An Overview of Model and Simulation Verification, Validation, and Accreditation

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Today, much greater emphasis is being placed on both the correctness and credibility of models and simulations because of increased concern about the legal liabilities associated with them and reduced defense budgets which are forcing greater reliance on models and simulations within DoD. Consequently, model and simulation verification, validation, and accreditation (VV&A) has become increasingly important. Each military service is developing formal VV&A processes. This article provides an introduction to VV&A, reviews recent VV&A activities within DoD, describes a paradigm for VV&A, discusses application of VV&A to distributed simulation, and addresses a variety of VV&A techniques and issues.

INTRODUCTION

Advances in computer hardware and software have made tremendous progress in modeling and simulation possible. As a result, models and simulations (M&S) are playing ever-increasing roles in all aspects of system development and operation. (Note: Throughout this article M&S is used for both the singular and plural forms, consistent with its use within the DoD community.) In the earliest stages of system development, M&S are used to explore concepts and define system requirements. As concept transitions to design, they serve as key elements in the definition of the design and evaluation of the system. They may also serve as part of the environment within which training and planning for system operation occur. And they are becoming a common part of advanced system control processes such as those employed in modern aircraft,

ships, plants, and especially in equipment using software with second-generation model-based expert systems.

Because M&S are acquiring such influence, it becomes increasingly important that they be correct and that appropriate confidence is placed in their performance. When incorrect they can lead to inadequate system concepts and requirements, poor system design, poor training, and even system failure, possibly with catastrophic results. Loss of at least one fly-by-wire aircraft has been attributed to M&S inadequacies.[1]

Verification and validation (V&V) are processes that can increase both the correctness and confidence that can be placed in M&S results. A review of V&V efforts serves as a basis for making accreditation decisions for a given M&S. V&V is never complete or

perfect. Some kinds of errors in software, like the "5000 year error," are so obscure that they are very difficult to prevent or even detect before a disaster occurs.[2]

M&S V&V is more than software V&V. M&S, especially distributed simulations, may include hardware as well as software (e.g., hardware-in-the-loop simulations) and people (e.g., man-in-the-loop simulations). M&S V&V must also consider data appropriateness and must relate both M&S fidelity and accuracy to intended M&S applications.

This article reviews contemporary M&S verification, validation, and accreditation (VV&A) activities within the defense community that are intended to improve our ability to determine the correctness of DoD M&S and the confidence placed in them. A paradigm for VV&A that originated at APL and undergirds naval VV&A processes will be described, a recognized process for performing VV&A for distributed simulation will be presented, and a variety of VV&A techniques and issues will be addressed.

CURRENT DOD VV&A ACTIVITIES

The need for improvement in defense M&S management has long been recognized. To that end, the Deputy Secretary of Defense established the Defense Modeling and Simulation Office in 1991 to "promote the effective and efficient use of modeling and simulation."[3] DoD Directive 5000.59 on M&S management was issued on 4 January 1994. That directive requires each military service and defense component to establish VV&A policies, procedures, and guidelines for M&S. A draft DoD instruction on VV&A for DoD M&S is in preparation. The Joint Staff published its instruction (JSI 8104.01) on VV&A of joint M&S on 12 January 1995.

In addition to standards and guidance for defense software V&V, the Army published regulation AR 5-11 in 1992, which addresses overall management of Army M&S, and PAM 5-11 in 1993, a pamphlet which provides guidance on performing M&S VV&A and includes descriptions of VV&A processes and techniques. The Air Force is developing a policy directive on and an expanded VV&A guidance in the form of an M&S VV&A instruction. A draft of the instruction from the Secretary of the Navy on both Navy and Marine Corps M&S was published in early 1995. Naval VV&A is expected to be based on the VV&A paradigm defined in the Navy's April 1993 Interim Policy Guidance document.[4]

The significance of these endeavors is that the VV&A of M&S used within the defense community will take on a formalism that has previously been absent. In addition, V&V will be done more rigorously, and more commonality in VV&A among the military services is likely.

