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HISTORY OF VERIFICATION AND VALIDATION OF SIMULATION MODELS

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ABSTRACT

This paper gives the history of verification and validation of discrete-event simulation models as seen through the eyes of its authors and their experiences. The history is divided into three time periods: the early era covering years up to 1970, the awareness era covering the years of the 1970s and 1980s, and the modern era covering the years of 1990 to the present.

1 INTRODUCTION

This paper about the history of Verification and Validation (V&V) of discrete-event simulation models is written by Robert G. Sargent (RGS) and Osman Balci (OB) largely based on their many years of working in this field. RGS started work in the area of V&V of computer-based models in the 1970s as part of his research work for Rome Air Development Center (RADC) of the U.S. Air Force. One item of continued usage that came out of RGS's V&V research for RADC is the well-known "Simplified Version of the Model Development Process" diagram and its associated V&V processes (Sargent 1981, 1984, 2013). RGS's V&V work over the years has been primarily involved with developing validation techniques and methods, developing V&V processes, and giving V&V tutorials. OB's work in V&V began with his Ph.D. work under RGS in the late 1970s resulting in his Ph.D. dissertation (Balci 1981) on the validation of multivariate response simulation models. He joined the computer science faculty of Virginia Tech on the completion of his Ph.D. His continued work in V&V includes developing techniques and processes for verification, validation, and assessment of simulation models, and giving V&V tutorials. Most of his V&V research work has been sponsored by the U.S. Department of Defense (DoD) and NASA.

The definitions of V&V have been inconsistent over time. We give here the definitions that have commonly been used since the late 1980s and are used in this paper. While the specific wordings for the definitions of V&V have varied; general definitions are "verification is concerned with ensuring the programmed model behaves as the users believe it does" and "validation is concerned with whether the model adequately represents a system for the model's purpose".

There are different bibliographies for V&V. Analyzing the 1980 Bibliography on Validation of Simulation Models (Balci and Sargent 1980), we find 22 publications up to 1970, 62 publications for 1970–1975, and 41 publications for 1976–1980 giving a total of 125 papers. Analyzing the 1984 Bibliography on the Credibility, Assessment, and Validation of Simulation and Mathematical Models (Balci and Sargent 1984b), we find that it contains 308 publications with 21 publications up to 1970, 164 publications for 1970–1979, and 123 publications for 1980–1984. Analyzing a 1996 version of the on-line V&V bibliography that OB maintained during the mid-1990s, we find 6 publications up to 1970, 91 publications in the 1970s, 216 publications in the 1980s, and 200 publications for 1990–1996 giving a total of 513 papers. We note that this latter bibliography had both methodology and application papers and is no longer on-line. See Table 1 for a summary view of the paper counts for each bibliography by decade. We

observe from these three bibliographies that V&V had little activity prior to 1970 and much activity starting in the 1970s. Furthermore, most of the methodology papers were regarding validation and processes for V&V, and almost none on verification.

Table 1: Breakdown of bibliographies count by decade.

Bibliography	Prior 1970	1970s	1980s	1990s	Total
1980	22	62 + 41 = 103			125
1984	21	164	123		308
1996	6	91	216	200	513

The remainder of this paper is organized into four sections. The next three sections discuss different eras of V&V of simulation models: first, the early era up to 1970; next, the awareness era of the 1970s and 1980s; and then the modern era from 1990 to the present. Concluding remarks are given in the last section.

2 THE EARLY ERA: YEARS UP TO 1970

There was general agreement from the very early years of operations research (OR) that an OR project should consist of six phases (Churchman, Ackoff, and Arnoff 1957). The fourth phase was testing the model and the solution derived from it. This is basically doing model validation. Thus, model validation was a concern from the beginning of OR in the 1940s. Verification was not an issue in the very early years of OR because digital computers had not yet come into usage and thus there were no computer-based models.

