Proceedings of the 2017 Winter Simulation Conference
W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

A PERSPECTIVE ON FIFTY-FIVE YEARS OF THE EVOLUTION OF SCIENTIFIC RESPECT FOR SIMULATION

Robert G. Sargent

Syracuse University
Department of Electrical Engineering
and Computer Science
4-206 Center for Science & Technology
Syracuse, NY 13244, USA

ABSTRACT

This paper gives a personal perspective on the evolution of discrete-event simulation—concentrating on how it moved from having an image from the 1950s through the 1980s of being a "brute force programming effort" and as a problem-solving "method of last resort" to today's status where simulation enjoys "considerable scientific respect." These days, simulation is often the solution "method of choice" and has gained much "scholarly respect." This evolution changed simulation's reliance on the use of "ad hoc methods" of solution on "early digital computers" to using simulation software systems containing "science-based methods" of solution on "modern day computers." Remember: *Simulation today has considerable scientific respect, and this respect is the result of the evolution of simulation.*

1 INTRODUCTION

This paper presents a description of my observation of and participation in the evolution of discrete-event simulation, hereafter referred to as simulation, covering the time period of 1961–2017. The focus in this commentary is on the scientific respect for simulation during this period.

From the earliest days of simulation, the 1950s, through at least the 1980s, simulation "lacked scientific respect" as simulation had an image of being a "brute force programming effort" and a "method of last resort" for solving problems. And furthermore, during the latter part of the 1960s and in the 1970s, simulation and the individuals working on the development of simulation often "lacked scholarly respect." These are discussed in Section 2. Today, simulation has "considerable scientific respect" as simulation is often the problem solution "method of choice" and the field of simulation has "scholarly respect" as do the individuals working in simulation development. *This change in scientific respect for simulation occurred because of the evolution of simulation.* This paper describes this evolution, which has been continuous since it started in the 1950s and consists of many processes. My view is that the portion of the evolution that took place during the time period covering the 1960s through the 1990s removed the negative image of simulation and initiated increasing scientific respect for simulation. Discussion of the different processes comprising this evolution in a chronological integrated way is extremely difficult, thus they are discussed individually or in groups in Section 3. The primary driving force for the evolution of simulation is that simulation is usually the only method available for studying complex systems. Achieving significant scientific respect through this evolution is discussed in Section 4 and concluding remarks are given in Section 5. (See Nance and Sargent (2002) for an overall perspective on the evolution of simulation.)

I was first exposed to simulation in the fall of 1961 when I was a first semester graduate student at the University of Michigan. Simulation was covered in the last one-third of a required course on "data processing." There were no simulation text books, no "how to do simulation" source materials, and no simulation languages available. (The first book on discrete-event simulation was by Tocher (1963).) Thus, simulation was taught purely by lectures. We were taught the "event world view," and we programmed simulation models using the MAD (Michigan Algorithm Decoder) computer language, which is similar to FORTRAN. The computer system used was an IBM 709, which was a batch-oriented system using punched cards for inputs. Students usually got a computer job turnaround in two days while faculty usually had a one-day turnaround. Thus, to get a computer program debugged usually took at least several days. The only function available for simulation programs was a "simplistic random number generator." All other functions needed for simulation such as random variate generators and a time flow mechanism that included an event list algorithm had to be written into the computer program. This approach was common at the few universities where simulation was being taught during this time period. Also at the University of Michigan, I took a one semester graduate course in simulation during the spring of 1963 that covered various aspects of simulation including variance reduction techniques and again used the MAD language for developing simulations. The course material was covered purely by lectures as there was not yet any simulation course material available. This simulation course was followed by my doing a semester project on simulating queueing systems as part of a second course in queueing systems under Professor Ralph Disney. Discussions occurred between Professor Disney and me on doing a Ph.D. dissertation on the simulation of queueing systems; however, I decided to do my dissertation on another topic instead.

Upon receiving my PhD. in 1966, I joined Syracuse University as a faculty member in Industrial Engineering to participate in a new interdisciplinary graduate program in Systems and Information Science. I spent my entire professional career at Syracuse. My teaching included courses in simulation, stochastic modeling, and system performance evaluation. I received sponsored research support during most of my career from the Rome Air Development Center (RADC) of the U.S. Air Force on computer-based models that included simulation. My contributions to the simulation community were in the forms of both service and scholarly publications.

2 THE EARLY DAYS

Simulation on digital computers started in the 1950s as digital computers became available. Simulation models had to be written in a computer language that was available on the computer being used. No support functions were available to aid in writing a simulation program except possibly a simplistic random number generator; thus all support functions had to be written for each simulation program. The early computers were physically very large machines, had operating systems that used sequential batch processing, used punched cards for input, had little memory, were very slow computationally, and usually took a day or so to have a submitted job returned. These types of computers were commonly used at least through the 1970s. As a result it took a long period of time to obtain a correctly executing simulation model. Furthermore, there was a lack of science-based methods for performing simulation studies. Even after the early simulation languages became available in the late 1960s, obtaining a correctly running simulation model using a simulation language took a considerable amount of time. As a result, performing simulation studies took on the image of developing computer programs, which was largely true, because little time remained in a study to do an analysis of the simulation model for which a paucity of science-based knowledge existed on how to do. As a result simulation as a problem-solving method was often referred to as the "method of last resort".