There are other defense M&S VV&A activities. Programs that already have formal VV&A processes for M&S within their purview include the Joint Tactical Commanders Group SMART (Susceptibility Model Assessment and Range Test) Project as well as the Tomahawk and HARM (High-Speed Anti-Radar Missile) Simulation Management Boards. Threat and training simulators have specified validation and acceptance processes. The Military Operations Research Society has been conducting symposia and workshops on simulation validation since 1989, and the Defense Modeling and Simulation Office has a variety of technical working groups addressing M&S VV&A and data certification issues.

One result of the defense VV&A endeavors has been to create a widely accepted set of definitions for M&S VV&A, where previously there were many, sometimes contradictory definitions. The following definitions are from the DoD Directive on M&S:

- Verification: The process of determining that a model implementation accurately represents the developer's conceptual description and specifications
- Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the model's intended uses
- Accreditation: The official certification that a model or simulation is acceptable for a specific purpose

IDEAS UNDERGIRDING A VV&A PARADIGM

In mid-1992, the Navy's M&S Office asked the Space and Naval Warfare Systems Command (SPAWAR) to draft Navy VV&A processes, and APL was assigned to lead the development of those processes. The authors served as principal investigators in this effort. A major challenge of the task was its scope. The M&S VV&A processes were to address all aspects of Navy M&S. Defense M&S are characterized by five application areas:

1. Research and development
2. Analysis
3. Test and evaluation
4. Production and logistics
5. Education, training, and military operations

M&S may be applied singly, in cooperation, or even in a geographically distributed fashion. Actual equipment and systems (live forces), manned weapon simulators (virtual forces), and entities simulated within a computer (constructive forces) may be involved in an

M&S implementation. Navy M&S VV&A processes must address this entire spectrum, both for future and existing M&S, the latter often called "legacy M&S."

We conducted a search of the literature to ascertain what work had already been performed in this area within the academic, commercial, and defense arenas. More than 1500 items were reviewed and a bibliography published[5] containing 370 of the more significant articles, reports, standards, and case histories, most of which have appeared within the past 5 years. The following six insights from this literature review guided development of an M&S VV&A paradigm for the Navy.[6]

Definition and Validation of the M&S Conceptual Model

An essential element of an M&S development process is the conceptual model, which defines the theories, assumptions, and algorithms (modules) as well as the interactions and communications among modules that underlie the M&S. The conceptual model serves as a bridge between the defined requirements and the M&S design. Validation of the conceptual model asserts that it is a reasonable representation of the subject to be modeled, given the intended uses of the M&S. By validating the conceptual model at the onset of the M&S development process, the developer avoids the potential pitfalls of inaccurately representing the system and not meeting the proposed requirements.

Importance of V&V Integration into the M&S Development Life Cycle

To be effective, V&V must be performed throughout the M&S life cycle, from initial development through modification or enhancement of the M&S. Current software engineering practices stress the need for testing and documentation throughout the development process. If deferred until after the M&S is developed and implemented, the ability to perform effective V&V becomes increasingly difficult, if not impossible, and much more expensive.

Importance of Documentation

Documentation of the M&S is essential for their efficient and effective use. Documentation should include descriptions of specifications, functionality, data requirements, etc. All VV&A processes and reviews conducted throughout the M&S life cycle should be fully and formally documented. If not documented, future VV&A efforts (e.g., those conducted when a modification or enhancement is made to the M&S or when an M&S is considered for a different application) cannot build upon lessons learned, and a new VV&A

effort will be required after M&S development and implementation are completed.

Essential Role of Data and Data Validity

A crucial factor in M&S validation is the data used to drive the M&S. Data used throughout M&S development and implementation must be judged suitable, accurate, and complete. All data must provide appropriate representation and must have been measured or estimated with suitable accuracy. In addition, data transformations conducted on intrinsic data must be performed appropriately, and all data dependencies must be represented sufficiently.

Potential of V&V Automation

As M&S become increasingly large and complex, and as the use of distributed simulations (i.e., disparate simulations at multiple locations networked together for a specific application) becomes more commonplace, the ability to perform manual VV&A will become increasingly more difficult. Manual techniques are inadequate to support required examination of the large volume of data, indicating a need for improved, automatic validation techniques. Advances in computer hardware and software make automation of various V&V activities possible.