Discrete-event simulation started with the availability of digital computers in the 1950s. Developers of simulation models should be concerned with V&V of their simulation models. Initially, V&V were rarely addressed or written about in a simulation study. When V&V were discussed, there were not clear usages of the two terms. The usages of V&V were sometimes interchanged resulting in opposite meanings of V&V, often only one of the terms was used to cover both meanings, and sometimes other terminology was used. This continued throughout the early era. Most of the papers in the Proceedings of the 1968 and 1969 simulation conference, which is now called the Winter Simulation Conference (WSC), were reviewed and found to be mainly application papers and almost none of them mentioned V&V. If V&V were discussed, the terms, if used, were usually not used as we use the terms today; see, e.g., the application papers by Hixson (1969) and Barker and Watson (1969). Most of the few papers written on the methodology of V&V of simulation models during the early era had the same problem with the usage of V&V terms as the simulation application papers. One example is the well known paper of Naylor and Finger (1967) whose title was "Verification of Computer Simulation Models" and the content discussed various validation methods and techniques.

There were a few important papers that discussed V&V during the early era. The Fishman and Kiviat (1968) paper, which discussed simulation statistics, was perhaps the first paper that contained clear definitions of V&V that are essentially the V&V definitions used today; namely, "verification determines whether a model with a particular mathematical structure and data base actually behaves as an experimenter assumes it does" and "validation tests whether a simulation model reasonably approximates a real system". Furthermore, Fishman and Kiviat stated that "V&V insure that a simulation model is properly designed; only after a model has been verified and validated can an experimenter justifiably use a model to probe system behavior." They did not discuss how to do V&V, only that it is necessary to do V&V.

An important extremely early simulation paper was "Some Problems of Digital Systems Simulation" by Conway, Johnson, and Maxwell (1959). This paper had three sections: common characteristics of

system simulations, problems in construction of a digital simulator, and problems in the use of a simulator. Validation was discussed as a problem in the use of a simulator and the paper stated that some assurance of validity should be provided whereas verification was not mentioned among the many problems discussed regarding the construction of a simulator.

Thomas H. Naylor, one of the early pioneers of simulation, had an interest in V&V and authored numerous books including one of the first books on simulation (Naylor et al. 1966). The Naylor and Finger (1967) article was one of the first articles to discuss various validation techniques and methods. Of particular interest in this heavily referenced article is the discussion of the three philosophy of science methods for validation: *rationalism*—requires a model to be logically developed (correctly) from a set of clearly stated assumptions, *empiricism*—requires every model assumption and outcome to be empirically validated, and *positive economics*—requires only that the model outcomes are correct and is not concerned with a model's assumptions or structure (causal relationships or mechanisms); and the suggestion that they be combined into a method of model validation called "*multistage validation*". This multistage validation method is a three-stage procedure incorporating the methodologies of rationalism, empiricism, and positive economics and implies that all three methodologies are required to validate a simulation model. There was an interesting statement made in the Schrank and Holt (1967) critique of this article: "The problems of building complex simulation models and getting them to operate on computers has consumed so much time and energy that the validation problem has been neglected." This explains why there was little attention paid to V&V during the early era.

RGS first met Naylor at the Symposium of the Design of Computer Simulation Experiments (Naylor 1969) held at Duke University in 1968 sponsored by the College of Simulation and Gaming of The Institute of the Management Sciences (TIMS) and Duke University, and found him to be a very dynamic individual. At this symposium, Richard L. Van Horn presented the paper "Validation" (Van Horn 1969) that became the paper "Validation of Simulation Results" (Van Horn 1971). These papers mentioned the definitions of V&V from Fishman and Kiviat (1968) and used the definition of validation as "the process of building an acceptable level of confidence that an inference about a simulation process is a correct or valid inference for the actual process". The latter paper was popularly received, heavily referenced, and included validation methods for the three stages of the multistage validation method of Naylor and Finger (1967).

The first books on simulation appeared in the early era. The only book that discussed V&V in any depth is the book by Naylor et al. (1966). This book gives a nine step procedure for simulation with Step 7 being Validation. However, Chapter 8 of the book discussing Step 7 has the title "The Problem of Verification." In this chapter, it says "verify or validate" a model, thus using the two terms as being interchangeable. Step 6 of the procedure is "Formation of a Computer Program" and lists six activities for this step with none of the activities being referred to as verification. The paper by Burdick and Naylor (1966), which discusses the design of computer simulation experiments, refers to the Naylor et al. (1966) book, and then gives the same simulation procedure as in the book. Furthermore, it says to see Chapter 8 of the book for details on model validation. Thus, one sees the lack of standard use of terminology for verification and validation.

