what should be included in the model in the form of variables and parameters, descriptive relationships and constraints, and criterion for judgment of effectiveness. Remember that nobody solves the problem; rather, everybody solves the model that he has constructed of the problem. This concept helps to keep the model and the art of modeling in the proper perspective" (Shannon, 1975). In theory, the creation of a simulation normally appears to be a straightforward process. Development begins with collecting the requirements that the sponsor/user has set forth for the model. Development ends when those requirements are demonstrated in a manner meaningful to the sponsor/user; however, many simulation developments have failed to demonstrate their usefulness, and there are many reasons why M&S fails to deliver upon its promises. Foremost among these reasons is that M&S is an activity having very few, if any, formal laws to guide simulation developments. There is no Moore's Law that every M&S practitioner can rely upon (Moore, 1965). "It depends" is the most frequent answer provided to a customer's question during a simulation development. At present, simulation development remains an "art" that M&S professionals are trying to solidify into a science.

M&S engineering has taken many shapes and forms historically, and several academic institutions even offer degree programs focusing on this subject matter; however, as it exists in practice today, M&S engineering is an *art* because it is a maturing developmental process residing in an undefined region sandwiched between systems and software engineering (see Figure 1).

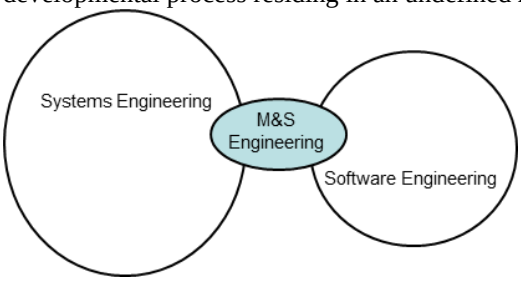

Figure 1. M&S Engineering Placement

Systems and software engineering were once in this same state and over time have matured into more formal engineering disciplines taught in multiple universities. The principles and techniques of systems and software engineering are documented in detail in books filling bookstore and library bookshelves. Systems and software engineering have numerous practitioners and large support frameworks of international and national organizations. M&S engineering has not yet attained the same status. The following questions will help to explore the undefined region inhabited by M&S engineering (Borah, 2007).

To start the exploration, systems engineering from Figure 1 will be examined. Thomé (1993) defined systems engineering as, "an interdisciplinary approach for enabling the realization and deployment of successful systems. It can be viewed as the application of engineering techniques to the engineering of systems, as well as the application of a systems approach to engineering efforts." The International Council of Systems Engineering (INCOSE, 2007) stated that systems engineering, "integrates other disciplines and specialty groups into a team effort, forming a structured development process that proceeds from concept to production to operation and disposal. Systems engineering considers both the business and the technical needs of all customers, with the goal of providing a quality product that meets the user needs." On the other side of the undefined region in Figure 1, software engineering will be examined. Software engineering is, "the application of a systematic, disciplined, quantifiable approach to the development, operation, and maintenance of software" (IEEE, 2000).

So, then, what is M&S engineering? Modeling is "a technique of system analysis and design using mathematical or physical idealizations of all or a portion of the system" (IEEE, 2000). Simulation is "the imitation of a real-world process or system over time" (Banks, Carson, and Nelson, 1996). More simply, a simulation is "a method for implementing a model over time" (Rothenburg, 1991). Therefore, M&S engineering is a set of practices used to create a model or simulation. Consequently, M&S engineering is different from systems engineering because the scope of M&S is more limited. M&S is perceived to be a narrowly defined technique whereas systems engineering is a broadly applicable process. M&S is concerned with the analysis or imitation of all or a portion of a system. M&S engineering is also different from software engineering in that M&S is not exclusively implemented by software. M&S can be either abstract or physical and consequently may not require the use of computers. M&S is related to each of these more well understood engineering methodologies but not subsumed by either.