Need for Configuration Management

The life cycle of an M&S does not end with its initial implementation but continues through any and all modifications and enhancements of the M&S configuration. Changes to the configuration must be recorded along with a description of the archival method used and identification of operational versions of the M&S, the unique characteristics of each version, and the input data and version used for a specific M&S application.

THE VV&A PARADIGM

The VV&A paradigm (Fig. 1) was developed to support the definition of processes that could address the full spectrum of Navy M&S VV&A. This paradigm accommodates and facilitates V&V automation, encourages inclusion of V&V from the earliest stages of M&S concept and development, and requires appropriate V&V documentation. It is compatible with all major software development processes. During the development process, conceptual validation and design verification reviews should be performed when the conceptual model and the M&S specification are mature. Code developed before conceptual validation and design verification reviews may not be useful in the
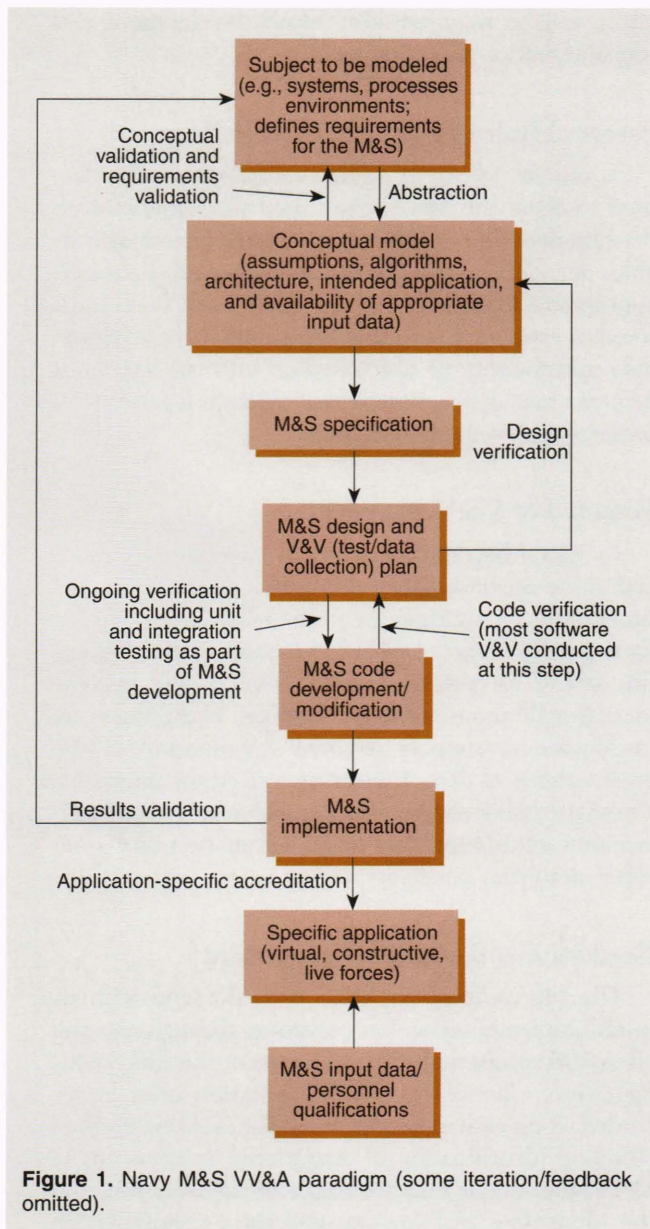
Figure 1. Navy M&S VV&A paradigm (some iteration/feedback omitted).

both natural and man-made environments, logic and rules (i.e., doctrine and tactics) by which forces are employed, and interactions among the entities of the subject over time. The subject can be described as a collection of systems and processes along with the environments within which they interact. The conceptual model is an abstraction based on this description.

Conceptual Model

Before commencing final M&S design and specification, a conceptual model of the subject to be represented should be articulated. The conceptual model is a statement of assumptions, algorithms, and architecture that relates the elements of the model to one another (and to other M&S in distributed simulation environments) for the intended application(s) of the M&S. The model must also address the availability of appropriate input data for the M&S. It may be developed directly from the defined system requirements or by an iterative process of draft concept, draft design, and perhaps even draft code. Failure to develop an adequate conceptual model before final M&S design and coding has been a major cause of past M&S inadequacies.

