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VERIFICATION, VALIDATION AND ACCREDITATION OF SIMULATION MODELS

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ABSTRACT

This paper presents guidelines for conducting verification, validation and accreditation (VV&A) of simulation models. Fifteen guiding principles are introduced to help the researchers, practitioners and managers better comprehend what VV&A is all about. The VV&A activities are described in the modeling and simulation life cycle. A taxonomy of more than 77 V&V techniques is provided to assist simulationists in selecting proper approaches for conventional simulation model V&V. Another taxonomy of 38 V&V techniques is presented for object-oriented simulation models.

1. INTRODUCTION

Assuring total quality in a modeling and simulation (M&S) effort involves the measurement and assessment of a variety of quality characteristics such as accuracy, execution efficiency, maintainability, portability, reusability, and usability (human-computer interface). This paper is concerned only with the *accuracy* quality characteristic. Verification, validation, testing, accreditation, certification and credibility assessment activities primarily deal with the measurement and assessment of *accuracy* of models and simulations (M&S).

Model Verification is substantiating that the model is transformed from one form into another, as intended, with sufficient accuracy. Model verification deals with building the model *right*. The accuracy of transforming a problem formulation into a model specification or the accuracy of converting a model representation from a micro flowchart form into an executable computer program is evaluated in model verification.

Model Validation is substantiating that the model, within its domain of applicability, behaves with satisfactory accuracy consistent with the M&S objectives. Model validation deals with building the *right* model.

An activity of accuracy assessment can be labeled as verification or validation based on an answer to the following question: In assessing the accuracy, is the model behavior compared with respect to the corresponding system behavior through mental or computer execution? If the answer is "yes" then model validation is conducted; otherwise, it implies that the transformational accuracy is judged implying model verification.

Model Testing is ascertaining whether inaccuracies or errors exist in the model. In model testing, the model is subjected to test data or test cases to determine if it functions properly. "Test failed" implies the failure of the model, not the test. A test is devised and testing is conducted to perform either validation or verification or both. Some tests are devised to evaluate the behavioral accuracy (i.e., validity) of the model, and some tests are intended to judge the accuracy of model transformation from one form into another (verification). Sometimes, the whole process is called *model VV&T.*

Accreditation is "the official certification that a model or simulation is acceptable for use for a specific purpose." (DoD Directive 5000.59 http://triton.dmso.mil/docslib/mspolicy/directive.html).

The purpose of this paper is to present guidelines for conducting VV&A. Section 2 presents VV&A principles. Section 3 describes the VV&A activities in the M&S life cycle. Two taxonomies of V&V techniques are presented in Section 4. Concluding remarks are given in Section 5.

2. VV&A PRINCIPLES

According to the Webster's dictionary, a principle is defined as "1. an accepted or professed rule of action or conduct. 2. a fundamental, primary, or general law or truth from which others are derived. 3. a fundamental doctrine or tenet; a distinctive ruling opinion." All three definitions above apply to the way the term "principle" is used herein.

Principles are important to understand the foundations of VV&A. The principles help the researchers, practitioners and managers better comprehend what VV&A is all about. They serve to provide the underpinnings for over 77 V&V techniques for conventional simulation models and 38 V&V techniques for object-oriented simulation models presented in Section 4. Understanding and applying these principles is crucially important for the success of a M&S effort.

The fifteen principles presented herein are established based on the experience described in the published literature and the author's experience during his V&V research since 1978. The principles are listed in Table 1 in no particular order. For detailed descriptions of these principles, please see (Balci 1997; DoD 1996).

3. VV&A IN THE M&S LIFE CYCLE

VV&A activities in the M&S life cycle are depicted in Figure 1 (DoD 1996, p. 3-18). For another description of V&V activities throughout the M&S life cycle, see (Balci 1997).

V&V is not a phase or step in the M&S life cycle, but a continuous activity throughout the entire life cycle as enunciated by Principle 1 in Table 1. The life cycle should not be interpreted as strictly sequential. The sequential representation of some arrows is intended to show the direction of development throughout the life cycle. The life cycle is iterative in nature and reverse transitions are expected. Deficiencies identified by a VV&A activity may necessitate returning to an earlier process and starting all over again.