3 THE AWARENESS ERA: YEARS OF THE 1970'S AND THE 1980'S

The awareness era was an extremely busy era with numerous activities and developments in and related to V&V. Among the developments were standard definitions for V&V, how V&V relate to the model development process, developed processes and methods to use in V&V, and recognitions that V&V are necessary for simulation and computer-based models. Some of the types of activities that occurred regarding V&V were workshops, research, tutorials, and presentations at conferences. It is not possible to present the developments and activities of V&V in a time sequence during the awareness era because of the large number of them; thus, individual V&V developments and activities during this era are discussed separately.

There were several individuals that contributed to V&V in this era. Three of the most important were probably OB, Saul I. Gass, and RGS. Gass's major contributions in V&V and related areas started in the early 1970's and continued through the 1980's; and consisted mainly of working with the U. S. National Bureau of Standards and the General Accounting Office (GAO), performing V&V research, and promoting V&V by organizing sessions at national and international operations research meetings and writing articles about V&V. (An overview of OB's and RGS's V&V contributions were covered in the Introduction.)

The issue of whether computer-based models used by the U.S. Government are "correct" became a concern of the U.S. Congress in 1974 and they asked the GAO to investigate. This request from Congress was prompted in part because of the use of computer simulation models to develop the "Project Independence Blueprint" for energy independence during the "U.S. energy crisis". Gass assisted GAO in developing a Report on "Guidelines for Model Evaluation" (U.S. General Accounting Office 1979) as part of GAO's response to congress. This report contained a flowchart giving the modeling steps for developing models that included V&V with their definitions, some specifics for performing V&V, what should be included in model documentation, and what should be included in conducting model evaluation. This report had an impact on model development and model use for and in the U.S. Government. Gass and Thompson (1980) published an abridged version of this report in *Operations Research* which made the operations research community aware of this information. We note that the GAO developed several reports between 1974 and 1979 on the usage of computer-based models and also the report "DoD Simulations: Improvement Assessment Procedures would increase the credibility of Results" (U.S. General Accounting Office 1987) that included discussion of V&V using definitions of V&V as discussed in the Introduction Section of this paper.

Gass did research on model confidence and evaluation (Gass 1977a, 1977b, 1983, 1993, Gass et al. 1991, and Gass and Joel 1987). One approach to V&V discussed by Gass (1977a, 1977b) was to use Independent Verification and Validation (IV&V), which was used in the field of Software Engineering (Brown, Fabisch, and Rifenbert 1975). IV&V has become one of the popular approaches for performing V&V of large scale policy and defense models. Another approach put forth by Gass was to use a scoring model to evaluate V&V as has OB (1989). The use of a scoring model for V&V has mixed opinions (see, e.g., Sargent 1991) as there are supporters and opposers of using this approach for V&V. Both IV&V and scoring models are discussed further in the next section.

There were several workshops and symposiums held on validation and assessments of models during this era sponsored by different organizations including the U.S. government. Some examples are the 1978 "Workshop on Validation of Computer-Based Mathematical Models in Energy Related Research and Development" sponsored by the National Science Foundation where RGS gave a paper (Sargent 1979a); the "Workshop on Simulation, Validation, and War Gaming" in El Paso, Texas, February 1979 sponsored by the U.S. Army Research Office, where RGS gave the presentation "Validation of Simulation Models"; the 1979 and 1980 symposiums titled "Symposium on the Validation and Assessment of Energy Models" (Gass 1980, 1981) sponsored by the National Bureau of Standards; and the "Workshop on Model Validation and Assessment" organized by Gass at the Ninth International Conference on Operational Research, Hamburg, Germany, July 1981, where RGS spoke on "Model Validation". These workshops and symposiums on validation illustrate the desire of the sponsoring organizations to make professionals aware of the importance of performing V&V on computer-based models.