However, the most distinct difference between either systems or software engineering and M&S engineering is the *imitative* nature of M&S. The need to imitate an existing or proposed system requires three analytical cycles during model development as opposed to one analysis cycle for the systems and software engineering processes. A system being simulated must first be analyzed and partially understood before it can be imitated. Then as it is being imitated, additional analysis must occur to identify what features and aspects of the system will be imitated and then later how they will be imitated. Finally, in a third analytical cycle, the model is compared to the referent, with revisions to the model as needed. These three analytical cycles greatly increase the complexity of developing a simulation. At times, what is being imitated or modeled can be easily judged to be representative, but as a system or subsystem grows increasingly complex, a standardized, universal approach would reduce ambiguity, document assumptions for years and potential simulationist and users to come, and support systems engineering activities such as VV&A. A proposed method to do this incorporates Model Development Index levels.

THEORY

Model Development Index (MDI) Levels

The concept of *model maturity levels* grew out of the realization that no common methodology had been developed to evaluate the state of model development (maturity) such that current or potential, future users could assess the capability to meet their needs given the MDR documentation. An original concept (McAllister, 2023) evolved into *Model Development Index* (MDI) levels, but the original purpose has remained constant: to provide a single, objective, and universal means of assessing the state and maturity of all models with a consistent set of terms, attributes, and metrics. The notion of grading the maturity of a model used in simulation is not new. Various agencies have defined maturity as the state of development at a point in time toward a desired level of geometry, functionality, or fidelity.

The MDI assessment process is based on previous work at Sandia National Laboratories (SNL, 2007a; SNL, 2007b), NASA (2016), and the Simulation Interoperability Standards Organization (SISO, 1999; 2007). The DoD previously sought to use Technology Readiness Levels to assess model maturity with little lasting success. Nevertheless, MDI levels are patterned after TRLs 1 through 9, for ease of translation among stakeholders who have a strong intuition for TRL definitions within a developmental system.

There are three main components of the MDI: (a) criteria to define the levels of model maturity, (b) measures to assess maturity, and (c) the documentary evidence required to demonstrate maturity. The MDI assessment artifacts represent, at any point in time, the documentation of the maturity of models used for various programs, analytical purposes, and decisions. The MDI is tightly integrated with VV&A efforts. The artifacts from VV&A are used as evidence to assess MDI levels, consistent with DoD guidance, MIL-STD-3022 (DoD, 2008), and Digital Engineering, Modeling and Simulation (M&S) Community of Practice (DEM&S CoP) recommended practices. In fact, the MDRs can be written in such a way that the achievement of each successive MDI level is recorded.

Systems Engineering and Model Maturity

The goal of systems engineering processes, activities, and artifacts is to provide the technical framework for the realization of capability requirements to a successfully fielded system. Methodical systems engineering processes transform top-level capability requirements down to detailed design documentation referred to as the product baseline (DoD, 2022). Early execution of systems engineering activities was found to be critical to the success of DoD acquisition programs (GAO, 2016). Early systems engineering activities include an Analysis of Alternatives (AoA) (DoD, 2015) and other trade-off studies to balance the capability requirements against cost, schedule, risk and performance. It is common practice to use M&S to conduct AoA and other trade-off studies. Because the systems under study range from mature programs of record to *clean sheet* concepts, so do the models that represent these systems. All M&S used for DoD processes, products, and decisions must go through a VV&A process for the intended use of those M&S (DoD, 2009). This presents one of the early challenges for systems engineering: how to VV&A a system model for use in AoA and trade-off studies that has very little or no supporting empirical referent data? The MDI process and tools presented in this paper provide a formal method for documenting the M&S level of maturity at each phase of the model development cycle. Since the system model development cycle follows the actual system, use of low MDI concept models may be sufficient and accredited for use in early trade-off and AoA studies.