Conducting V&V for the first time in the life cycle when the M&S application is complete is analogous to the teacher who gives only a final examination (Hetzel 1984). No opportunity is provided throughout the semester to notify the student that he or she has serious deficiencies. Severe problems may go undetected until it is too late to do anything but fail the student. Frequent tests and homeworks throughout the semester are intended to inform the students about their deficiencies so that they can study more to improve their knowledge as the course progresses.

The situation in conducting V&V is exactly analogous. The VV&A activities throughout the entire M&S life cycle, shown in Figure 1, are intended to reveal any quality deficiencies that might be present as the M&S progresses from the problem definition to the completion of the M&S application. This allows us to identify and rectify quality deficiencies during the life cycle phase in which they occur.

As enunciated by Principle 10 in Table 1, errors should be detected as early as possible in the M&S life cycle. Delaying V&V to later stages in the life cycle increases the probability of committing Type I & II errors (Balci 1997; Balci et al. 1996).

Table 1: Principles of VV&A

1	V&V must be conducted throughout the entire M&S life cycle.
2	The outcome of VV&A should not be considered as a binary variable where the model or simulation is absolutely correct or absolutely incorrect.
3	A simulation model is built with respect to the M&S objectives and its credibility is judged with respect to those objectives.
4	V&V requires independence to prevent developer's bias.
5	VV&A is difficult and requires creativity and insight.
6	Credibility can be claimed only for the prescribed conditions for which the model or simulation is verified, validated and accredited.
7	Complete simulation model testing is not possible.
8	VV&A must be planned and documented.
9	Type I, II and III errors must be prevented.
10	Errors should be detected as early as possible in the M&S life cycle.
11	Multiple response problem must be recognized and resolved properly.
12	Successfully testing each submodel (module) does not imply overall model credibility.
13	Double validation problem must be recognized and resolved properly.
14	Simulation model validity does not guarantee the credibility and acceptability of simulation results.
15	A well-formulated problem is essential to the acceptability and accreditation of M&S results.