There were numerous presentations, papers, and tutorials given on V&V at different simulation conferences starting in the mid-1970's. RGS gave his first presentation on V&V when he was asked to speak on "Validation Techniques" at the Simulation and Simscript Conference, held in Washington, D.C., March 1978. This presentation led RGS to have numerous invitations to have presentations, papers, and tutorials on V&V at other simulation conferences and universities during this era including the U.S. Army Research Office "Workshop on Stochastic Models in Fire Control", Ft. Belvoir, Virginia, November 1978; ACM SIGSIM "Workshop on Methodology of Simulation", March 1979, Tampa, Florida; SIMULATION

'80 Conference, Interlaken, Switzerland, June 1980; the National Science Foundation "Workshop on Model Acceptance", April 1981; NATO "Advanced Study Institute on Simulation and Model-Based Methodologies: An Integrative View", Ottawa, Ontario, Canada, August 1982; and for the Winter Simulation Conferences starting in 1979 (Sargent 1979b) and continuing to the present time. We note that Gass and OB, e.g. Balci (1986, 1989), also, among others, gave several presentations and papers at various simulation and operations research conferences nationally and internationally on V&V and related areas. These presentations and papers made professionals from different application domains aware of the importance of performing V&V on simulation models.

We now discuss some of RGS's V&V research. As stated in the Introduction, RGS's research in the area of V&V started in the 1970's as part of sponsored research from RADC to assist them in the development of computer-based models. An early area of research concentration was the development and evaluation of models for performance evaluation of computer systems. Part of this work involved evaluating simulation models of computer systems that had been developed for RADC by contractors. This evaluation work provided knowledge to RGS on verification, validation, and documentation of computer-based models. This work led to the 1981 RADC report (Sargent 1981) on 'an assessment procedure for computer-based models' that contains the well-known diagram called the "Simplified Version of the Model Development Process" (Sargent 1981, 1984, 2013).

We now discuss the Ph.D. dissertation research of Harold A. Anderson, Jr., an IBM employee who came to Syracuse University to obtain his Ph.D. His dissertation research with RGS as his Ph.D. advisor involved investigating scheduling rules for interactive computer systems, which can be modeled as queueing networks (Anderson 1972). Data for his dissertation was obtained from an experimental interactive computer system that was located at IBM's Watson Research Center. The analysis of this data showed that the arrivals to the computer system from terminals could be modeled as a Poisson process and that the service time requests of different types of jobs had long tails and high coefficient of variation and thus should not be modeled as exponential distributions (Anderson and Sargent 1972). This analysis was one of the first to investigate the statistical distribution behavior of computer system data. Because the service times were not exponential, it was decided to investigate scheduling rules using simulation instead of an analytic queueing network model because queueing network models usually assume exponential distributions. (Note: This was one of the first three Ph.D. dissertations investigating performance evaluation models of interactive computer systems. The other two used analytic queueing network models assuming exponential distributions: J. P. Buzen (1973) at Harvard University and C. G. Moore (1971) at the University of Michigan. Buzen's work used no data and did not address model validation. Moore's work contained a model of the Michigan Terminal System (MTS) that used means of computer system data. His work discussed model validation and he observed that the MTS was far more variable than his model for various performance measures.) Validating the simulation model developed by Anderson presented challenges as the use of standard statistical tests comparing system and simulation data was not possible. Thus, it was decided to use various types of graphs to compare system and simulation data to obtain a sufficiently valid model (Anderson 1972 and Anderson and Sargent 1974). In performing validation of the simulation model, an error was found in the programming of the scheduling rule in the computer system's operating system. This research convinced RGS that it was necessary to use graphical approaches for validating many simulation models. RGS proceeded to develop graphical approaches to validate simulation models that include the use of histograms, box (and whisker) plots, and behavior graphs using scatter plots where the simulation data are used as the references (Sargent 1996); and these graphical approaches are included in RGS's tutorials on V&V. Furthermore, this led RGS to propose the use of simulation and Monte Carlo generated data as an alternative for references for comparisons of different sets of data instead of using theoretical distributions such as the t-distribution (Sargent 2001a).