It is well documented in several textbooks the use of models and simulations to successfully support systems engineering processes, activities, and artifacts throughout the lifecycle of a program (Yilmaz & Oren, 2009; Rainey & Tolk, 2015). Yilmaz and Oren (2009) described how agent-directed simulations (ADS) can be used in the design, development, and test of complex systems adapting to dynamic environments involving interactions between software agents and objects. Furthermore, they describe how systems, and in many cases systems of systems (SoS), can be translated into a set of characteristics that are associated with agents. Thus, ADS play a critical role in the systems engineering processes of design, interfaces, behaviors, performance, and quality of these systems. Although, these textbook references describe the importance of VV&A of M&S and processes for completing VV&A, there is no discussion or understanding about the state of M&S development (maturity). The use of M&S is now ubiquitous in major programs' systems engineering processes, but with little guidance on how to develop and maintain the M&S consistent with their purpose. This brings up another challenge for simulationists; understanding when model development is complete. Since the goal of M&S is to represent the real system in the real environment, how does the developer know when the model representation is sufficient and ready for accreditation? During M&S development, understanding the state of maturity through the MDI process, provides simulationist and systems engineers a formal method to know when M&S development is sufficiently complete for its intended use.

A best practice in M&S development is to anticipate a model will be reused for other purposes on the same program or on different programs. Models are often reused when starting with developed models is deemed more cost effective and efficient than starting from scratch. M&S reuse is also a common beginning when model development is needed on DoD systems (DoD, 2022). The reuse of models presents significant challenges for the simulationist to understand what components and data of the model are applicable, thereby making them a good candidate for reuse, and what components are not applicable and making them a poor candidate for reuse. Andres, Tolk, and Turnista (2011) described applicability considerations for the reuse of M&S such as differences in scope, structure, and resolution. The authors further elaborated on the applicability of the model's original environment and intended use, the interoperability of components, and the Level of Conceptual Interoperability Model (LCIM). Figure 2 shows the LCIM index ranges from level one through six, with increasing levels defining increasing capability for interoperation and data sharing among model components (Andrew, Tolk, & Turnista; 2011). M&S developed using the MDI methods and tools support specific documentation on M&S conceptual model artifacts and assessed model maturity. These documentation and tools provide evidence to allow the simulationist a way to systems engineer the reuse of M&S for its new purpose.

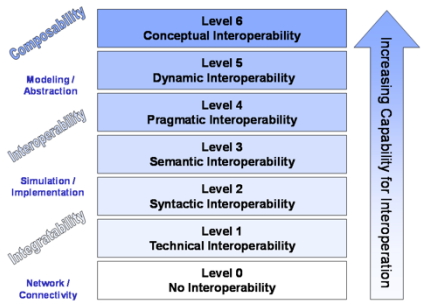

Figure 2. Levels of Conceptual Interoperability Model (Andrew, Tolk, &Turnista, 2011)

Figure 3. Digital Engineering Strategy

Digital Engineering (DE) is transforming systems engineering practices across a range of industries with the promise of increasing quality, adaptability, efficiency and affordability over the product life cycle. DE is defined in DoD (2018) as "integrated digital approach using authoritative sources of system data and models as a continuum across disciplines to support life cycle activities from concept through disposal." The DoD DE goal is to embrace the commercial innovations in computational power to move DoD acquisition away from monolithic, paper-driven processes. DE will enable the use of models to digitally represent the system, data, processes, products and components as part of an *authoritative source of truth* for systems engineering artifacts (DoD 2022). On DoD systems, models are developed and matured through the acquisition life cycle of the program and must be managed and controlled as part of the program's DE approach (DoD 2022).

DoD DE strategy comprises five goals reproduced in Fig 3. The first goal is to formalize the development, integration, and use of models. To achieve this goal programs must formalize the methods by which they develop, assess, and VV&A M&S for their intended use. DoD guidance and instruction in the above references provide very little information on implementation methods for how to achieve these ambitious DE goals. The MDI maturity method presented here provides a framework for the realization of DoD guidance on M&S development and use on systems and systems-of-systems throughout their life cycle.

MDI and Model Maturity

The MDI is a description, indicator, and assessment of the state of development of a model that relies upon objective evidence (artifacts) showing that model attributes have been developed and proven through rigorous, industry-standard processes (e.g., V&V, T&E). The process is tied to objective evaluations of model development, verification, and

validation, which is rigorously documented along the way. The assessment of MDI level is also iterative, and a model can return to lower levels of maturity if testing reveals new information or requires an assumption to be updated.