Conceptual Validation

Both the conceptual model and its conceptual validation review should be documented. The review explains why (or why not) the assumptions, algorithms, modeling concepts, anticipated data availability, and architecture of the conceptual model are expected to provide an acceptable representation of the subject modeled, based on the defined requirements, for intended applications of the M&S. Any interactions expected with other M&S (as in a distributed simulation) must be considered. Conceptual validation should occur before commitment to further M&S development.

M&S Specification

The M&S specification must define the hardware, software, and personnel that comprise the M&S in accordance with appropriate standards. In addition, the specification should address both hardware and software aspects of the M&S, including those for networks and protocols in distributed M&S.

M&S Design and V&V Plan

M&S design describes the M&S construction and serves as a "blueprint" for the developer. Software elements defined in the design should be developed in accordance with contemporary standard software

process of moving from a mature M&S specification to the actual M&S code. This paradigm is suitable for use in VV&A of both existing and new M&S.

Subject to be Modeled

Examples of subjects that may be represented in an M&S include a hardware component such as a radome, a piece of equipment such as a radio receiver, a system such as a tank or missile system, a platform such as a ship or aircraft, a military unit or group of units, all of the military forces involved in a conflict, production and logistical processes, and any other item that might be addressed within the scope of the M&S application areas specified earlier. The subject represented includes

development procedures. The design should include a V&V plan for the M&S that addresses not only the software elements but also considers management tasks, schedules, and resources as well as analytical activities (scope, limitations, constraints, methodology, sources of data, testing, and acceptability criteria) for V&V during M&S development. Sometimes an independent V&V plan is needed.

Design Verification

Design verification is a formal, documented review process that determines whether the M&S design and specification accurately represents the conceptual model. (Some use requirements verification or requirements validation for design verification.)

M&S Code Development/Modification

M&S code development is the process during which M&S software is written, preferably in accordance with contemporary software engineering standards of program structure, documentation, testing, and quality assurance. Modern software development technology should be used to enhance M&S documentation and configuration management. On-line documentation may be developed and maintained directly from existing and evolving software development tools, with both textual and graphical representation of the code.

Code Verification

Code verification is the formal review process that determines whether the software portions of the M&S accurately represent the M&S design and specification and that the computer code performs as intended. It includes timing and protocol constraints on M&S processing and accommodation for unanticipated input values for an M&S that must interact with hardware, operators, or other M&S in a distributed simulation. Consideration of software unit and integration testing results is part of code verification.

M&S Implementation

M&S implementation is the combination of computer codes, processes, equipment, and networks, in addition to operators and personnel that compose the M&S.

Results Validation

Results validation is the formal, documented review process that compares the M&S responses with known or expected behavior from the subject it represents to ascertain that the responses are sufficiently accurate for intended uses. Validation includes controlled tests and

sensitivity analyses of results for M&S parts as well as for the entire M&S. The M&S developer of a model with stochastic processes is expected to provide guidance regarding the number of iterations required for statistically significant results.

Specific Application

A specific application is an application of the M&S to a particular problem. If the M&S is distributed, it may involve live forces and virtual forces in simulators as well as forces generated by computer code.

Application-Specific Accreditation

Application-specific accreditation certifies that an M&S, the associated input data/databases, and the M&S users/operators/analysts are appropriate for a specified application.

VV&A FOR DISTRIBUTED INTERACTIVE SIMULATION

The DoD is moving toward a vision of a synthetic battlefield. SIMNET was one of the pioneering efforts in realizing this vision. It allowed for the interaction of homogeneous or similar simulations to interact within a distributed, virtual environment. The follow-on to SIMNET, the Distributed Interactive Simulation (DIS), develops an infrastructure that will allow heterogeneous, dissimilar simulations at varying locations to communicate and interact in a virtual environment. Dissimilar simulations may combine live forces on instrumented exercise ranges, virtual forces in simulators, and computer-generated constructive forces.

Distributed simulations pose special VV&A challenges. There is potential for incompatibility of M&S assumptions. It may not be possible to correlate the data and databases used by the simulations. In addition, fidelity levels among M&S in a distributed simulation may vary widely, and unexpected interactions may occur among the participating M&S.