OB asked RGS to be his Ph.D. advisor as OB wanted to do his dissertation research in validation of simulation models (Balci 1981). OB's validation research had a major impact on V&V. Many professionals view the paper published in *Communications of ACM* (Balci and Sargent 1981) based on his dissertation research as formalizing and providing an excellent framework for V&V (see, e.g., Goldsman, Nance, and

Wilson 2010, page 571). This framework formulated model validation as a hypothesis test and described type I error, α, rejecting the validity of a valid model, as the model builder's risk and type II error, β, accepting the validity of an invalid model, as the model user's risk. Furthermore, this work considered the cost of data collection and allowed the specification of the errors to consider model accuracy through the use of the operating characteristic (OC) curve. Another part of his dissertation considered the use of simultaneous confidence intervals for model validation and included a practical validation procedure for their use (Balci and Sargent 1984a). Also included in his dissertation work was the use of the Hotelling's Two-sample T^2 test for validating multivariate response simulation models (Balci and Sargent 1982a, 1982b). An article describing the use of this T^2 test for simulation model validation was published in the 1982 December issue of *Simulation* (Balci and Sargent 1982a) and was featured on its cover. Numerous copies of this issue were taken to the 1982 Winter Simulation Conference (WSC) for the attendees. The reason for this was that the Society for Computer Simulation (SCS) wanted to publicize that they were into discrete-event simulation as well as continuous simulation, which was their emphasis when SCS was founded. While not planned, distributing copies of this issue at WSC also had the effect of publicizing V&V and OB and RGS as researchers in V&V. OB's dissertation work was also appropriate for validating multiple response trace-driven simulations (Balci and Sargent 1983).

Bor-Chung Chen also did his Ph.D. dissertation with RGS on validation of simulation models (Chen 1985). His research primarily involved developing statistical methods using standardized time series for comparing means and variances of two stochastic processes (Chen and Sargent 1985, 1987, 1990). These statistical methods can be used in simulation model validation by having the two processes represent the outputs of a simulation model and a system that are being compared to determine a model's validity.

Several of the simulation books published in the 1970's included a discussion on validation. As an example, the simulation book by Shannon (1975) had a chapter titled "Validation and Analysis". This chapter used the definitions of V&V from Fishman and Kiviat (1968), and then proceeded to discuss various validation techniques emphasizing statistical approaches. No discussion occurred regarding verification. An earlier chapter contained the steps of a simulation study that included a validation step but none for verification. Most of the simulation books published in the 1980's contained information on V&V, including the definitions that are commonly used today and also how V&V relate to the model development process. However, the amount of discussion on verification and also on validation varied, and these books had more discussion on validation than verification. One different approach to V&V was in Bernard Zeigler's two books (1976 and 1984) where he discussed V&V using general systems theory.

There was much interest in V&V terminology in the late 1970's and early 1980's. For example, SCS appointed a committee chaired by Stewart Schlesinger (1979) that developed specific definitions for V&V and other terms. Their developed definition of model validation is the wording often used today for validation of simulation models and is the wording RGS uses: "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". The "Guidelines for Model Evaluation" (U.S. General Accounting Office 1979) contained definitions for V&V. Individuals presenting papers and tutorials on V&V at the various conferences mentioned above had definitions for V&V. OB and RGS 1981 paper contained V&V definitions as did other published journal papers regarding V&V. The simulation books also contained definitions of V&V. The result of all of these various V&V definitions was that by the mid–1980s the meanings of V&V had become standardized as given in Section 1 but with different ways of how the meanings were worded.

Bringing V&V into the model development process occurred almost everywhere during this era. Either methodology flowcharts or graphical diagrams were used. The flowcharts and the diagrams varied from being simple to complex. The more complex ones included different and more methodology than the simple ones and were often developed specifically for large scale simulations. The content regarding V&V in the early flowcharts varied from publication to publication: some of the flow charts contained both V&V, e.g., the report "Guidelines for Model Evaluation" (U.S. General Accounting Office 1979)

and Law and Kelton (1982); some flowcharts did not include verification, e.g., Shannon (1975); and other flowcharts used "debug the simulator", e.g., Emshoff and Sisson (1970), or similar terminology instead of verification. Regarding graphical diagrams, a simple one is the "Simplified Version of the Model Development Process" diagram and its associated processes developed by Sargent (1981, 1984, 2013), and a complex one is the "Life Cycle of a Simulation Study" diagram and its associated processes developed by Balci (1986). Banks, Gerstein, and Searles (1988) reviewed work using both simple and complex diagrams and flowcharts and concluded that the simple diagrams more clearly illuminated model V&V. On the other hand, the more complex diagrams and flowcharts may work better for the development of large scale simulations.

