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Past challenges and the future of discrete event simulation

Andrew J Collins, Farinaz Sabz Ali Pour, and Craig A Jordan

Abstract

The American scientist Carl Sagan once said: "You have to know the past to understand the present." We argue that having a meaningful dialogue on the future of simulation requires a baseline understanding of previous discussions on its future. For this paper, we conduct a review of the discrete event simulation (DES) literature that focuses on its future to understand better the path that DES has been following, both in terms of who is using simulation and what directions they think DES should take. Our review involves a qualitative literature review of DES and a quantitative bibliometric analysis of the Modeling and Simulation (M&S) literature. The results from the bibliometric study imply that demographics of the M&S community are rapidly changing, both in terms of the nations that use M&S and the academic disciplines from which new simulationists hail. This change in demographics has the potential to help aid the community face some of its future challenges. Our qualitative literature review indicates that DES still faces some significant challenges: these include integrating human behavior; using simulation for exploration, not replication; determining return on investment; and communication issues across a splitting community.

Keywords

Discrete event simulation, future of simulation, bibliometric analysis

1. Introduction

Discrete event simulation (DES) is applied to many domains to help solve problems. From defense to transportation to healthcare, DES helps users understand complex issues and learn how to handle related problems. Over its history, DES has changed due to technological advancements and new requirements by its customers. In this paper, we follow this journey of advancement, and its related challenges, to understand where we are right now and where we, the DES community, might be going in the future.

By community, it is meant ''a collaborative group of users who must exchange information in pursuit of their shared goals, interests, missions, or business processes and who therefore must have shared vocabulary for the information they exchange'' as defined by the North Atlantic Treaty Organization (NATO).[1] We do not limit this definition to formally recognized DES communities but all communities that use DES. This includes users, developers, customers, vendors, and so on, from any industry or nation. However, such an inclusive range of topics and application areas would be difficult to cover in a single paper adequately, and, as such, this paper does not attempt to cover all of DES and its advancements. Its focus is, primarily, on the academic DES community.

DES is one of the most popular fields of simulation,[2] initiated in the 1950s.[3] Throughout the history of DES, multiple software packages have emerged, and numerous successful applications have been reported.[4] Nance[5] defines DES as the ''utilization of a mathematical model of a physical system that portrays state changes at precise points in simulation time.'' More simply put, a DES breaks down the dynamic changes in a system into discrete events and resolves each event one at a time; this resolution might result in new events being created. The

Old Dominion University, USA

Corresponding author:
Andrew J Collins, Old Dominion University, 2101 Engineering Systems Building, Norfolk, VA 23529, USA.
Email: ajcollin@odu.edu

popularity of DES stems from its natural ability to match the formal logic of finite-state machines.

This paper shows the results of a review of the historic DES literature describing who is using simulation and what directions they think DES should take. To try to cover all of the Modeling and Simulation (M&S) enterprise in a single literature review would be a fool's errand, even when limited to just DES, and, as such, the focus of the review is on papers that explore the future of DES or its challenges. By better understanding the path that DES has taken, the paper hopes to give the reader insight into the future direction of M&S in general.

The automation of computational modeling started to emerge after the Second World War.[6] To cover this long history, our analysis of the literature has been split into decades. Our research was also divided into two types, namely, a prose discussion and a bibliometric analysis. The prose discussion gives a brief summary of the significant events of each decade, including some important events from non-DES M&S where appropriate. The end of each decade's discussion is followed by a review of the DES-related challenges and predictions for DES (or M&S in general) presented in that decade. Although a solitary prose discussion has been the de facto standard for literature reviews in the simulation community, some have argued that a more quantitative approach should be employed.[7] To respond to this suggestion, we conducted a bibliometric analysis of the literature using metadata of that literature, namely, the author's country of origin and the publication date. This quantitative analysis allowed for a much larger sample to be considered than the prose summary. The quantitative analysis considered approximately 23,000 articles, whereas we limited the prose description to approximately 130 articles. We did not limit the quantitative analysis to only DES-related papers (although we mainly considered journals that publish DES studies); as such, it provided a much broader view of M&S. The prose discussion is given in the next section, followed by the quantitative analysis.

2. Chronological history of the challenges of M&S—a prose discussion

This section provides a limited review of the history of DES, including discussions on what the extant literature has previously said about the challenges that DES faces. This review has been split into several sections; each section represents a decade of DES history, except for the first section, which covers all history before 1960. Each section provides a brief discussion on related events of the decade followed by a review of the challenges that were set by the community in that decade; where possible, any predictions, about the future of M&S, from that decade were also included in each section.

The information provided in the following sections was mainly drawn from the academic literature. The gray literature, that is, reports and articles that are not formally published and peer-reviewed, were purposely avoided, where possible, due to the difficulty they impose on the reader to find these source materials. The articles were drawn from several sources, including academic journals (e.g., *Simulation* and *Journal of Simulation* (JOS)), conference proceedings (e.g., *ModSim World Conference* and *Winter Simulation Conference*), and industrial sources (e.g., *the Society for Modeling and Simulation International (SCS) M&S Magazine*, and the *North Atlantic Treaty Organization (NATO) workshops*).

Our focus was on the DES literature, which included a discussion of strengths, challenges, and, most importantly, its future forecasts. We do not claim to have found and covered all articles that relate to these discussions, and the papers were mainly drawn from the sources described above. To limit the number of articles considered, we avoided discussing those related to a specific topic area, for example, training, or articles that related to the development of specific DES unless they made a more general comment on DES.

Each section only includes the challenges and predictions made in that decade from the literature. We do not claim that we have found all papers that talk about DES challenges and predictions that have been written over the past 60 years although we have made our best attempt to do so.