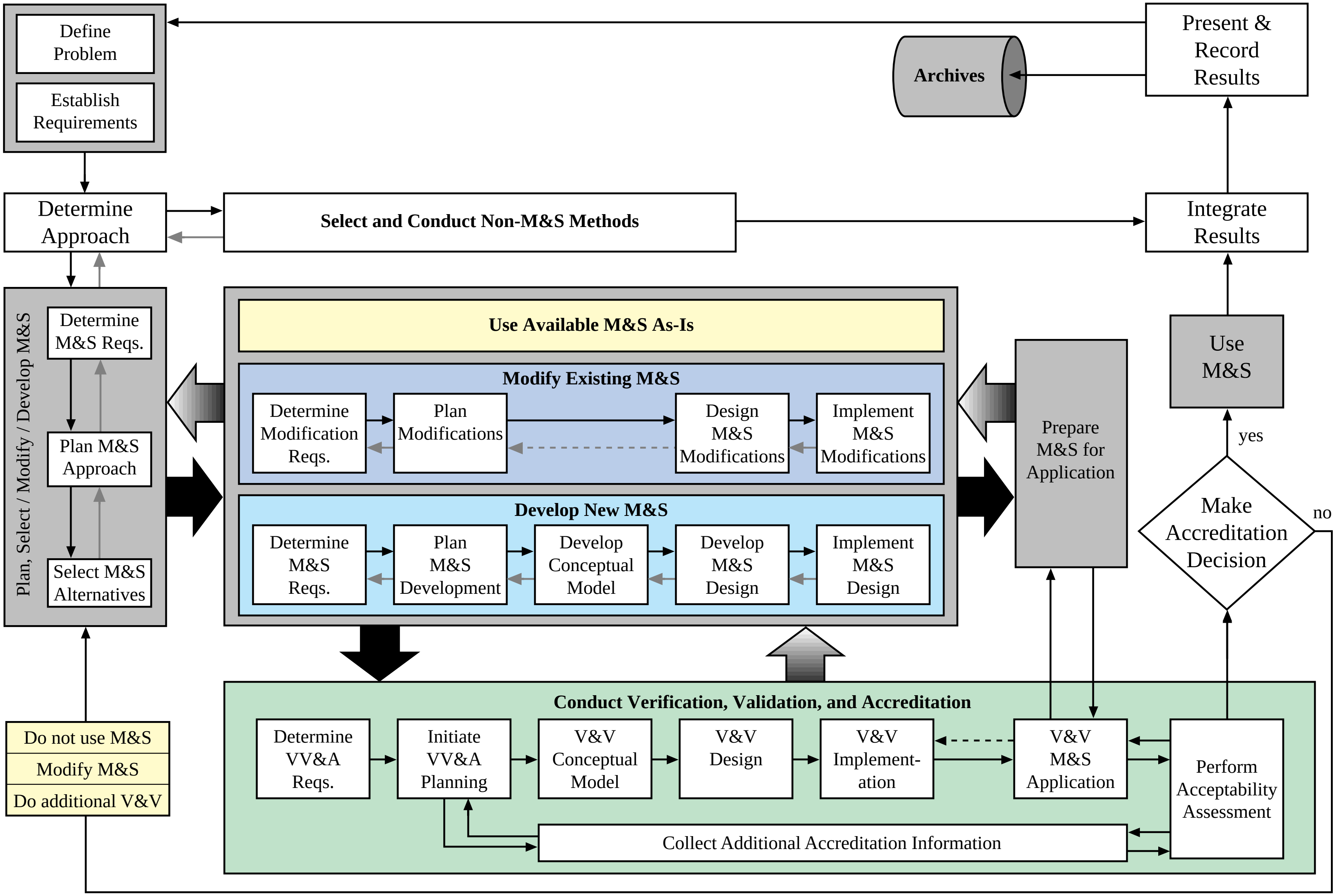

Figure 1: VV&A in the M&S Life Cycle (DoD 1996, p. 3-18)

4. V&V TECHNIQUES

V&V techniques are introduced in this section for conventional and object-oriented simulation models.

4.1 V&V Techniques for Conventional Simulation Models

A taxonomy of more than 77 V&V techniques for conventional simulation models is presented in Figure 2. Most of these techniques come from the software engineering discipline and the remaining are specific to the modeling and simulation field. Detailed descriptions of these techniques can be found in (Balci 1997; DoD 1996; Balci et al. 1996).

The taxonomy in Figure 2 classifies the V&V techniques into four primary categories: informal, static, dynamic, and formal. A primary category is further divided into secondary categories as shown in italics. The use of mathematical and logic formalism by the techniques in each primary category increases from informal to formal from left to right. Likewise, the complexity also increases as the primary category becomes more formal.

It should be noted that some of the categories presented in Figure 2 possess similar characteristics and in fact have techniques which overlap from one category to another. However, a distinct difference between each classification exists.

Informal techniques are among the most commonly used. They are called informal because the tools and approaches used rely heavily on human reasoning and subjectivity without stringent mathematical formalism. The “informal” label does not imply any lack of structure or formal guidelines for the use of the techniques. In fact, these techniques are applied using well structured approaches under formal guidelines and they can be very effective if employed properly.

Static techniques are concerned with accuracy assessment on the basis of characteristics of the static model design and source code. Static techniques do not require machine execution of the model, but mental execution can be used. The techniques are very popular and widely used, with many automated tools available to assist in the V&V process. The simulation language compiler is itself a static V&V tool. These techniques can obtain a variety of information about the structure of the model, modeling techniques and practices employed, data and control flow within the model, and syntactical accuracy. (Whitner and Balci 1989)

Dynamic techniques require model execution and are intended for evaluating the model based on its execution behavior. Most dynamic V&V techniques require model instrumentation.