There was much effort on identifying and developing validation techniques in this era; several are mentioned above. Various validation techniques are given in, e. g., Banks (1989), Balci (1989), Law and Kelton (1982), Sargent (1984), Shannon (1975), and Van Horn (1971). Some techniques are objective such as the statistical method developed by Schruben (1980) for use with the Turing test and some are subjective such as the use of graphical models for conceptual validity suggested by Sargent (1986b). Reitman et al. (1970) introduced the use of animation to aid performing V&V. There are too many validation techniques to list all of them.

One question that is often asked about V&V is the following: "Does an algorithm exist that can be used to determine which validation techniques should be used to validate a specific simulation model?". The answer is no due to many reasons including: V&V is situation dependent—a set of V&V techniques that work well for one type of simulation model may not be effective for another (Balci 2010), differences in the systems being modeled, different environments that systems operate in, differences among simulation models, and different information needed from models for different types of decision making. RGS investigated using expert aids for validation (Sargent 1986a) and also an advisory system for operational validity (Rao and Sargent 1988) to assist in selecting validation techniques to use for validation of simulation models. The conclusion of these two investigations was that it is not practical to develop expert aids or an advisory system for model validation (at that time).

As mentioned in the Introduction Section, there were not many papers written on verification of simulation models. The known papers discussing verification methods, techniques, and tests for simulation models published during this era are Chattergy and Pooch (1977), Fairley (1976), Shannon (1981), and Whitner and Balci (1989). The latter paper is very thorough and gives verification techniques for different categories of verifying a programmed simulation model. Verification techniques for simulation models are discussed in some books on simulation, e.g., Law and Kelton (1982), and in tutorials, e.g., Sargent (1984). We note that software engineering applies to verification of simulation models as discussed in, e.g., Whitner and Balci (1989).

4 THE MODERN ERA: YEARS STARTING FROM 1990

Similarly to the awareness era, the modern era was also an extremely busy one with numerous activities and developments in and related to V&V. Among the developments that occurred were: V&V became required of simulation models by DoD and a few other large organizations; new processes, methods, and techniques were developed for V&V; and significant dissemination of knowledge about V&V. New challenges arose for V&V due to more complex systems being simulated and new simulation model paradigms being used such as agent-based models and hybrid models, e.g., systems dynamics/agent-based simulation models (Eldabi et al. 2016). A variety of activities occurred regarding V&V including research, tutorials, V&V short courses, V&V presentations at conferences, and conferences on validation. There were several individuals in addition to OB and RGS that made contributions during this era. It is not possible to present the accomplishments and activities of V&V in a time sequence during the modern era because of the large number of them; thus, individual V&V accomplishments and activities during this era are discussed separately as was done in the awareness era.

Jack P. C. Kleijnen contributed several papers on validation of simulation models and metamodels beginning in the mid-1990's. These covered a variety of topics including statistical methods such as bootstrapping for validating regular and trace-driven simulations, case studies, tutorials, and ways of validating metamodels. Many of his publications were co-authored including one with RGS (Kleijnen and Sargent 2000) on fitting and validating metamodels that has received much attention. This paper was developed when RGS visited Kleijnen during RGS's sabbatical leave in 1997.