Let's look at some comments made about simulation during its early days. In 1958, Harling (1958) wrote in his *Operations Research* paper reviewing simulation: "It has been often said that a simulation is a last resort." In 1967, Schrank and Holt (1967) wrote in a critique of the highly referenced Naylor and Finger (1967) paper on validation of simulation models in *Management Science*: "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." In 1969, Wagner (1969) wrote in the well-known textbook *Principles of Operations Research* on page 890: "when ALL ELSE FAILS…" and "...simulation is a 'method of last resort.' " And then *later* than the early days, Schruben (1987) wrote in the Chairman's Message of the 1987 Fall Issue of the *Newsletter of the TIMS College on Simulation and Gaming*: "Simulation carries with it the image of unsophisticated brute force problem solving with ad-hoc "what-if?" experimentation. Simulation is frequently referred to as the "method of last resort," … ." One can readily see the (negative) image that simulation had as stated in a variety of different types of publications into the 1980s.

Let's look at the two epithets that were often used about simulation in its early days: "brute force programming effort" and "method of last resort." These two epithets are indeed true for the early days of simulation. However, there is much more regarding the use of simulation than the negative connotations that go with these epithets. *Yes*, it took much programming effort to develop a computer simulation whether written in a higher level computer language like FORTRAN or in an early simulation language. Writing a computer program for almost any use of the computer took much effort in the early computer days. Thus, simulation was no different in this respect than many other uses of the computer. *Yes*, the use of simulation was the least preferred method of solutions for solving a problem. However, the bottom line is that simulation is often the *only* method available to solve complex problems. Thus, simulation came into much use as a problem-solving method.

Let's look at a couple of surveys on the use of simulation for problem-solving. Shannon and Biles (1970) surveyed 100 nonacademic full members of the Operations Research Society of America (ORSA) asking them to rank their use of 12 specified methods used to solve problems. Simulation was third following Probability and Statistics that was first and Economic Analysis that was second. Weston (1973) surveyed the largest 1000 U.S. firms regarding the use of specific methods for corporate planning. The results showed that Simulation was the most used method at 29 percent of the firms followed by Linear Programming at 21 percent. These surveys show that simulation is one of the most used methods for problem-solving even though it is the least preferred method. While these surveys did not ask why a specific problem-solving method was used to solve a specific problem, it should be obvious that the simplest method of solution would usually be used. Thus, simulation was being used as it was the only solution method available for studying many system problems.

In addition to these two epithets, both the field of simulation and those individuals working in the development of simulation often received a "lack of scholarly respect," especially in the late 1960s and 1970s. My view is that this lack of scholarly respect for simulation and individuals working in simulation development came mainly from individuals who were more "academic and scholarly oriented" in the fields of operations research, management science, and industrial and systems engineering who did not work in simulation. Moreover, their lack of an understanding of what was involved with simulation differentiated them from problem-solving-oriented individuals. Interestingly, this lack of scholarly respect seemed to exist far less in individuals working in the field of computer science. The individuals who worked in developing the field of simulation in the early days were motivated to do so because (1) they were using (or wanted to use) simulation as a problem-solving method or (2) they were interested in developing science-based methods to be used in simulation.

Prominent individuals who made contributions to the development of simulation because they were using simulation for problem-solving were Richard Conway who was solving scheduling problems, Julian Reitman who was designing large scale systems such as airline reservation systems and military systems, and K. D. Tocher who was solving problems in the steel industry in the United Kingdom. Numerous individuals made developments on specific science-based methods for simulation during its early days; many of them can be found in the various papers on different aspects of the history of simulation that are contained in the *Proceedings of the 2017 Winter Simulation Conference*. Three such individuals who made specific science-based contributions were George Fishman on simulation output analysis, Philip

Kiviat on modeling and simulation languages, and Harry Markowitz on various versions of the Simscript simulation language.

3 THE EVOLUTION

This section discusses the evolutionary processes that precipitated the gaining of respect for simulation. Two aspects of scientific respect are of primary interest in this paper. One aspect is having simulation become a "method of choice" for problem-solving (instead of a method of last resort) and the other aspect is having simulation and individuals working in simulation development receive "scholarly respect." These were not the situations during the early days of simulation as discussed in Section 2. The evolution that caused this change in scientific respect involved numerous different processes (or activities) occurring that often overlapped each other in some time-wise fashion that caused countless changes in different aspects of simulation. The evolution of simulation started in the 1950s and still continues today. My opinion is that the evolutionary processes that took place primarily from the 1960s through the 1990s were what caused simulation to start receiving positive scientific respect, and this respect continues to increase as simulation evolution continues to evolve. These processes are discussed individually or in groups as it is not practical to discuss these evolutionary processes in an integrated time sequence.