The insertion of additional code (probes or stubs) into the executable model for the purpose of collecting information about model behavior during execution is called *model instrumentation*. Probe locations are determined manually or automatically based on static analysis of model structure. Automated instrumentation is accomplished by a preprocessor which analyzes the model static structure (usually via graph-based analysis) and inserts probes at appropriate places.

Dynamic V&V techniques are usually applied using the following three steps. In Step 1, the executable model is instrumented. In Step 2, the instrumented model is executed and in Step 3, the model output is analyzed and dynamic model behavior is evaluated.

Formal techniques are based on mathematical proof of correctness. If attainable, proof of correctness is the most effective means of model V&V. Unfortunately, “if attainable” is the overriding point with regard to formal V&V techniques. Current state-of-the-art proof of correctness techniques are simply not capable of being applied to even a reasonably complex simulation model. However, formal techniques serve as the foundation for other V&V techniques.

4.2 V&V Techniques for Object-Oriented Simulation Models

The object-oriented paradigm (OOP) provides numerous advantages such as maintainability and reusability over the procedural paradigm. However, model accuracy assessment, which is a very difficult task under the procedural paradigm, is made even more difficult under the OOP. The OOP introduces new complexities and challenges for the process of V&V. The dynamic and diverse patterns of interactions among groups of objects, nonsequential representation, the partition of the model structure in inheritance and aggregation relationships, and the incremental and iterative nature of model development all contribute to making the V&V a very challenging process. A taxonomy of 38 V&V techniques for object-oriented simulation models is presented in Figure 3 (Yilmaz and Balci 1997). These techniques come from the software engineering discipline and are applicable for object-oriented simulation model V&V.

Conventional techniques refer to the techniques in the taxonomy of Figure 2, and are used for V&V of object-oriented simulation models without any adaptation or extension for OOP. In particular, these techniques are applicable for method level testing since the methods of classes are actually functions and procedures that use imperative language constructs. (Yilmaz and Balci 1997) *Adaptive techniques* refer to those procedural V&V techniques that can be used in a new way by adapting or extending to include object-orientation. (Yilmaz and Balci 1997)

V&V Techniques for Simulation Models

Informal

- Audit
- Desk Checking
- Documentation Checking
- Face Validation
- Inspections
- Reviews
- Turing Test
- Walkthroughs

Static

- Cause-Effect Graphing
- *Control Analysis*
  - Calling Structure Analysis
  - Concurrent Process Analysis
  - Control Flow Analysis
  - State Transition Analysis
- *Data Analysis*
  - Data Dependency Analysis
  - Data Flow Analysis
- Fault/Failure Analysis
- *Interface Analysis*
  - Model Interface Analysis
  - User Interface Analysis
- Semantic Analysis
- Structural Analysis
- Symbolic Evaluation
- Syntax Analysis
- Traceability Assessment

Dynamic

- Acceptance Testing
- Alpha Testing
- Assertion Checking
- Beta Testing
- Bottom-Up Testing
- Comparison Testing
- *Compliance Testing*
  - Authorization Testing
  - Performance Testing
  - Security Testing
  - Standards Testing
- Debugging
- *Execution Testing*
  - Execution Monitoring
  - Execution Profiling
  - Execution Tracing
- Fault/Failure Insertion Testing
- Field Testing
- Functional (Black-Box)Testing
- Graphical Comparisons
- *Interface Testing*
  - Data Interface Testing
  - Model Interface Testing
  - User Interface Testing
- Object-Flow Testing
- Partition Testing
- Predictive Validation
- Product Testing
- Regression Testing
- Sensitivity Analysis
- *Special Input Testing*
  - Boundary Value Testing
  - Equivalence Partitioning Testing
  - Extreme Input Testing
  - Invalid Input Testing
  - Real-Time Input Testing
  - Self-Driven Input Testing
  - Stress Testing
  - Trace-Driven Input Testing
- *Statistical Techniques*
- *Structural (White-Box)Testing*
  - Branch Testing
  - Condition Testing
  - Data Flow Testing
  - Loop Testing
  - Path Testing
  - Statement Testing
- Submodel/Module Testing
- Symbolic Debugging
- Top-Down Testing
- Visualization/Animation