There was a wide dissemination of tutorial type information about V&V given in various ways during this era. There were journal articles, e.g., Balci (1997), Kleijnen (1995), Robinson (1999), and Sargent (2013). There were chapters in books, e.g., Law (2015), and Sargent (2015b). V&V topics were in encyclopedias, e.g., Sargent (1992) and Balci (1996), and handbooks, e.g., Balci (1998a). There were tutorials on V&V at most of the WSCs during this era: RGS regularly gave one that was continuously updated, OB frequently gave one, and occasionally a different person gave one, e.g., Kleijnen (1999) and Law (2006). In some years there were more than one tutorial paper; e.g., at the 1998 WSC, OB gave an introductory tutorial (Balci 1998b), RGS gave an advanced tutorial (Sargent 1998), and Nayani and Mollaghasemi (1998) gave a case study. At the fortieth anniversary of WSC in 2007, there were ten landmark papers selected from among all the papers given during the forty years of WSC and RGS's series of tutorials on V&V was one of the ten selected papers (Goldsman et al. 2007). There were two books written on V&V: Knepell and Arangno (1993) and Oberkampf and Roy (2010). Kleindorfer and Ganeshan (1993) had a paper discussing the philosophy of validation. Lastly, there were short courses on V&V given, e.g., by Law (2017), and lectures on V&V given by RGS at the International Summer School on Trends in Computing (SSTiC), Universitat Rovira i Virgili, Spain in 2013 and 2014.

There were conferences and workshops regarding V&V during this era. There was the Simulation Validation Workshop SIMVAL 99 (Glasow and Pace 1999) sponsored by the Military Operations Research Society (MORS) and SCS, in which OB and RGS participated. There were two Conferences on "Validating Models for Adversary Behavior" regarding Homeland Security, one in 2013 and the other in 2015; RGS spoke at both. There was the USA-NATO Assessment of climate change Mitigation Pathways and Evaluation of the Robustness of mitigation cost Estimates - Program on Integrated Assessment Model Development, Diagnostics, and Inter-model comparison (AMPERE-PIAMDDI**)** Workshop on the "Evaluation of Integrated Assessment Models" held in Spain during May 2013 where RGS was one of the key speakers (http://ampere-project.eu/web/index.php?option=com_content&view=article&id=48).

RGS's research on V&V continued during this era. Dale Pace of John Hopkins University Applied Physics Laboratory asked RGS to develop a more detailed graphical paradigm/diagram than the "Simplified Version of the Modeling Process" paradigm that would contain the "real world" and other specified content for some V&V research he was doing for the DoD. This new "Real World and Simulation World Relationships with Verification and Validation" paradigm is contained in Sargent (2001b) along with some references where Pace used it. This new paradigm has also been used by Nance and Arthur (2006) and Nance (Sargent et al. 2006) as a simulation *project* life-cycle model. RGS also developed an "interval hypothesis test" for validating simulation models (Sargent 2015a, and Sargent, Goldsman, and Yaacoub 2015, 2016). In addition, there are the two research publications that were previously mentioned: Sargent (1996) discussed in the awareness era and Kleijnen and Sargent (2000).

IV&V and the use of scoring models for V&V were introduced in the Awareness Era. Work on these approaches to V&V continued in this era. Robinson and Brooks (2010) reviewed both of these approaches in their paper that discussed IV&V for a special use of an industrial simulation. IV&V is only used for special applications of industrial simulations due to the expense of using it. OB developed the Evaluation Environment Methodology for Verification, Validation and Accreditation (VV&A) of simulation models and incorporated it into a web-based software system with funding from the U. S. Navy (Balci et al. 2002a, Balci et al. 2002b). A scoring model is used in this methodology. This software and methodology were successfully employed in more than a dozen DoD projects for VV&A of complex simulation models.

DoD, the largest user of simulation, sponsors work in VV&A with organizations and individuals. This work is sponsored by different units of DoD and their Modeling and Simulation Coordination Office (DMSCO). (DoD usually refers to Modeling and Simulation (M&S) instead of using only the term simulation.) DoD, through research sponsored by DMSCO, is moving VV&A towards a more science-base approach as discussed in "VV&A of M&S in the DoD: Moving from Art to Science" (Diem, Henninger, and Youngblood 2010). Unfortunately, much of the VV&A work sponsored by DoD is not available to the public; and recently access to DMSCO's website became restricted and thus VV&A information located there is no longer available to the public. DoD established DoD Instruction 5000.61 (2009), first released in April 1996, that establishes policy, assigns responsibilities, and prescribes procedures for the *requirement of VV&A* of models, simulations, distributed simulations, and their associated data.