The DIS community uses a workshop forum made up of representatives from DoD, industry, and academia to define standards, protocols, guidelines, and recommended practices for DIS exercises. These standards are promoted as candidate Institute of Electrical and Electronics Engineers standards or supporting documents, and, when approved, become authoritative guidance for DIS exercises. A VV&A subgroup was established within the DIS workshop structure in 1993. It has three co-chairs who represent the Army, Air Force, and Navy. The authors have served or are serving as the Navy co-chair.

Figure 2 shows the VV&A process defined for DIS exercises.[7] This process has been accepted by a
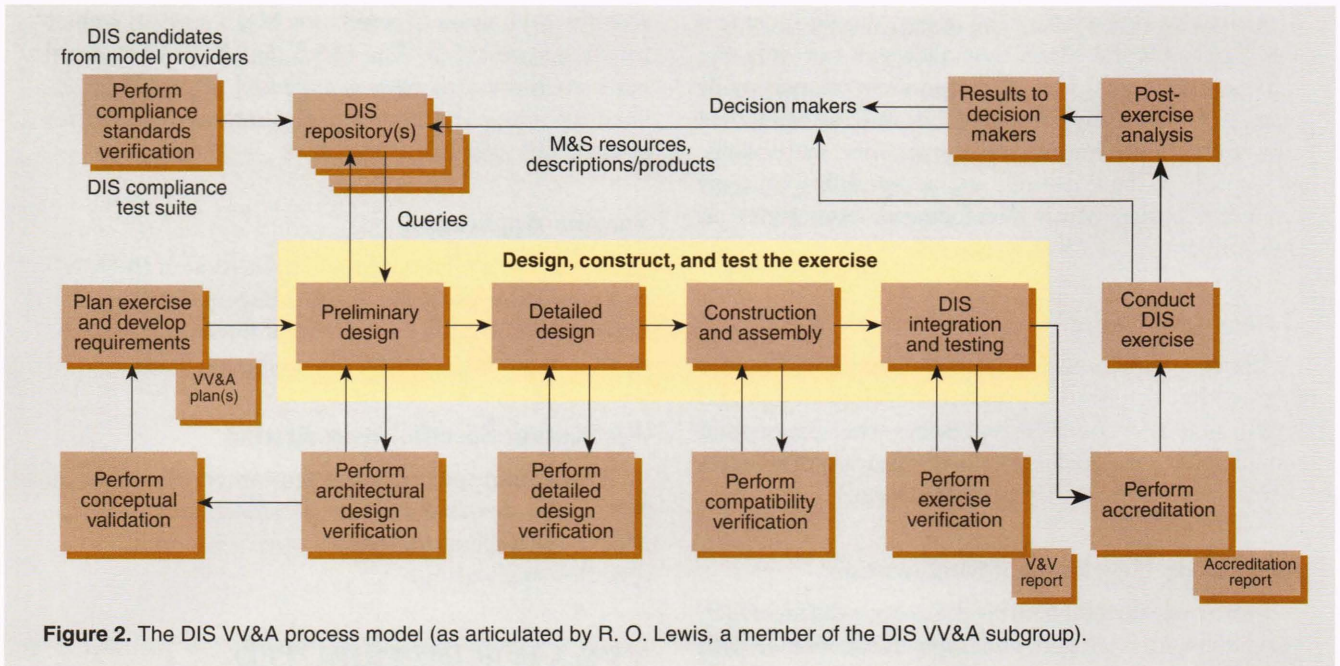
Figure 2. The DIS VV&A process model (as articulated by R. O. Lewis, a member of the DIS VV&A subgroup).

consensus agreement of the DIS VV&A subgroup and is discussed in the recommended practices documents being developed for DIS VV&A and exercise control. The VV&A process parallels the DIS exercise development process. Each simulation component in a DIS exercise is assumed to have undergone some level of VV&A, independent of a DIS exercise. The VV&A should be in accordance with the VV&A guidelines for the military service responsible for a particular M&S. Selected steps shown in Fig. 2 are described below.

Step 1: Develop VV&A plans. VV&A planning should begin in the earliest stages of DIS exercise development when exercise plans and associated exercise requirements are being produced. Such planning focuses on the type of systems that must be represented and levels of fidelity required. VV&A and testing plans should be conceptualized and drafted at this point so that the DIS exercise requirements can be validated.