Formal

- Induction
- Inductive Assertions
- Inference
- Lambda Calculus
- Logical Deduction
- Predicate Calculus
- Predicate Transformation
- Proof of Correctness

Figure 2: A Taxonomy of Verification and Validation Techniques for Conventional Simulation Models

V&V Techniques for Object-Oriented Simulation Models

Conventional

Adaptive

- Adequacy Criteria-Based Testing
- Class Testing by Pointer Examination
- *Data Flow Testing*
  - Flow Graph-Based Class Testing
  - Hierarchical Data Flow Testing
  - Intra-Class Data Flow Testing
- Domain Dependent Testing
- Extended Data-Flow Analysis
- Fault-Based Testing
- Hypothesis-Based Testing
- Modal-Based Testing
- *Three-View Model Testing*
  - Object Model Testing
  - Functional Model Testing
  - Dynamic Model Testing

Specific

- *Algebraic Specification-Based Testing*
  - ASTOOT Testing Strategy
  - DAISTISH Testing Strategy
  - DAISTS Testing Strategy
- Class Firewall Technique
- Component Certification Technique
- Flattened Regular Expression Testing Technique (FREE Approach)
- *FOOT Testing Strategy*
  - Identity Method
  - Set and Examine Method
  - Inheritance Method
- *Inheritance Testing*
  - Hierarchical Incremental Testing
  - Repeated Inheritance Testing
- *Integration Testing*
  - Composition-Based Integration Testing
  - Incremental Integration Testing
  - Interaction Testing
  - Object-Integration Testing
  - Propagation-Based Integration Testing
  - Wave Front Integration Testing
- Method Sequence Testing
- Modifier Sequence Testing
- Modular Type/Subtype Verification
- PACT Strategy for Component Testing
- *State Testing*
  - State-Based Functional Testing
  - State-Based Testing
  - Object State Testing
  - Graph-Based Class Testing

Figure 3: A Taxonomy of Verification and Validation Techniques for Object-Oriented Simulation Models

Specific techniques are the new techniques created based on object-oriented formalisms and are intended for the sole purpose of object-oriented software V&V that can also be used for object-oriented simulation model V&V. (Yilmaz and Balci 1997)

5. CONCLUDING REMARKS

The life cycle application of V&V is extremely important for successful completion of complex and large-scale M&S efforts. This point must be clearly understood by the sponsor of the M&S effort and the organization conducting the M&S. The sponsor must furnish funds under the contractual agreement and require the contractor to apply V&V *throughout* the entire M&S life cycle.

Assessing credibility throughout the life cycle is an onerous task. Applying the V&V techniques throughout the life cycle is time consuming and costly. In practice, under time pressure to complete a M&S effort, the V&V and documentation are sacrificed first. Computer-aided assistance for credibility assessment is required to alleviate these problems. More research is needed to bring automation to the application of V&V techniques.

The question of which of the applicable V&V techniques should be selected for a particular V&V activity in the life cycle should be answered by taking the following into consideration: (a) model type, (b) simulation type,

(c) problem domain, and (d) M&S objectives.

How much to test or when to stop testing depends on the M&S objectives. The testing should continue until sufficient confidence is achieved in credibility and acceptability of M&S results. The sufficiency of the confidence is dictated by the M&S objectives.

Establishing a simulation quality assurance (SQA) program within the organization conducting the M&S effort is extremely important for successful credibility assessment. The SQA management structure goes beyond V&V and is also responsible for assessing other model quality characteristics such as maintainability, reusability, and usability (human-computer interface). The management of the SQA program and the management of the simulation project must be independent of each other and neither should be able to overrule the other.

Subjectivity is, and will always be, part of the credibility assessment for a reasonably complex simulation study. The reason for subjectivity is two-fold: modeling is an art and credibility assessment is situation dependent.

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