Model maturity—the MDI level—is assessed as a logical function of nine objective attributes within three categories that correspond generally to three phases in the model development process (plus an operational and accreditation phase):

- Conception: description, concept model, geometry.
- Verification: reliability and stability, suitability and maintainability, repeatability.
- Validation: referent, accuracy, precision.

The overall MDI level is no higher than the lowest rating among the nine individual attributes. Any user, among many potential users, decides if the state of the instrument (based on its MDI level and associated artifacts) is suitable for their intended purpose, which is analogous to how accreditation works among various users.

Model Maturity Concepts

Fidelity is the state of truthfulness—how accurately and precisely the model replicates the performance or behavior of the real-world system (DoD, 2024; SISO, 2007). *Foundation* is the degree to which the model is based on physics principles (i.e., a spectrum from physics-based models to less emulative, effects-based or empirical models) (NASA, 2016; SISO, 1999; SISO, 2007). *Emulation* is the degree to which the geometry, entities, and components of the real-world system are represented in the model (NASA, 2016; SISO, 1999; SISO, 2007). This is to say, a model may be high-fidelity while being mostly effects-based due to *real-time running* or *memory* requirements, which may require a lower degree of emulation. Commonly, simulations used within man-in-the-loop environments cannot devote the additional resources to emulate the atmosphere or environment that may be required for acquisition-based, engineering-based decision, but whether trainer-simulator use or engineering use, the model can be evaluated to have a common maturity.

Model maturity is assessed by examining artifacts demonstrating the extent to which a model replicates actual foundation, emulation, and fidelity using the real-world system as a referent. The model maturity assessment process documented in an MDR provides users with an understanding of the model's capabilities and maturity at a point in time; this understanding requires a consistent application of the terms, attributes, and criteria. Every user of a model has different needs. Using an objective assessment rubric and relying on documented evidence of maturity and state of development provides users a reliable, consistent way to decide if a model is suitable for their use. Additionally, it provides program stakeholders with a sense of the model's state of development.

The accuracy and precision (fidelity) of a model are rarely the sole indicators of its state of development. All models are inaccurate and imprecise, to varying degrees; however, the accuracy and precision of a model are among the considerations when assessing the model's utility by any individual user. The maturity level of the model certainly includes an assessment of the existing accuracy and precision. But more appropriately, the maturity level of the model reflects the objective evidence of that accuracy and precision; the developmental process that led to its attributes; the evidence of a rigorous V&V process; and the outcomes and products of that V&V process—part of which is a calculation of the model's current accuracy and precision.

MDI Assessment Tool

The MDI tool is a single, objective rubric (captured in a spreadsheet) to assess the state of development (maturity) of a single model at a given point in time, for the benefit of all M&S stakeholders. The spreadsheet tool has three main parts:

- A description of the model, the real system it represents, its overall purpose, type of use, and users.
- The MDI level rubric—the assessment tool (a table of attributes, criteria, and required documentation).
- A summary of the assessment of the model at a point in time, which addresses the attributes.

The MDI assessment tool is best explained within the context of the overall development of a model, within the VV&A process, and as part of or as an input to an MDR. The MDR is the formal vehicle that reports, at any point in time or milestone, the current state and maturity of a model. Part of that is the assessment of the MDI. The MDR provides a

formal context for the expression of the MDI. The MDI, the results of the MDI assessment process, and the completed MDI tool/rubric are components of the MDR.

Assessing Model Maturity

The questions that must be addressed when validating a model, and assessing model maturity in conjunction with validation, are the following:

- What objective evidence in the form of artifacts, analysis, and metrics (agreed upon by the accreditation authority) is available that demonstrates the attributes of the model?
- What referent was used to determine the model's accuracy and precision?
- What processes were used to validate the model? (and, how rigorous were they?)

The MDI level assessment process relies on a staggered approach to assessing model maturity, that recognizes the nine distinct attributes (criteria) within three categories/phases illustrated in Table 1. As the MDI level increases from 1 to 9, the demands for supporting information become more rigorous based on more objective and empirical referents (e.g., more sophisticated testing moving from bench-top tests to developmental flight tests to operational flight tests). Table 1 depicts the MDI tool, showing a model assessment at MDI level 7.