Step 2: Perform compliance standards verification. At this stage, the live forces, the virtual forces in simulators, and the constructive forces in M&S proposed as DIS components are tested to verify that they can adequately communicate using the DIS protocol data units, called PDUs. Compliance with the DIS protocol standards ensures that the proposed DIS entity "talks the talk." A special challenge for some DIS exercises that involve substantial numbers of live forces is that all of the forces may not be assembled until the exercise actually commences.

Verification of compliance with DIS standards and protocols can occur before or during DIS exercise development. The Institute for Simulation in Training at the University of Central Florida, in association with the Army's STRICOM (Simulation, Training, and Instrumentation Command), has developed a compliance test suite to assist in testing for protocol compliance.

Step 3: Perform architectural design verification. This phase of VV&A is tied to development of the preliminary design or conceptual model for the DIS exercise. The conceptual model provides an initial "best guess" regarding a proposed configuration of DIS-compatible components that would satisfy the exercise requirements. Information contained in a yet-to-be-defined DIS M&S repository(s) regarding matters such as candidate DIS components, their associated component-level VV&A histories, and fidelity characteristics is expected to assist the process of making design decisions. The conceptual model/preliminary design is verified for correctness and completeness.

Step 4: Perform conceptual validation. During this phase the conceptual model, as defined in the previous step, is validated against the exercise requirements. Traceability of requirements to the conceptual model/ preliminary design is stressed. Steps 1 through 4 are iterated until a conceptual model that satisfactorily meets the required objectives is defined.

Step 5: Perform detailed design validation. In the detailed design phase, the preliminary design/conceptual model discussed in steps 3 and 4 is elaborated upon and expanded. Verification at this stage ensures that the detailed design is correct and complete and maintains traceability to the requirements.

Step 6: Perform compatibility verification. At this point the compatibility of the components within the DIS exercise configuration is verified.

Step 7: Perform exercise validation. This phase of the V&V process examines how well the DIS exercise configuration represents the behavior, appearance, performance, fidelity constraints, and interoperability levels for the intended application.

Step 8: Perform accreditation. The V&V effort conducted for the exercise is reviewed by the accrediting authority (i.e., exercise user/sponsor), and an accreditation decision for formal acceptance is made.

Step 9: Develop VV&A reports. Descriptions and results of the VV&A effort are documented and funneled to the DIS repository as evidence of VV&A activity and for potential use in follow-on or future DIS exercises.

V&V TECHNIQUES

Defense M&S may involve hardware, actual equipment, and personnel in addition to computer programs. Because consideration of V&V techniques for hardware and humans involved in M&S is beyond the scope of this article, those described here address only V&V for M&S computer programs. Some are common to general software V&V, whereas others are peculiar to M&S V&V. Although over 100 V&V techniques exist,[8] we present only major, general techniques.

Most software and M&S defects are detectable by a number of V&V techniques. No single technique is indispensable, but no single technique is likely to detect or prevent every possible M&S defect.

M&S that involve expert systems or other artificial intelligence techniques pose special V&V challenges. Although much attention is being given to techniques for testing and validating expert systems, little is yet possible beyond determining the internal consistency and logical completeness of rule sets used in expert systems.

In the past few years, we have seen an increased focus on proving the correctness of software for safety-critical systems or other applications where high assurance of software performance integrity is essential.[9] V&V, using techniques that produce mathematically proven software, is a process being pursed by many in this arena.[10]

M&S V&V is not an exact science. It is mainly judgment-based, even in relatively simple M&S. We describe briefly a variety of techniques pertinent to different elements of the VV&A paradigm presented in Fig. 1. (These techniques are typical of those in the 1993 Army Pamphlet 5-11 on M&S VV&A, the 1993 Navy Interim Policy Guidance on M&S VV&A, and, e.g., those presented in Ref. 11.) The names for some of the techniques appear more than once, but the exact application of the same-name technique is not always identical.

Conceptual Validation Methods

Face validation. Face validation is a subjective review by people knowledgeable about the system being modeled to determine if the prospective M&S and its expected behavior are reasonable for the intended application. This determination is based on the algorithms and architecture of the conceptual model.