Some of these evolutionary processes resulted in simulation changing from the use of "ad hoc methods" of solution on "early digital computers" to the use of "science-based methods" of solution on "modern day computers." In order for a newly developed method to have an impact, it first must be developed and then must be communicated to the appropriate audience. The evolutionary processes that led to new methods to cause this change in simulation will be called the technology evolution and will be discussed in Subsection 3.1. This technology evolution allowed simulation to become a solution method of choice. The communication of new developments will be discussed in Subsection 3.2. Section 3.3 will contain a discussion of other processes beyond those in Subsections 3.1 and 3.2 that aided simulation and simulation developers to receive scholarly respect.

Let's next look at some survey results and comments that occurred about simulation during its evolution. A longitudinal study by Harpell, Lane, and Mansour (1989) contained surveys for the years of 1973, 1978, and 1983, and extended in Lane, Mansour, and Harpell (1993) to include 1988, asked educators and practitioners separately to rank which quantitative techniques they believe are most important to teach regarding problem-solving. The survey results of the *practitioners* in 1973 ranked simulation fourth below statistics as first, linear programming as second, and probability as third; and in the years of 1978, 1983, and 1988 ranked simulation second below statistics, which was ranked first, and above linear programming, which was ranked third. *Educators* ranked simulation third in 1973 and 1978 and second in 1983 and 1988, statistics first in 1973, second in 1978, and third in 1983 and 1988, and linear programming second in 1973, and first in 1978, 1983, and 1988. These results illustrate that the importance of simulation increased as time moved forward. No (known) surveys exist for later dates because as discussed by Morgan (1989), the declining response rates for these types of surveys no longer allow this method of investigation (use of surveys) of MS/OR activity. It is interesting to look at what Wagner (1988) said about simulation in his 1988 Harold Larnder Memorial Lecture; especially, after what he had written in his 1969 book about simulation that is discussed above: "Computer simulation models have enabled companies to test strategies before implementing them and thereby substantially reduce the risk of adopting an unworkable approach. … Of all of the techniques, computer simulation is the most resource intensive. Nevertheless, the number of applications of this approach probably exceeds that of mathematical programming by a factor of 10 to 1." In 2012, Powers, Sanchez, and Lucas (2012) showed, using different sets of actual data, that simulation publications are growing at an exponential rate whereas publications in linear programming and optimization are growing far more slowly, illuminating that simulation as a solution method is rapidly increasing compared to other types of problem solution methods. In 2015, Lucas et al. (2015) wrote "Times have changed. … After more than half a century of dramatic progress in simulation technology, it is time to retire the outdated notion that simulation is a "method of last resort". … In the face of astounding advances in affordable processing power, modeling paradigms and tools, and supporting analysis capabilities, … simulation—done properly—should often be the method of choice."

3.1 Technology Evolution

The individual processes that underlie the technology evolution of simulation belong to one of three groups: computer technology developments, simulation methodology developments, and simulation software developments. Each of these groups will be discussed at a high level in separate subsections. The results of these evolutional processes removed the image of simulation being a "brute force programming effort" and has allowed simulation to become a solution "method of choice" instead of a "method of last resort." The reason for these changes is because the technology used in simulation has reached a very high level.

3.1.1 Computer Technology Developments

The evolution of digital computers has been incredible as the changes that occurred in each of the following aspects of computers have been major: cost reduction, physical size reduction, increased processing speed, increased memory size, software improvements, graphic capabilities, and ease of use. The early (digital) computers, say in the 1950s, were physically large, were sequential batch processing oriented, used punched cards for inputs, were very slow computationally as compared to today's computers, had relatively little memory, and had no graphics. Turnaround time for processing computer jobs were usually one day or longer. Interactive computers became available in the late 1960s that allowed users to interact directly with a computer from individual terminals thus avoiding the use of punched cards and providing immediate job turn around. Desk-top personal computers came along in the 1980s to be followed by laptop computers in the 1990s. These computer developments significantly reduced computer cost and increased ease of use, allowing the cost of conducting simulations to become relatively inexpensive. Computer graphics became available in the 1980s with personal computers, and became readily accessible in the 1990s with significant improvements. Each new generation of computers was faster with more memory as computer speed doubled every two years and computer memory per unit cost doubled every fourteen months. According to Lucas et al. (2015), floating point operations on computers have increased since the 1950s more than a trillion fold as has data storage (memory) with respect to costs. Furthermore, general computer software has improved immensely. These computer technology developments, along with the simulation software developments discussed, below removed the issue of simulation being a "brute force programming effort" and provided for inexpensive development and experimentation of simulation models.

Similar to the evolution of sequential computers just discussed, the development of parallel computers and networks of computers over time have made them cost-effective. These types of computers systems are sometimes used to perform large-scale simulation; however, they do require specialized types of (discrete-event) simulation software. A history paper on parallel discrete-event simulation (PDES), which began in the 1970s, by Fujimoto et al., is contained in these *Proceedings*. Likewise, simulation on networks of computers is discussed in the paper "A History of United States Military Simulation" by Hill and Miller, which is also contained in these *Proceedings*.