Table 1. Model Assessment at MDI Level 7 (nine criteria, three categories, and four phases)

MDI Level	Color	Phase	Conception			Verification			Validation		
			Description	Concept Model	Geometry	Reliability & Stability	Suitability & Maintainability	Repeatability	Referent	Accuracy (Fidelity)	Precision (Uncertainty)
1	Black	Concept Phase	✓	✓	✓						
2	Crimson		✓	✓	✓						
3	Red	Verification Phase	✓	✓	✓	✓	✓	✓			
4	Orange		✓	✓	✓	✓	✓	✓	✓	✓	✓
5	Yellow					✓	✓	✓	✓	✓	✓
6	Green	Validation Phase				✓	✓	✓	✓	✓	✓
7	Aqua								✓	✓	✓
8	Blue								✓	✓	
9	Purple	Ops & Accreditation Phase							✓		
Note: The overall MDI level is equal to the lowest individual criterion rating.											

For each MDI level within each phase, detailed explanations are provided in the rubric table. The following is an illustration with examples from MDI level 7 in the validation phase denoted by the white circle in Table 1:

- Definition of the MDI level ("Initial quantitative validation of model based on empirically derived referent.")
- Description of the MDI level ("Referent based on empirical ground/lab testing.")
- Supporting information required ("Descriptive statistics assessing model accuracy, margins, uncertainties, and sensitivities of responses to independent variables and control factors. Inferential statistics and hypothesis testing including confidence intervals over the entire factor space.")

Each of the nine attributes is clearly defined in the rubric. As an example, excerpted from the rubric table, the *Reliability & Stability* attribute within the *Verification* category/phase is defined as:

> the extent to which the model runs dependably (without interruption) and without mathematical errors. The correctness of the algorithms used in the code relative to the mathematical model. Correctness of source code. The extent to which SQE [software quality engineering] methods and benchmarks are used to assess the software code. The extent to which mathematical, numeric, algorithmic, and coding errors and poor SQE practices corrupt results and prevent or delay progress to the next phase.

Achievement of an MDL requires specific documentary evidence that the criteria have been met. Achieving MDI level 5, the criterion for the *Reliability & Stability* attribute within the *Verification* category/phase is the following:

Evidence is provided that all modules of the code were developed, managed, and assessed using SQE practices. Formal software unit/regression testing was compared to documented analytical benchmarks performed by the developer and peer-reviewed. Coverage of most of the critical software modules, relevant factor space, and underlying physics during code assessment. Formal quantitative methods were used to identify software coding/numerical errors. Impact of errors on the accuracy of outputs and readiness to progress is known with moderate impact—may result in delayed progression.

Summary of MDI Levels

To emphasize, the MDI level is not achieved because a test of the real system was successful or even accomplished; or that a credible SME or stakeholder declared the model to be at that level. What is required in the MDI process is the presentation of dependable, reliable, and objective artifacts documenting the following:

- There is an acceptable level of detail in descriptions of the model.
- Rigorous, industry-accepted, scientific techniques were used to develop the model.
- Rigorous analytical techniques were used to verify and validate the model.
- Clearly defined referents relevant for the MDI level were used for validation.

What follows is a discussion of the application of MDI levels and how these might be used in a VV&A process of a notional air launched missile.

