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AN INTRODUCTION TO VERIFICATION AND VALIDATION OF SIMULATION MODELS

Robert G. Sargent

Department of Electrical Engineering and Computer Science
L.C. Smith College of Engineering and Computer Science
Syracuse University
Syracuse, NY 13244, USA

ABSTRACT

Model verification and validation are defined, and why model verification and validation are important is discussed. The three approaches to deciding model validity are described. A graphical paradigm that shows how verification and validation are related to the model development process and a flowchart that shows how verification and validation is part of the model development process are presented and discussed. A recommended procedure for verification and validation is given.

1 INTRODUCTION

An introduction to verification and validation of simulation models is given in this paper. Verification and validation are concerned with determining whether a model and its results are "correct" for a specific use or purpose. Formally, model verification is defined as "ensuring that the computer program of the computerized model and its implementation are correct" and model validation is defined as the "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model." Our discussion of verification and validation of simulation models will be primarily concerned with simulation models that are used to predict system behaviors such as systems outputs. Two related topics are model credibility and model usability. Model credibility is concerned with developing in (potential) users the confidence they require in order to use a model and in the information derived from that model. Model usability is determining that the model and its user instructions are easy to use.

It is important that verification and validation of a simulation model be performed for each use or purpose of a model. If the purpose of a simulation model is to answer a variety of questions, the validity of the model needs to be determined with respect to each question. The developers and users of simulation models, the decision makers using information obtained from the results of these models, and the individuals affected by decisions based on such models are all rightly concerned with whether a model and its results are "correct" for each question being addressed.

Numerous sets of experimental conditions are usually required to define the domain of a model's intended applicability. (A set of experimental conditions contain a set of values for the set of variables that define the domain of applicability.) A model may be valid for one set of experimental conditions and invalid in another. A model is considered valid for a set of experimental conditions if the model's accuracy is within its *acceptable range of accuracy*, which is the accuracy required of the model for its intended purpose. This usually requires that the model's output variables of interest (i.e., the model variables used in answering the questions that the model is being developed to answer) be identified and then their acceptable range of accuracy specified. A model's acceptable range of accuracy should be specified prior to starting the development of the model or very early in the model development process. If the variables of

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interest are random variables, then properties and functions of the random variables such as means and variances are usually what is of primary interest and are what is used in determining model validity. Several versions of a model are usually developed prior to obtaining a satisfactory valid model. The substantiation that a model is valid, i.e., performing model verification and validation, is generally considered to be a process and is usually part of the (total) model development process.

The remainder of the paper is organized as follows: Section 2 presents the three decision-making approaches to deciding model validity, Section 3 describes how verification and validation relate to the model development process, Section 4 gives a recommended validation procedure, and Section 5 contains the summary.

2 DECISION-MAKING APPROACHES

There are three basic decision-making approaches for deciding whether a simulation model is valid. Each of these three approaches uses a different decision-maker. All of the approaches require the model development team to conduct verification and validation as part of the model development process, which is discussed in Section 3. One decision-making approach, and a frequently used one, is for the model development team itself to make the decision as to whether a simulation model is valid. The decision is based on the results of the various tests and evaluations conducted as part of the model development process. It is usually better, however, to use one of the next two decision-making approaches, depending on which situation applies.

A better decision-making approach is to have the user(s) of a simulation model decide the validity of the model. In this approach the users of the simulation model are heavily involved with the model development team when the team is conducting verification and validation of the model and the users determine if the model is satisfactory in each phase of verification and validation. This approach is generally used with a model development team whose size is not large. Also, this approach aids in model credibility.

Another decision-making approach, usually called "independent verification and validation" (IV&V), uses a third party to decide whether the simulation model is valid. The third party (the IV&V team) is independent of both the simulation development team(s) and the model sponsor/user(s). The IV&V approach is generally used with the development of large-scale simulation models, whose development usually involves several teams. The IV&V team needs to have a *thorough* understanding of the intended purpose(s) of the simulation model in order to conduct IV&V. There are two common ways that the IV&V team conducts IV&V: (a) IV&V is conducted concurrently with the development of the simulation model and (b) IV&V is conducted after the simulation model has been developed.