3.1.2 Simulation Methodology Developments

Every aspect of simulation methodology has had evolution resulting in science-based methods for simulation use today as contrasted to the ad hoc methods used in simulation's early days. These science-based methods have changed simulation enormously. The evolutions of the different aspects of the methodology have resulted in some aspects becoming mature and thus currently receiving very few new developments, whereas other aspects of simulation are still evolving and thus are continuing to receive many new science-based developments. There is a set of papers in these *Proceedings* on the histories of the various aspects of simulation methodology that discuss how each aspect has evolved. A brief overview of the evolution of different aspects of the methodology is given in the next paragraph.

Input modeling for simulation is still evolving whereas the generation of random numbers and random variates has matured. Modeling had a set of "world views" (or model paradigms) established in the early days and not much changed until recently when some new world views have occurred such as "agent-based models" and a variety of "hybrid models." Verification and validation of models went through a period of much evolution in the 1970s and 1980s and have largely matured. Output analysis, design of experiments for simulation, and variance reduction techniques have been evolving since the early days and continue to evolve. Seeking better solutions using ranking and selection methods and obtaining optimum output values using a variety of methods were of interest since the early days of simulation; and in recent years, these methods have had significant developments.

3.1.3 Simulation Software Developments

The evolution that has occurred in computer simulation software cannot be over emphasized. The reason that this significant evolution became possible is because of the evolution that has and is occurring in computer technology, which was discussed in Subsection 3.1.1. In the very early days of simulation, simulations had to be performed using an "early computer system" with their limited capabilities, which were discussed above. The computer language commonly used for simulation was FORTRAN, which had no support functions for simulation and thus the necessary simulation functions had to be programed for each simulation study. In the late 1960s, Simulation Programming Languages (SPLs) started to appear, which were rudimentary compared to later SPLs. The early SPLs contained a specific modeling world view, the basic support functions needed for simulation such as random number and random variate generators and a time flow mechanism containing an event list processing algorithm, and 'elementary' data collection and analysis capability. These early SPLs were often not computationally efficient and used punched cards for computer inputs (as required of "early computers"). In the 1970s and 1980s, SPLs evolved to have additional modeling and analysis capabilities; be computational efficient by using, e.g., efficient compilers and event list algorithms; and be available for use on interactive computer systems and personal computers with their advantages. As computer graphics became available in the late 1980s and 1990s, SPLs were complemented with graphics to aid in model development, to display model outputs and data analysis results, and to provide for model animation. Thus, software for computer simulations in the 1990s started becoming computer Simulation Software Systems (S^3s) instead of being SPLs. (For an overview of SPLs, see Nance (1996).)

The evolution of S^3s since about 2000 has been primarily in adding additional aspects of simulation methodology into the S^3s along with replacing existing methods with new methods as they occur, always using the very latest computer technology. (We use S^3 instead of M&S (Modeling and Simulation) software that is sometimes used for modern simulation software because these new S^3s have capabilities for several aspects of simulation beyond modeling and the execution of simulation models.) These (new) S^3s include increased input modeling and analysis capabilities, increased modeling capabilities such as new modeling world views (model paradigms) and graphical modeling, increased output analysis capabilities, output optimum-seeking methods, use of experimental designs, increased use of graphics and animation capabilities, increased output reports capabilities, etc., over earlier simulation software that only had SPLs with supplemental capabilities such as animation. The latest S^3s are providing cost-effective ways of performing simulation studies resulting in simulation often becoming the "method of choice" for problem-solving. As evolution continues in computer technology and in simulation methodology, evolution of S^3s will also continue. (See Nance and Overstreet (2017) in these *Proceeding*s for further information on evolution of simulation software.)

Two early SPLs deserve specific recognition and to be commented on: Simula and GPSS–General Purpose Simulation System. Both of these SPLs made substantial contributions to both simulation and computer software, thus giving scientific respect to simulation. GPSS brought the process (or network) view of modeling into simulation, whose use still continues, and processes to the computer-science community. Simula brought into simulation and computer programming the object-oriented approach. Each of these simulation languages have an oral history video about them in the Computer Simulation Archive (https://d.lib.ncsu.edu/computer-simulation/). (Also, see the paper by Roberts and Pegden (2017) in these *Proceedings*.)

3.2 Communication of Technology Developments

Technology developments must be communicated to be put into practice. This communication must go to those individuals working in the field in which the developments occurred; in our case to those working in simulation. Sometimes it is desirable for new technology to be communicated to others not working in the field, but that is not of major concern here. New technologies in simulation are primarily communicated through books, journals, and conferences (and workshops) and these are discussed in the next three subsections.