APPLICATION

It is counter-intuitive that developing a simulation that was originally intended to reduce the complexity and ambiguity of a real-world system becomes itself a very complex undertaking. It is often said that "the devil is in the details". This is generally understood to mean that the complexity of building something occurs as it is implemented and with what underlying assumptions or decisions were required initially; however, the unpleasant reality of M&S engineering is that the start of the simulation development project is unexpectedly highly complex and dynamic. If the complex tasks of early M&S engineering are not done well, then the entire simulation development project goes wrong from the very start with the issues not realized until much later in the development cycle. That is why the almost continuous cycle of test-model-simulate-evaluate-revise is necessary—to ensure that the model and the real system remain in agreement. Another reason that it is difficult to construct a simulation is that modeling is an intellectual activity. The simulation is a collection of individual models that the simulation developer has arranged in a meaningful manner. A simulation by its essence does not have a tangible physical presence that can be easily seen and understood. Artifacts can be created that show a particular aspect of the simulation, but these artifacts should not be mistaken for the full simulation. A well-formed simulation will embody models, each keyed to a particular interest of a stakeholder or group of stakeholders. To illustrate this point, it might be useful to compare constructing a simulation to the development of architectural plans for building a house. Early on, the house is an intellectual construct—it does not exist and has no physical presence. There is a lot on which it will eventually be built but little more. The prospective homeowners have assembled their ideas together with those of the architect. Several different views of the house are created. One might be a color drawing depicting how the completed house will be painted. Another might be a floor plan indicating all the electrical outlets. A third might be the floor plan showing the plumbing. Individually, these plans are components that make up a full simulation of the house. The same is true for the artifacts of a simulation. A word processing document, a graphics tool diagram, and CASE tool files are not by themselves the full simulation. Each represents a component of the simulation. Together they present different perspectives of the conceptual model.

Notional Air Launched Missile Example

Taking a notional missile and evaluating the development process of the simulation as an example, one can see how the MDI assessment process can be implemented. At inception, a user defines baseline requirements. In very general terms: the missile must fly a given distance at a given speed at a certain altitude with a particular guidance and control system. These requirements need to be transformed into useful, credible model. Several questions immediately arise. What modeling technique will produce the desired results? Should this be a continuous or discrete event model? What should the model comprise? What entities and behaviors are relevant? The simulationist strives to understand the answer the user is seeking and starts with an abstract view of the simulation problem. As the simulationist achieves a deeper appreciation of the simulation, a generalized conceptual picture of

the modeling problem is generated. The general conceptual picture is captured as an Operational View 1 diagram in DoDAF notation in Figure 4.

Figure 4. Air Launched Missile Operational View 1

This is the start of the generation of documentation which will be required to substantiate VV&A activities, and which represent a key component of the MDI assessment process. An example MDR template, such as presented in Figure 5, is used in the MDI process to track model development, assess simulation suitability, plan referent data collection, and adequately prepare for VV&A reports.

The MDR template is a critical and complementary component of MDI process. One reason it is important has been stated—it is the repository for VV&A documentation. A second reason is more subtle. The format of the MDR template provides a standardized structure for model development documentation. This structure assists the simulationist and the user by setting their expectations with respect to information about the model and where to find such information within the numerous documents. The simulationist is informed on what documentation should be provided, and this is consistent with the documentation required to demonstrate the attainment of various MDIs and provided in the MDI tool/rubric. The user is informed where background information on the model can be found. Far too often, important VV&A artifacts such as model developer assumptions or inherent computing limitations are not documented by a model developer. If such artifacts are documented at all, they often take the form of cryptic notes embedded in software code, which may be unintelligible to future users.

The notional MDR Template (Figure 5) normally has 10 chapters, which can be traced back to the nine MDI levels; however, the MDR template is malleable and can be adapted to the model development style being used in any kind of program.

Chapter	Purpose	Sections	Subsections
Model Recognition	To produce a set of requirements that will drive Model design activities and provide criteria by with the success of the Model development will be judged.	Introduction	
		Intended Use	
		Modeling and Simulation Application	
Model Definition	To produce an implementation-independent conceptual depiction of the real-world that must be represented in the Model application.	Assumptions	
		Limitations	
		Capabilities	
		Requirements	
		Risk and Impacts	
		Interfaces	Data Import
			Data Fetch
			Data Export
		Referent Data Identification	
Model Design	To translate the Model Definition data into a Model capable of implementing as a simulation.	Behavioral Diagrams and Algorithms	
		Data Structures	
		Model Integration Updates	
Model Implementation	To monitor and document Model development activity.	Model Development	
Verification	To ensure all features, functions, behaviors, and interactions defined in Model Design can be traced to requirements expressed in Model Definition and have been articulated in the simulation.	Test Plan	
		Test Descriptions	
		Test Results	
Integration and Test	To verify all requirements expressed in the Model's Intended Use (Model Recognition) have been implemented testing the Model in a representative simulation domain.	Test Descriptions	Non-functional Tests
			Close Loop Tests
			Functional Tests
		Integration and Test Results	Non-functional Tests
			Close Loop Tests
			Functional Tests
Validation Plans	To document validation requirements, expected data, validation tools, and processes.		
Validation Results	To evaluate the resultant data, performance of the validation tools, and the processes.		
Maintenance	To document Model notes, information and maintenance plans.		
Appendices		Acronyms	
		Bibliography	Government Documents
			Non-government Documents
		To Be Determined/ To Be Resolved Resolution Issue Tables	