Peer review. Closely related to face validation is the review of the M&S by knowledgeable agents, some of whom should be independent of the M&S development. Peer review has multiple purposes in conceptual validation. It can help ensure that the M&S sponsor/user agrees with the specific purposes for which the M&S is being developed (i.e., its intended applications).

Analysis of input–output relationships. Examination of input–output relationships serves numerous functions. The relationship between the fidelity and credibility of output data to those attributes of the input data can be addressed.

Logic trace analysis. Logic trace analysis involves a review of the expected behavior of specific entities as they are traced through the logic of the conceptual model. This technique involves examination and testing of the model's logic flow and its input–output relationships. In addition, logic trace involves tracking the behavior of selected entities logically and structurally through the M&S and its submodels to determine if the logic is correct relative to the real system modeled (if necessary realism of parameter values is expected to be maintained).

Architecture analysis. Architecture analysis involves consideration of the relationships among the various parts of the M&S and its submodels. Assessment of the significance of assumptions about dependencies (or independence) among the submodels and their processes is a critical element of conceptual model validation.

Algorithm review. The purpose of algorithm review is to determine that the algorithms of the M&S will have adequate fidelity and application robustness to satisfy the intended uses of the M&S; establish the scientific basis for the algorithms of the M&S by identifying any limitations associated with the algorithms as well as identifying any incompatible, inappropriate, or restrictive premises imbedded within the algorithms. Important elements of this review include specific identification of sources upon which the algorithm is based (including sensitivity studies related to the algorithm), identification of higher-fidelity elements of algorithms that will be lost in the M&S because they are not processed by other elements of the M&S, and specification of the accuracy or resolution capabilities of the individual algorithms and their combined use in the M&S.

Design Verification Methods

Mathematical proofs. This method employs mathematical and logic formalisms to test requirements specifications and M&S design definition. Relationships between data elements and processes are defined and contradictions identified.

Computer-aided software engineering (CASE) tools. This method employs automated CASE tools to aid in software development. Tools range from those providing design methodology support (developing specifications and designs) to those providing extensive program management assistance, including data dictionary and consistency-checking support functions.

Documentation review. This is a review primarily of the specification document, design documentation, and code to ensure that all of the requirements are addressed in an appropriate, complete, and balanced manner.

Design walk-throughs. This is a review, sometimes done by a group of peers not directly involved in the M&S development, of the design for the M&S. Documented design walk-throughs greatly aid the verification process because they represent a history of the evolution of the M&S design. Formal design walk-throughs with the model proponents or intended users are the quickest way to ensure that the design matches their expectations and requirements.

Flow diagram reviews. These are reviews of procedural flowcharts, top-down structured diagrams, pseudocode, data flow diagrams, or applicable object-oriented diagrams. Some of these materials are also used in design walk-throughs.

Code Verification Methods

Sensitivity analyses. This is a check of the algorithms and code to ensure that the M&S is reacting to varying sets of input in an expected, mathematical manner. These analyses must verify that the model is sensitive to those variables of interest that are to be considered when the model is used and include the following:

- Preparing and running tests with two or more sets of input data that differ in a predictable manner
- Preparing and running tests with boundary values to determine if the M&S produces consistent and logical results

Code walk-throughs. Code walk-throughs are usually conducted with members of the development team and involve detailed discussions about the implementation of the algorithms that make up the M&S. These walk-throughs are designed to ensure efficiency, correctness, and completeness in the implementation. They often serve as a forum for team members to discuss interfaces among code modules. Documented code walk-throughs

also serve as a historical record of changes in implementation. It is most important to capture the reason for changes, not just the changes alone.

CASE and automated test tools. The use of CASE and other automated tools assists conversion of logical process descriptions into computer-based methodologies. CASE tools are used commonly to aid the developer in creating user interfaces, reports, and tests for the M&S. Typically, they also have self-documenting features that help describe M&S features for code verification and other V&V efforts.

Stress testing. This is a method that tests how "userproof" the model is by designing a set of test data to ensure that normal data produce normal results and that boundary data produce acceptable results. Trying to "break" the M&S by testing the code at the extreme range of inputs will ensure a set of documented limitations. The results of the stress tests can also help the M&S developer decide if the boundary limits of the input data are acceptable.