3.2.1 Books

A large number of books have been written on various aspects of simulation. These include books on simulation in general, specific types of simulation, simulation languages, etc. Perhaps the first three books written on simulation for digital computers are *Industrial Dynamics* by Forrester (1961), *SIMSCRIPT—A Programming Language* by Markowitz, Karr, and Hausner (1963), and *The Art of Simulation* by Tocher (1963), with the latter being considered the first book on discrete-event simulation. Schriber (1992), in his paper discussing the Renaissance Period (1976-1985) of the Winter Simulation Conference as part of the Twenty-fifty Anniversary of the Winter Simulation Conference, discussed (discrete-event) simulation books covering the time period from the beginning of simulation up to 1992. He partitioned the books into different categories with most categories having numerous books. One exception was a special category for the books by Zeigler (1976, 1984, and 1990) because of their singularity. Zeigler's 1976 book gives a theory for simulation that is based on general system theory and this theory is considered the only major theory for simulation. This book showed that simulation has a solid foundation and is not just some ad hoc way of solving problems. Other categories of Schriber's partitioning include textbooks—books for use in teaching simulation, books on simulation languages, methodology-oriented books, and books that contained treatment of both simulation languages and simulation methodology. Books continue to be published since 1992 in the various categories used by Schriber. Some of these are later editions of earlier publications and many are new. Contents of books for different time periods readily show the technology evolution that has occurred over time. Books convey new simulation technology to individuals involved with simulation and support scientific respect for simulation. Furthermore, books are used for simulation education.

3.2.2 Journals

The publishing of simulation articles in journals is a thorny issue. There is the positive side in that journals helped simulation achieve scientific respect through their establishment of simulation departments and quality simulation publications. Then there is the negative side in that it has not always been possible to publish simulation articles in journals due to bias and also sometimes due to the lack of knowledge of various aspects of simulation by editors and referees. I will first discuss the positive side and then the negative side.

Two processes that greatly aided simulation to achieve scientific respect were the publishing of simulation articles in journals and the establishment of journal departments to handled simulation articles. Simulation articles were historically published in journals as non-department articles and still are in journals that do not have a department that handles simulation articles. With the establishment of "simulation departments" in various journals starting in the late 1970s, simulation articles became handled by that journal department. (The quotes are put around 'simulation departments' because some of these departments (also called areas) had various names of which 'simulation' was sometimes only a part.) These "simulation departments" were established in *IIE Transactions* in 1976 with Richard E. Nance as department editor, in *Management Science* in 1978 with George S. Fishman as department editor, in *Operations Research* in 1978 with Nance as department editor, in *Communications of the ACM (CACM)* in 1980 with Robert G. Sargent as department editor, and in the *ORSA Journal on Computing* in 1989 with Nance as the editor handling simulation. These "simulation departments" all became pure simulation departments over time if they were not that originally and thus coverage of articles in these departments became only simulation. *CACM* discontinued publishing research papers in the late 1980s and as a result the *ACM Transactions on Modeling and Computer Simulation (TOMACS)* was established in 1990 with Nance as Editor-in-Chief. In 1984 the journal *Transactions of the Society of Computer Simulation* was established with Olgierd A. Palusinski as editor, which was for both continuous and discrete-event simulation. One can readily see that there was much activity in establishing "simulation departments" in journals starting in the late 1970s and 1980s that resulted in much scientific respect occurring for simulation, especially since the quality of the published articles was kept extremely high. In 2006, the *Journal of Simulation* began as a publication of the Operational Research Society.

On the negative side, there has been (and still is) bias by journal editors and referees regarding publication of simulation articles. The changing of journal editors, which occurs regularly in journals, often results in changing of the biases towards simulation by journals due to the biases of their editors. Editors sometimes pick referees who have similar biases as they do, often unintentionally, and sometimes referees have other biases. Historically, there was bias against anything simulation by some editors-in-chief of journals, but this has almost disappeared; however, today they sometimes limit the number of papers or journal pages for simulation to a low number. More critical is the bias against papers that are not "mathematical" enough. This has occurred in the past and is still occurring; including by editors of simulation departments. Thus, it is sometimes difficult or impossible to get papers that are on the "soft-side" of simulation published in journals due to biases. These biases against simulation are often because of a lack of scientific respect for some or all aspects of simulation. Another issue related to publishing articles in journals is the lack of knowledge of certain aspects of simulation by editors, including simulation department editors, leading to the inability to publish in journals regarding those aspects of simulation. I will discuss only the modeling aspect of simulation. I believe there is almost universal lack of knowledge by editors, referees, and many others in simulation regarding modeling, and also a lack of respect and appreciation for earlier work in modeling. As a consequence, it is almost impossible to publish simulation-modeling articles in journals, resulting in modeling ideas' frequently being published only in the *Proceedings of the Winter Simulation Conference*.

3.2.3 Conferences and Workshops

Conferences (also called symposiums) can have a single occurrence or numerous occurrences over several years. Their subject matter can be general or on a specific topic. They usually have published proceedings. The conference proceedings are primarily for those working in the subject matter of the conference but they are often looked at, and selected papers read, by others. Some conferences that occur annually obtain *considerable* scientific respect. One such conference is the Winter Simulation Conference (WSC) that has occurred for fifty years and is considered the premier simulation conference. This conference helped develop scientific respect for simulation. It brings together simulation researchers, simulation users, and simulation vendors. The papers presented are peer-refereed and are of high quality, and often new developments in simulation are first presented at this conference prior to being published in journals. This conference is sponsored by multiple societies, has commercial exhibits, has a Ph.D. colloquium, has keynote and titan talks, and is a true international conference. Of special interest are the ten Landmark papers that were selected for the 40^{th} anniversary of WSC as the 'best" from among all of the papers presented at WSC during its first 40 years. Such papers demonstrate the quality occurring in simulation. This year's *Proceedings* contain a set of papers discussing the History of Simulation, including the History of WSC. There are numerous other simulation conferences; some are single-occurrence and others are multiple-occurrence. For a discussion of the major ones, see Nance and Sargent (2002).