Figure 5. MDR Template

The next developmental step is the creation of a logical view of the proposed model. In this step, the abstract view is transformed into a model describing the logical groupings of represented entities and the general internal and external relationships between the entities. As an example, Figure 6 depicts the notional air launched missile logical model. Examples of major entity groupings are Blue forces, Red forces, and the Environment; although conceivably, there could be other entities. Each of the major groups are broken down into entity subgroupings or individual entity models denoted by *M*. In this notional example, the Blue forces logical subgroups are Aircraft 1, Aircraft 2, and Missile 1. These subgroups are composed of multiple models, *M1*, *M2*, *and M3*, intended to simulate aspects of the proposed simulation. The logical view of the proposed model and simulation using the model is significant because it allows the simulationist an early opportunity to review the model and identify potential shortfalls or inconsistencies. Perhaps, the Red forces have logical subgroupings for Target 1 and Target 2 but are missing a subgrouping for their weapons or countermeasures. Are the Red forces going to be simply simulated as cooperative targets without any capabilities for offense or defense? Once the logical view reaches an acceptable state for continued development, the functional decomposition of the proposed model starts.

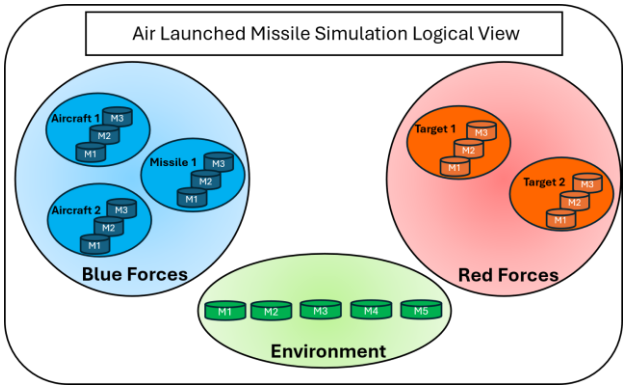

Figure 6. Notional Air Launched Missile Logical Model

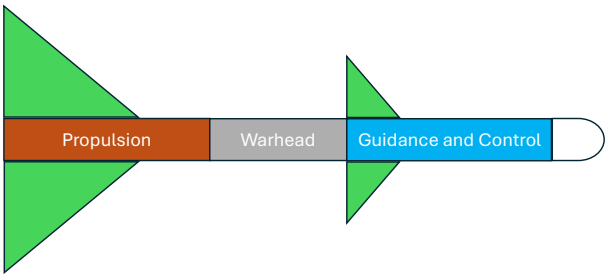

Figure 7. Missile Simulation Generalized Component Visualization

A simulationist begins breaking down the missile simulation (Figure 7) into modular physics-based models. Absent flight test data initially, the M&S engineers translate subject matter expert judgement into models such as drag or propulsion models. The simulation can begin running with only subject matter expert judgement and first-principles physics. With only a description from the user, a concept model, basic geometric information, and absent additional rigor and documentation required at MDI level 2, the drag model is at MDI level 1. In contrast, the propulsion model, which might have outputs of mass loss rate, heat, and thrust, among other variables, can be repeatedly demonstrated in a lab environment and has already progressed and assessed to be at MDI level 4. That level indicates that the MDI level 4 criteria and documentation have been provided covering all nine attributes across the three categories/phases. However, working through this example, given that the drag model is still at MDI level 1, the full system would be assessed at MDI level 1 at this point in time.