In the concurrent way of conducting IV&V, the model development team(s) gives their model verification and validation test results to the IV&V team as the simulation model is being developed. The IV&V team evaluates these results and provides feedback to the model development team regarding whether the model verification and validation is satisfying the model requirements and when not, what the difficulties are. When conducting IV&V this way, the development of a simulation model should not progress to the next stage of development until the model has satisfied the verification and validation requirements in its current stage. It is the author's opinion that this is the better of the two ways to conduct IV&V.

When IV&V is conducted after the simulation model has been completely developed, the evaluation performed by the IV&V team can range from simply evaluating the verification and validation conducted by the model development team to performing a separate thorough verification and validation effort themselves. Performing a complete IV&V effort after the model has been completely developed is usually both extremely costly and time consuming. This author's view is that if IV&V is going to be conducted on a completed simulation model then it is usually best to *only* evaluate the verification and validation that has already been performed.

The IV&V approach is also useful for model credibility. When verification and validation is conducted by an independent (third) party and they conclude the simulation model is valid, there is a much greater likelihood that others will accept the model as valid and results from the model as being "correct". Cases where this decision-making approach is helpful are (i) when the problem associated with the model has a high cost or involves a high risk situation and (ii) when public acceptance of results based on the model is desired.

3 MODEL DEVELOPMENT PROCESS WITH VERIFICATION AND VALIDATION

In this section a graphical paradigm is presented in subsection 3.1 that relates model verification and validation to the model development process. Then in subsection 3.2 the model development process is described that includes verification and validation.

3.1 A Simple Graphical Paradigm

There are two common ways to view how verification and validation relate to the model development process. One way uses a simple view and the other uses a complex view. A simple graphical paradigm is presented in Figure 1 that was developed by this author called the Simplified View of the Model Development Process (Sargent 1981, 1982, 1983, 2001, 2011, 2013). A more complex paradigm developed by this author that includes both the "Simulation World" and the "Real World" is contained in Sargent (2001, 2013).

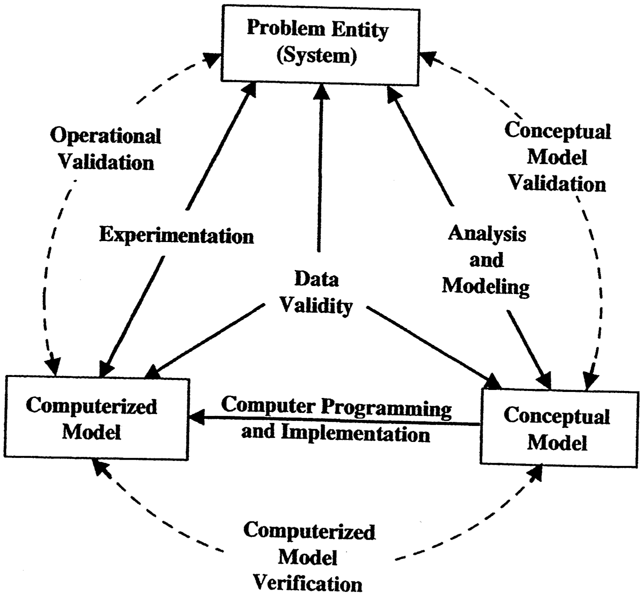

Figure 1: Simplified version of the model development process.

Consider the simplified version of the model development process in Figure 1. The *problem entity* is the system (real or proposed), idea, situation, policy, or phenomena to be modeled; the *conceptual model* is the mathematical/logical/graphical representation (mimic) of the problem entity developed for a particular study; and the *computerized model* is the conceptual model implemented on a computer. The conceptual model is developed through an *analysis and modeling phase*, the computerized model is developed through a *computer programming and implementation phase*, and inferences about the problem entity are obtained by conducting computer experiments on the computerized model in the *experimentation phase*.

We now relate model verification and validation to this simplified version of the model development process. (See Figure 1.) *Conceptual model validation* is defined as determining that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is "reasonable" for the intended purpose of the model. *Computerized model verification* is defined as assuring that the computer programming and implementation of the conceptual model are correct. *Operational validation* is defined as determining that the model's output behavior has a satisfactory range of accuracy for the model's intended purpose over the domain of the model's intended applicability. *Data validity* is defined as ensuring that the data necessary for model building, model evaluation and testing, and conducting the model experiments to solve the problem are adequate and correct.