Workshops for simulation started in the 1950s and continue to date. Workshops are usually on the state-of-art of a topic. Most of the workshops have some type of publication; sometimes proceedings, sometimes books, sometime special journal issues, and sometimes just handouts at the workshop. These workshops and their publications are usually specifically for those working on the workshop topic. Their purposes are to provide interaction among people on the workshop's topic and rapid dissemination of new ideas and developments. Workshops are important in creating new developments, which are often communicated via conferences and journals.

3.3 Additional Evolutionary Processes Affecting Scientific Respect

This section presents other processes not discussed above that have significantly affected scientific respect for simulation. They are presented in different subsections.

3.3.1 Professional Societies

There are several professional societies interested in simulation as demonstrated by those who are sponsors of the Winter Simulation Conference. Some societies are for simulation only and others have groups within them for simulation. Societies contribute to the importance and status of a field. Most of the simulation societies have changed their name over time. Probably the first simulation society was The Society for Modeling and Simulation International formed in 1952 with the name Simulation Councils, Inc. for only continuous simulation but now accommodates both continuous and discrete-event simulation. The Institute for Operations Research and the Management Sciences (INFORMS) Simulation Society (I-SIM) was originally formed in 1967 as The Institute of Management Sciences (TIMS) College on Simulation and Gaming. This organization has been an extremely active group over the years. They worked to establish the Department of Simulation in *Management Science* in 1978, have established three distinguished awards as discussed under awards, and hold periodic simulation workshops in addition to being a sponsor of WSC. The Association for Computing Machinery (ACM) Special Interest Group (SIG) on Simulation and Modeling (SIM) was formed in 1967 (without the word Modeling in it) as ACM SIGSIM. This group has had various activities over the years including publishing thirty-two issues of the ACM/SIGSIM *Simuletter* during 1972-1980 that were highly read, special conferences beyond being a sponsor of WSC, and having a highly recognized award. Other societies such as the Institute of Industrial and Systems Engineers (IISE) and Institute of Electrical and Electronics Engineers (IEEE) have groups whose interests include simulation. One important activity of most societies is that they have journals which communicate important ideas and aid in developing scientific respect for their subject matter such as for simulation, which is discussed in Subsection 3.2.2.

3.3.2 Awards

The INFORMS Simulation Society annually gives three awards. Each award has become distinguished, each aid in raising the stature of simulation, and each was among the first of its type to be given by any society. The oldest award is the Best Simulation Publication Award that was first given in 1981. It was initially for only papers published in *Management Science* but was extended to cover essentially any simulation publication beginning in 1986. The Distinguished Service Award for service to the simulation community was established in 1985. The most prestigious award is the Lifetime Professional Achievement Award (LPAA) that was first given in 1998. ACM SIGSIM established a Distinguished Contributions Award that was first given in 2007.

3.3.3 Non-Simulation Eminent Scholars Contributions to Simulation

There are some eminent scholars, whose primary areas were not simulation, who have made substantial contributions to simulation that have had significant effects on increasing scientific respect for simulation. Three such individuals are discussed in this subsection who have made contributions in different ways.

Robert E. Bechhofer, who was a Professor at Cornell University and is the "father of Ranking and Selection (R&S) methods, was "the person" responsible for bringing R&S methods into simulation. He taught R&S methods to Richard W. Conway, who was probably the first person to bring R&S into the simulation literature through his well-known 1963 publication. Bechhofer also taught R&S to others in simulation, including Edward J. Dudewicz and David Goldsman who have published numerous R&S papers in simulation. Bechhofer (1977) also presented a paper on R&S at the 1977 WSC at my request.

Donald E. Knuth, Professor Emeritus of The Art of Computer Programing at Stanford University, wrote as Chapter 3 in Volume 2 (1969) in his well-known *The Art of Computer Programming* series of books a comprehensive and definitive work (at that time) on the generation of random numbers. Knuth was also a co-developer of the Simulation Oriented Language (SOL) for Burroughs computers. SOL was one of the very early (mid-1960s) simulation languages and it had some very interesting aspects (Henriksen 2009, Nance 1996). Knuth's contributions to simulation bring with them scientific respect and this increases scientific respect for simulation.

Donald L. Iglehart, Professor Emeritus at Stanford University, who initially established himself as an eminent scholar in stochastic processes and who later in his career also performed simulation research, was the Ph.D. advisor to eleven individuals (among others) who made important contributions to simulation in their Ph.D. dissertations and/or in their research after completion of their Ph.Ds. Scientific respect was brought to simulation by this eminent scholar in a related field by being a Ph.D. advisor to these eleven students, especially since some of these eleven individuals received awards for some of their simulation publications.