The John Hopkins University Applied Physics Laboratory is one of the organizations that DoD sponsors major work with; and their VV&A role with DoD is discussed in the article "Simulation Verification, Validation, and Accreditation" (Youngblood et al. 2000). Paul Davis (1992) of the Rand Corporation, which is another organization that does much military work for DoD, proposed a framework for generalizing concepts and methods of VV&A for military simulations. Law had three contracts with DoD and the report "A Practitioner's Perspective on Simulation Validation" developed in 2006 is on the DMSCO's website, which is no longer accessible to the public. Other VV&A work performed by OB for DoD beyond what has been already discussed includes being a major co-author of DMSCO's "Verification, Validation and Accreditation Recommended Practices Guide", developed in 1996, that used to be available to the public on the DMSCO's website; and being a consultant on VV&A of large scale simulation models for the Missile Defense Agency between 1998 and 2002. Furthermore, OB, based on his real-life DoD experiences, has advocated conducting V&V under a Quality Assurance program integrated within the processes of a M&S life cycle to be able to form an accreditation (certification) decision about complex M&S applications (Balci 2001, 2004, 2010, 2012).

New V&V techniques continued to be developed in this era. The use of animation with simulation became popular during this era and as a result the use of animation as a V&V technique also became popular. OB described more than 75 V&V techniques that can be used throughout the entire life cycle of an M&S project (Balci 1994, 1998a). Research on V&V methods and processes for new M&S approaches continued during this era such as Zeigler and Nutaro's (2016) V&V work on systems of systems (Jamshidi 2008).

RGS did an informal survey on V&V at the 2016 WSC by asking several employees of vendors in the exhibit area who were involved with developing simulation applications about the use of V&V of simulation models they were involved in developing. The replies were that V&V are required by the Department of Defense and some large companies and as a result V&V are being done for simulation models for these organizations. For organizations that do not require V&V, the impressions that RGS obtained from these individuals were that about 50 percent of the simulation models were receiving at least adequate V&V, about 25 percent of the simulation models were receiving some but inadequate V&V, and about 25 percent of the simulation models were not receiving any V&V. No matter how inaccurate these estimates may be, it is clear that much education needs to be done to emphasize that V&V are to be performed in a simulation study. RGS also asked about V&V methods and techniques for simulation models. Three impressions were obtained from the individuals: (1) only a few methods and techniques are used in practice, (2) the methods and techniques available are adequate, and (3) statistical tests comparing model and system outputs are not often used because of the lack of system data.

Whereas individuals from the vendors seem satisfied with the available V&V methods and techniques, this does not seem to be the situation for academics and researchers using the newer model paradigms (also referred to as world views) of agent-based, object-oriented, and hybrid models (e.g., agent-base/system dynamics) for simulation modeling as they are concerned about how these simulation models should be validated. See, e.g., Brailsford in (Eldabi et al. 2016), for such a discussion. With the

exception of validating system dynamics models (see, e.g., Barlas (1989, 1996)), V&V have not addressed specific model paradigms. Research is needed to understand why there is a belief that the current validation procedures, methods, and techniques do not apply to these new types of model paradigms; and if new approaches are needed, then the appropriate research needs to be performed. Perhaps more complex models such as hybrid models being used and different aspects of systems being modeling are the underlying causes of this concern regarding performing V&V.

5 CONCLUDING REMARKS

What can be observed from these eras? We observe in the early era that no V&V methodology was available and rarely were V&V performed in simulation studies. We observe in the awareness era that the fundamentals of V&V were developed and awareness of V&V was made to professional communities. We observe in the modern era that development of V&V methodology continued and needs to continue, that some organizations made V&V a requirement of simulation studies, and that awareness of V&V continued and needs to continue because too many simulation studies are not including V&V. Performing V&V are perhaps the most challenging aspects of doing a simulation study. This challenge is not expected to change as each new simulation study is unique and that challenges performing V&V.

This history of V&V concentrated on discrete-event simulation. There is a related field of continuous simulation that primarily uses differential and partial differential equation models that has a separate V&V literature; see, e.g., Oberkampf and Roy (2010). Another related field is the calibration of models; see, e.g., Kennedy and O'Hagan (2001).

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