Implementation (Results) Validation Methods

Face validation. Face validation is the process of determining whether M&S results seem reasonable to personnel who are knowledgeable about the system under study. This method applies the knowledge and understanding of experts in the field (subject to their biases), and can produce a consensus within the community by appropriate selection of the number and breadth of experts represented.

Comparisons. Results from accepted algorithms used in a similar application can be part of both structural and output validation when compared with results made by the M&S under examination. Direct comparisons of code, documentation, input data, and results are the primary techniques used. Comparison with data points resulting from another M&S implies that the resulting degree of fidelity for the new M&S is only as good as the M&S with which it is being compared. Results from acceptable M&S are not the "real world" but may be the best data available for comparison.

Functional decomposition and testing. Also known as piecewise validation, this method is generally used after model development. Decomposing the model into functional components is often a great aid in the validation process. In large, complex simulations, functional area decomposition provides a logical means of performing piecewise design, testing, and analysis to determine the degree of fidelity represented by functional areas of the M&S.

Peer review. Peer review is a validation method that involves conducting critical and detailed examinations of internal representations of data inputs, key parameters, and resulting output. It is used by personnel who

are knowledgeable about modeling the functional areas represented in the M&S.

Model-test-model (M-T-M). The M-T-M validation method has three phases: pretest modeling, testing, and posttest modeling. It involves the modeling of test conditions by an M&S, a comparison of M&S outputs with actual test results, and calibration or modification of the M&S to better represent the results. The method produces an M&S that is validated only for a specific situation.

SELECTED V&V ISSUES

The most challenging V&V issue is how to perform acceptable V&V affordably. Funding has been a very contentious topic in V&V discussions within the defense community. There are three keys to affordable V&V. First, V&V must start in the earliest possible phase of M&S development and be considered an integral part of M&S development and use, otherwise it becomes very expensive. The cost of correcting errors in software increases dramatically, as much as a hundred-fold, when faults are detected late in the development process.[8] Second, V&V must be prioritized so that V&V resources can be concentrated both on ensuring correctness of the more critical M&S aspects and on detection/correction of the most common and most detectable faults. Third, automation must be exploited fully to allow maximum V&V coverage for a given level of resource expenditures. For example, the use of CASE tools that allow executable code generation from graphical descriptions of M&S designs eliminates opportunity for a number of potential code implementation errors and reduces the amount of effort required for code verification.

It is sometimes forgotten that M&S are not an end in themselves. They are tools to support other purposes. The analogy of a three-legged stool is appropriate, the legs being the M&S, the data it uses, and the analysis (application) to which it is applied. Deficiency in any of the three legs can be troublesome. However, good analysts can overcome many data and M&S limitations. For example, if precise values for some parameters are not available, a combination of sensitivity and boundary condition analyses might provide adequate insight to solve some problems, even though the desired input data are not available. Unfortunately, even a perfect M&S with proper data cannot prevent inappropriate analysis or application. A continuing problem within the defense community, as elsewhere, is use of M&S for applications beyond their appropriate realms.

By their nature, some M&S are not capable of absolute validation. This does not mean that they have no appropriate uses. They may be helpful in developing an improved understanding of the subject being modeled as well as providing an effective mechanism for communicating insights about that subject.[12]

Software and M&S that are used in safety-critical systems must have a high assurance of performing correctly under all circumstances. Processes are being developed which allow mathematically proven performance of code. This development moves the primary focus of V&V from implementation in code to requirements and design. Unfortunately, these processes have limited use. Europe seems to be leading the United States and the rest of the world in education about these processes.[13] Continued development of such processes and broadening of their applicability hold great promise for M&S whose performance must be proven to be acceptable.

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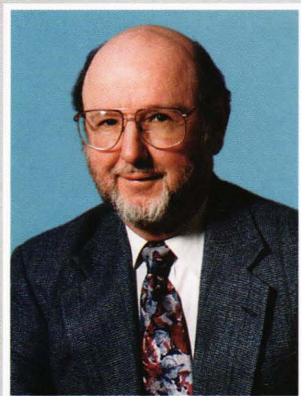
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