3.3.4 Computer Simulation Archive

The Computer Simulation Archive was established in 1998 at the North Carolina State University Libraries, whose website is http://d.lib.ncsu.edu/computer-simulation/about. The establishment of this archive brought considerable scientific respect to simulation as archives are usually established only for important fields. Being the recipient of a National Science Foundation (NSF) grant in 2011 to obtain video oral history interviews of the pioneers of simulation for the archive added further scientific respect to simulation. Twenty-five videos were developed with this grant, with each video having a length of around sixty minutes. These videos are available on the web and have received considerable viewing. (See http://d.lib.ncsu.edu/computer-simulation/videos.) Also, there is a set of papers on the archive in the History of Simulation track in these *Proceedings*.

4 ACHIEVING SCIENTIFIC RESPECT

Scientific respect for simulation has changed considerably over time. As discussed in Sections 1 and 2, there was a lack of respect for simulation as a problem-solving technique starting with the beginning of (digital) simulation in the 1950s and continuing until the early 1990s. The evolution of simulation discussed in Section 3 caused the respect for simulation as a problem-solving method to change from being a "method of last resort" to becoming in the 2010s a "method of choice." This became possible only because computer-technology developments allowed cost effective S^3s (simulation software systems) to become available that contain science-based methods for conducting simulation studies. The science-based methods and the S^3s came about as portions of the simulation evolution as discussed in Section 3. Furthermore, as discussed in Sections 1 and 2, there was a lack of scholarly respect for the field of simulation and for the individuals developing simulation by a significant portion of the scientific community during the latter part of the 1960s and the 1970s. This lack of scholarly respect changed to scholarly respect in the 1980s and beyond primarily because of the evolution of simulation discussed in Section 3. The quality of the science-based methods developed and published along with the establishment of "simulation departments" in journals was extremely important in causing this change in scholarly respect.

My view of how scientific respect for simulation changed across the decades of simulation is shown in Figure 1. A negative implies a negative view and a plus implies a positive view. The number of negatives or pluses implies the degree of negativity or positivity. As readily seen in the figure, my view is that scientific respect for simulation changed from being negative to positive in the 1990s. The quoted comments about scientific respect for simulation given in Sections 2 and 3 support this view (or at least do not conflict with this view). Furthermore, I believe that scientific respect will continue to be high for simulation in the future.

Decade	**1950s**	**1960s**	**1970s**	**1980s**	**1990s**	**2000s**	**2010s**
Scientific Respect	−	− −	− −	−	− +	+	+ ++

Figure 1: Scientific respect versus decades.

5 CONCLUDING REMARKS

This paper discussed how scientific respect for simulation was changed by the evolution of simulation. This evolution of simulation caused simulation to become a problem-solving method of choice instead of a problem-solving method of last resort; furthermore, it caused simulation and the developers of simulation to attain scholarly respect. This evolution came about by the natural occurrence of the development of a new scientific field, as contrasted to being specifically planned.

I expect the evolution of simulation will continue and also simulation to have considerable scientific respect and stature in the future. For example, I expect evolutionary processes to create new ways of how "big data" can be used directly in simulation models and also on how the generation of *distributions* of model output variables can be used in decision making instead of using, e.g., merely output means. An example of the latter is using simulation model data as statistical reference distributions for model validation (Sargent 2001, 2013; Sargent, Goldsman, and Yaacoub 2016). New computer technology, new science-based solution methods, and new simulation software systems will continue to be developed resulting in continued evolution of simulation. Continued and new ways and uses of simulation will cause increase scientific respect for simulation.

Let's remember and use: ***Simulation today has considerable scientific respect, and this respect is the result of the evolution of simulation.***

ACKNOWLEDGMENTS

I thank David Goldsman, W. David Kelton, Richard E. Nance, and Thomas J. Schriber for their comments on early versions of this paper. These comments caused the quality of this paper to improve.

REFERENCES

Bechhofer, R. E. 1977. "Selection in Factorial Experiments". In: *Proceedings of the 1977 Winter Simulation Conference*, edited by H. J. Highland, J. W. Schmidt, and R. G. Sargent, 65–70. Piscataway, New Jersey: Institute of Electrical and Electronic Engineers, Inc.

Conway, R. W. 1963. "Some Tactical Problems in Digital Simulation". *Management Sci.* 10(1): 47–61.

Forrester, J. 1961. *Industrial Dynamics*. Cambridge, MA: MIT Press.

Harling, J. 1958. "Simulation Techniques in Operations Research – A Review". *Operations Research* 6 (3): 307–319.

Harpell, J. L., M. S. Lane, and A. H. Mansour. 1989. "Operations Research in Practice: A Longitudinal Study". *Interfaces* 19 (3): 65–74.

Henriksen, J. O. 2009. "Efficient Modeling of Delays in Discrete-Event Simulation". In: *Advancing the Frontiers of Simulation*, edited by C. Alexopoulos, D. Goldsman, and J. R. Wilson, 105–141. New York: Springer.

Knuth, D. E. 1969. "Chapter 3 – Random Numbers". In: Volume 2 of *The Art of Computer Programing – Seminumerical Algorithms*. 1st ed. Reading, MA: Addison-Wesley.

Lane, M. S., A. H. Mansour, and J. L. Harpell. 1993. "Operations Research Techniques: A Longitudinal Update 1973–1988". *Interfaces* 23 (2): 63–68.