As time progresses, confidence is gained in the geometry and lab results become increasingly repeatable for the drag on the missile that the previously documented assumptions and findings can now be updated to capture the maturing drag model in the simulation. As this notional example illustrates, the drag model has met the attributes captured in the required artifacts and is assessed to be at MDI level 5 now. Simultaneously, design decisions were made to that resulted in the model not meeting the criteria for MDI level 3 for the six artifact-proven attributes under the conception and verification categories. For this illustrative example, this design change has not quite proven its suitability for the system regressing the model to a lower MDI level 2. Again, this fully fictitious system model would be assessed at an MDI level 2 at this point in time. This demonstrates how an MDI level might decrease, but the documentation still exists as criteria that track the changes and reasons, so that all stakeholders including the present and future M&S engineers are aware of the state of the model and system.

As time continues to march on and this example program develops, the notional missile is ready for flight testing outside of the lab environment. Given the previous work in the missile simulation from above, the stakeholders understand the model maturity with regards to several key areas and have various levels of confidence in these areas. For instance, how will the missile perform as a system when the missile is fully built? Like the house example above, having the plumbing correct does not directly mean the electrical wires are correct. Leveraging historical data from this illustrative example, the M&S team feels confident in the missile performance at a notional altitude and

distance, but the team is concerned about how high the missile can fly given the design change to the propulsion system and updated drag data. Therefore, the simulation is used to inform and design a specific flight test that can be used to validate the drag and propulsion system models. In this illustrative example, this specific flight test proves successful, and all three MDI level 7 attributes within the validation category have been proven coupled with documentation, so the simulation achieves MDI level 7 at this time; although, it is important to note that this is just one test of potentially many. Further, it is similarly important to note this only captures a snapshot in time, and with the required artifacts provided, MDI level 7 was achieved with the referent data the model was compared to at the time.

After multiple flight tests and obtaining statistically sufficient data, all of the models within this example simulation each, individually, achieved MDI level 9. This level is achieved when (a) the six attributes from conception and verification have met their highest rubric requirements; (b) the referent is empirical results from an operational environment, setting, conditions, and/or tactics (e.g., operational testing, WSEP, or operations); (c) comparisons between model and system (referent) are made using inferential statistics and hypothesis testing over the entire, relevant factor space; and, (d) rigorous statistical analysis was used to calculate uncertainties, sensitivities of response variables to control factors, and ranges over which acceptable accuracies can be guaranteed for the model.

In this illustrative example, the full model is now ready for accreditation. Each model has a report detailing and documenting assumptions made from inception, lessons learned from bench top and flight tests, and sufficient artifacts that an Accreditation Authority can confidently accredit the simulation to be used for a particular use case such as range safety or pre-flight predictions. This culminating event reflects years of rigorous documentation and commitment by the M&S team, but the pay-off is not so much this simulation accreditation; however, it is some time in the future, when this missile is undergoing an end-of-life extension coupled with a new guidance and control system and propulsion system. The *simulationist of the future* needs to look no further than the MDRs for the relevant assumptions. These reports were living documents that tracked previous changes, equations, assumptions, etc. The new simulationist quickly realizes that the governing equations used in the guidance and control system model require a new variable that was previously not required, which the M&S engineer documents and subsequently returns this model to MDI level 4, where testing and verification steps take place until the change can be flown and properly flight tested. When the propulsion MDR was referenced, the new propulsion system required no further updates to the model. In this case, the model was decremented to MDI level 7 as validation was required still. The simulation would then require re-accreditation as the system simulation would again revert to MDI level 4 as that is the lowest common denominator.

CONCLUSION

There are many reasons why a simulation-based acquisition may have advantages over traditional acquisitions. Simulation-based acquisitions offer agility in design, especially in early development or late-stage additions, offer cost-saving opportunities in a theoretically reduced, concentrated, and highly targeted flight-testing plan, and potentially offer a shorter path from idea to *thing*. Simulations can enable development of systems that are test environment or range limited, may have limited availability, or present security concerns in ways that physical testing cannot accomplish. In this paper, the background for M&S was presented; a theoretical framework was developed for grading the maturity of a given simulation model that is universally applicable with a general, malleable documentation template; and a short illustrative example of how this framework might be applied to a notional air launched missile was provided.

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