3.2 Model Development Process

A model should be developed for a specific purpose or use. Furthermore, a model should be developed such that it is a parsimonious model meaning that it is as simple as possible yet meets its purpose. A simulation model is a structural model meaning that the model contains logical and causal relationships that occur in the systems. (Note: Empirical models are developed purely from data with an example being a regression model. Empirical and structural models are two different types of models.) Developing a valid simulation model is an iterative process where several versions of a model are developed prior to obtaining a valid model.

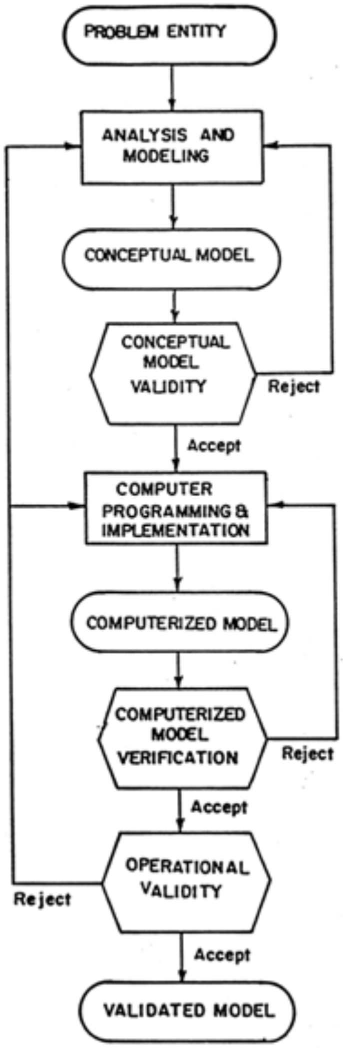

Figure 2: The model development iterative process.

The model development process should include model verification and validation. Following the paradigm given in Figure 1, the iterative process shown in Figure 2 can be used to develop a valid simulation model (Sargent 1984). We first develop a conceptual model through analyzing the problem entity and then developing a model of the problem entity, remembering that a parsimonious model is desired. Then conceptual model validation is performed. This process is repeated until the conceptual model is satisfactory. Next a computerized model is developed of the (validated) conceptual model by developing a simulation model of the conceptual model and implementing it on a computer. Then computerized model verification is performed. This process is repeated until the computerized model is satisfactory. Lastly, operational validation is performed on the computerized model. Model changes required by conducting operational validity can be in either the conceptual model or in the computerized model. Verification and validation must be performed again when any model change is made. This process is repeated until a valid simulation model is obtained. As stated above, several versions of a model are usually developed prior to obtaining a valid simulation model. (The specifics for conducting conceptual model validation, computerized model verification, and operational validity are discussed in, e.g., Sargent (1984, 2011, 2013).)

It is often too costly and time consuming to determine that a model is *absolutely* valid over the complete domain of its intended applicability. Instead, tests and evaluations are conducted until sufficient confidence is obtained that a model can be considered valid for its intended purpose or use (Sargent 1982, 1984). If a test determines that a model does not have sufficient accuracy for any one of the sets of experimental conditions, then the model is invalid. However, determining that a model has sufficient accuracy for numerous sets of experimental conditions does *not guarantee* that a model is valid everywhere in its applicable domain. Figure 3 contains two relationship curves regarding confidence that a model is valid (Confidence in Model) over the range of 0-100 percent as they would occur in most cases. (Note that these curves are qualitative conceptual curves and that they cannot be quantitatively calculated.) The cost curve (and a similar relationship holds for the amount of time) of performing model validation shows cost increases at an increasing rate as the confidence in the model increases. The value curve shows that the value of a model to a user increases as the confidence in a model increases but at a decreasing rate. (In some cases these curves may have a different shape for the lower confidence range but would usually be similar to what is shown in Figure 3 for the upper confidence range.) The cost of model validation is usually quite significant, especially when extremely high model confidence is required.