Lucas, T. W., W. D. Kelton, P. J. Sanchez, S. M. Sanchez, and B. L. Anderson. 2015. "Changing the Paradigm: Simulation, Now a Method of First Resort". *Naval Research Logistics* 62: 293–303.

Markowitz, H., H. W. Karr, and B. Hausner. 1963. *SIMSCRIPT – A Programming Language.* Englewood Cliffs, NJ: Prentice Hall.

Morgan, C. L. 1989. "A Survey of MS/OR Surveys". *Interfaces* 19 (6): 95–103.

Nance, R. E, 1996. "A History of Discrete Event Simulation Programming Languages". In: *History of Programming Languages – II*, edited by T. J. Bergin and R. G. Gibson, 369-427. New York: ACM Press.

Nance, R. E. and C. M. Overstreet. 2017. "History of Computer Simulation Software: An Initial Perspective". In: *Proceedings of the 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Nance, R. E. and R. G. Sargent. 2002. "Perspectives on the Evolution of Simulation". *Operations Research* 50(1):161-172.

Naylor, T. H., and J. M. Finger. 1967. "Verification of Computer Simulation Models". *Management Science* 14 (2): B92–B101.

Powers, M. J., S. M. Sanchez, and T. W. Lucas. 2012. "The Exponential Expansion of Simulation in Research". In: *Proceedings of the 2012 Winter Simulation Conference*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A. M. Uhrmacher, 1552–1563. Piscataway, New Jersey: Institute of Electrical and Electronic Engineers, Inc.

Roberts, S. D. and D. Pegden. 2017. "The History of Simulation Modeling". In: *Proceedings of the 2017 Winter Simulation Conference*, edited by W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Sargent, R. G. 2001a. "Graphical Displays of Simulation Model Data as Statistical References." In *Simulation 2001: Proceedings of Fourth St. Petersburg Workshop on Simulation*, edited by S. M. Ermakov, Yu. N. Kashaanov, and V. B. Melas, 109–118. St. Petersburg, Russia: Publishers of Chemistry Research Institute, St. Petersburg University.

Sargent, R. G. 2013. "Verification and Validation of Simulation Models". *Journal of Simulation* 7: 12–24.

Sargent, R. G., D. M. Goldsman, and T. Yaacoub. 2016. "A Tutorial on the Operational Validation of Simulation Models". In: *Proceedings of the 2016 Winter Simulation Conference*, edited by T. M. K.

Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 163–177. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Schrank, W. E., and C. C. Holt. 1967. "Critique of Verification of Computer Simulation Models". *Management Science* 14 (2): B104–B106.

Schriber, T. J. 1992. "The Renaissance Period (1976–1985)". In: *Proceedings of the 1992 Winter Simulation Conference*, edited by J. J. Swain, D. Goldsman, R. C. Crain, and J. R. Wilson, 7–17. Piscataway, New Jersey: Institute of Electrical and Electronic Engineers, Inc.

Schruben, L. 1987. "Chairman's Message". In: *Newsletter of the TIMS College on Simulation and Gaming* 11 (2): 2–3.

Shannon, R. E. and W. E. Biles. 1970. "The Utility of Certain Curriculum Topics to Operations Research Practitioners". *Operations Research* 18 (4): 741–745.

Tocher, K. D. 1963. *The Art of Simulation*. English Universities Press: London

Wagner, H. M. 1969. *Principles of Operations Research with Applications to Managerial Decisions*. 1st ed. Englewood Cliffs, NJ: Prentice Hall.

Wagner, H. M. 1988. "OR Forum – Operations Research: A Global Language for Business Strategy". *Operations Research* 36 (5): 797–803.

Weston, Jr., F. C. 1973. "Operations Research Techniques Relevant to Corporate Planning Function Practices: An Investigative Look". *The Academy of Management Journa*l 16 (3): 507–510.

Zeigler, B. P. 1976. *Theory of Modelling and Simulation.* New York: John Wiley & Sons.

Zeigler, B. P. 1984. *Multifacetted Modelling and Discrete Event Simulation*. London: Academic Press.

Zeigler, B. P. 1990. *Object-Oriented Simulation with Hierarchical, Modular Models*. London: Academic Press.

AUTHOR BIOGRAPHY

ROBERT G. SARGENT is a Professor Emeritus at Syracuse University. He has made numerous contributions to the simulation community in the forms of both service work and scholarly publications. His many honors and awards include being a recipient of the 1988 Distinguished Service Award and the 2002 Lifetime Professional Achievement Award from I-SIM, the 2010 Board of Directors James R Wilson Award and the 40th Anniversary Landmark Paper Award from WSC, and the 2012 Distinguished Contributions Award from ACM/SIGSIM. Moreover, he was elected a Fellow of INFORMS in 2005. He initiated the rebirth of the WSC in 1976, was General Chair of the 1977 WSC, and served on the Board of Directors of WSC for 10 years. Furthermore, he was the Founding President of the WSC Foundation, served as President of The Institute of Management Sciences College on Simulation and Gaming (now I-SIM), and initiated the establishment of the Computer Simulation Archive. His email address is rsargent@syr.edu.