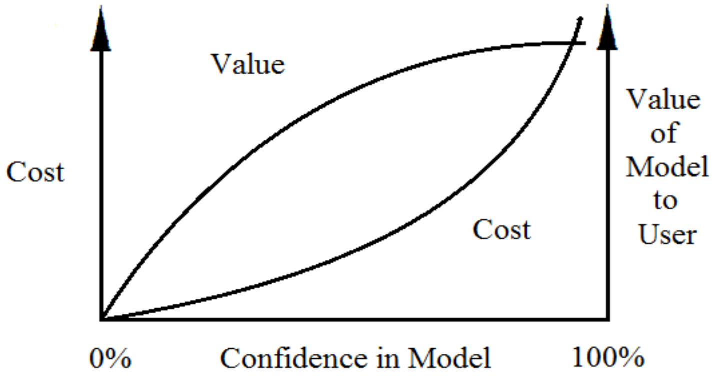

Figure 3: Confidence that model is valid.

4 RECOMMENDED PROCEDURE

This author recommends that the following eight steps be performed in model verification and validation:

1. An agreement be made prior to developing the model between (a) the model development team and (b) the model sponsors and (if possible) the users that specifies the decision-making approach and a minimum set of specific validation techniques to be used in determining model validity.
2. Specify the acceptable range of accuracy required of the simulation model's output variables of interest for the model's intended application prior to starting the development of the model or very early in the model development process.
3. Test, wherever possible, the assumptions and theories underlying the simulation model.
4. In each model iteration, perform at least face validity on the conceptual model.
5. In each model iteration, at least explore the simulation model's behavior using the computerized model.
6. In at least the last model iteration, make comparisons, if possible, between the simulation model and system behavior (output) data for at least a few sets of experimental conditions, and preferably for several sets.
7. Prepare the verification and validation documentation for inclusion in the simulation model documentation.
8. If the simulation model is to be used over a period of time, develop a schedule for periodic review of the model's validity.

Note: Discussions of the various validation techniques and model documentation can be found in, e.g., Sargent (1984, 2011, 2013).

Some simulation models are developed for repeated use. A procedure for reviewing the validity of these models over their life cycles needs to be developed, as specified in Step 8. No general procedure can be given because each situation is different. For example, if no data were available on the system when a simulation model was initially developed and validated, then revalidation of the model should take place prior to each usage of the model if new data or system understanding has occurred since the last validation.

5 SUMMARY

Model verification and validation are critical in the development of a simulation model because a model and its results need to be "correct." Every simulation project presents a new and unique challenge regarding model verification and validation. This introduction to verification and validation presented what it is, why it is important, who the decision-maker is, how it relates to the model development process through the use of a graphical paradigm and a flow chart, and a procedure for performing it. The specifics on how to do the verification and validation tests and evaluations can be found in, e.g., Sargent (2011, 2013).

There is considerable literature on model verification and validation. There are conference tutorials and papers (e.g., Sargent (2011)), journal articles (e.g., Gass (1983), Landry, Malouin, and Oral (1983), Sargent (2013)), discussions in textbooks (e.g., Banks et al. (2010), Law (2007), Robinson (2004), Zeigler, B. P., H. Praehofer, and T. G. Kim (2000)), U.S.A. Government Reports (e.g., DoDI 5000.61 (2009) and U. S. General Accounting Office (1987)), and books (Knepell and Arangno 1993, Oberkampf and Roy 2010) that can be used to further your knowledge on model verification and validation.

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AUTHOR BIOGRAPHY

ROBERT G. SARGENT is a Professor Emeritus of Syracuse University. He received his education at The University of Michigan. Dr. Sargent has served his profession in numerous ways including being the General Chair of the 1977 Winter Simulation Conference (WSC), serving on the WSC Board of Directors for ten years and chairing the Board for two years, being a Department Editor for the *Communications of the ACM*, holding the Presidency and other offices of what is now the INFORMS Simulation Society, serving as Founding President of the WSC Foundation, and initiating the founding of the Simulation Archive. He has received several awards and honors for his professional contributions including the INFORMS Simulation Society’s Lifetime Professional Achievement Award and their Distinguished Service Award, a WSC 40th anniversary landmark paper award, the WSC Wilson Award, ACM SIGSIM Distinguished Contributions Award, service awards from ACM and IIE, and a Fellow of INFORMS and of AAAS. His current research interests include the methodology areas of modeling and of simulation, model validation, and performance evaluation. Professor Sargent has published extensively and is listed in Who’s Who in America and in Who’s Who in the World. His e-mail is rsargent@syr.edu.