2.1. Pre-1960s

Simulation has been around for centuries, from the use of chess to train military leaders to mechanical flight simulators used in the First World War. Computer simulation came in the late 1940s.[8] The most critical event in the founding of computer simulation was the invention of the Monte Carlo method by Metropolis and Ulam in 1946.[9,10] Random number generators, essential to stochastic DES, were emerging before the 1960s with the first table of random numbers published by Tippett,[11] which included 41,600 random digits.[12]

The concepts of DES emerged in the late 1950s.[13] Conway et al.[14] used M&S for queueing networks that represented manufacturing systems such as job shops, still one of the significant applications of DES. Conway et al.[15] also began the academic discussion on DES, including discussions of the main characteristics of common DES models, the problems in constructing DES models with digital computers, and the issues of using DES models.

2.1.1. The future of simulation from the pre-1960s.

The prediction for the future of M&S, for the following decade, was the further development of DES. Outside of DES, there was widespread expectation that electronic computers could realize the potential of the Monte Carlo method.[16]

In summary, in the 1950s, the concepts of DES were developed, and there was a significant focus on academic research on the main characteristics of DES models with digital computers. With the increase in studies of the characteristics of DES models, more of the challenges were identified.

2.2. The 1960s

The beginning of DES, as a subject, occurred during the 1960s.[7] In the remainder of this paper, we refer to the subject of DES as simply "simulation." The decade saw the invention of many techniques that are still in use today, including Tocher's three-phased approach[17] and systems dynamics.[18]

The simulations of the early days of M&S were bespoke until Tocher and Owen[19] wrote the first general-purpose simulation software package at the United Steel Companies in Sheffield, UK, known as the General Simulation Program (GSP). For a while, it became the standard tool for developing simulations. A rival programming language was invented at IBM by Gordon[3,20] called the General Purpose Simulation System (GPSS).

The first significant simulation textbook appeared in this decade, starting with Keith Tocher's[21,22]"Art of Simulation," which highlighted many of the ideas relating to GSP. An interesting note was that the GPSS equivalent, "Simulation with GPSS," was not realized until 10 years later.[23] The 1960s also contained the first paper describing the modeling process[24] as well as the first papers that discussed verification and validation (V&V), by Fishman and Kiviat,[25] which discussed simulation statistics,[26] and the work of Naylor et al.[27] This desire for rigor was internally driven by the M&S community as "the customer knew very little and believed just about anything that was presented; if the computer printed it out, especially lengthy tables, it must be true";[28] sadly, this phenomenon still exists today.[29] Also, SIMULA (SIMulation LAnguage), as the language designed to facilitate the formal description of the layout and rules of operation of systems with discrete events (changes of state), was developed in 1965.[30] Simscript, an important language of DES, and the idea of Virtual Interactive Simulation (VIS) were introduced this decade.[31]

Object-Oriented Programming (OOP), which uses collections of independent components that provide a specified service by the interface that incorporates ideas of inheritance and polymorphism,[32] was developed in this decade for simulation application.[27] OOP is now a standard approach used in software development, not just simulations.

The decade also saw the first Winter Simulation Conference (WSC) in 1967, which has continued to this day;[33] it was initially called the C*onference on Applications of Simulation Using the GPSS*. There had been an earlier IBM symposium on Simulation and Gaming in Washington in 1965.

2.2.1. The future of simulation from the 1960s. It was only four years beyond GSP's introduction that the first journal paper on the future of computational simulation was published by Conway.[34] Many of the problems discussed in this paper are of limited concern to the modern simulationist due to the vastly superior computing power and data storage solutions available today.[35]

However, Conway's paper did contain at least one quote that remains relevant today: "With proper operating procedures, a simulation model can produce relative results much more efficient than absolute results." Even in those early days, simulationists recognized the power of simulation was not to replicate the real world but to explore its possibilities.

There were some concerns about the practical usage of simulation, as some saw it as the "tool of last resort,"[36] a view that would persist into the 1990s until cheap commercial simulation packages became available. It was also thought that "simulation was ... not for those with practical problems and deadlines";[28] this viewpoint was not helped by the DES community, whose focus was on the comparison of GSP and GPSS as opposed to "what can we do with the languages."[33] The problem of focusing on a comparison persists today with the comparison discussion of DES and Agent-Based Modeling (ABM) that has occurred in the literature;[37–39] the energy dedicated to these discussions would be better served in determining how to expand M&S to a broader audience.[40] It should be noted that some consider ABM just to be a form of DES.[41]

In looking to the future of M&S (i.e., the 1970s), Smith and Sheaham[42] wrote a paper that highlighted two concerns: showing the return on investment (ROI) on simulations and working in a restricted budgetary environment. Concerns still relevant today.[43] Another issue at the time was visualization, as discussed by Araten et al.[8]

The significant development of this decade was the invention of new techniques, including OOP and system dynamics. The start of the simulation conference (WSC) was notable; the publication of the first significant simulation textbook,[21] the first papers discussing the modeling process description,[24] and V&V[25] were the other important events of this decade.

The main concerns for the future, highlighted in this decade, were the practical usage of simulation, the need to expand M&S to a wider audience, the need to develop better visual simulation, and how to show ROI. All these concerns persist today.[40,43–45]

2.3. The 1970s

The 1970s saw a vast expansion of the DES world, which might be called its renaissance period,[46] and the decade saw the highest attendance of the WSC.[46] Robinson[2] called this decade the period of innovation. The decade also saw great technical leaps with the creation of Discrete Event System Specification (DEVS),[47] the birth of ABM,[48] and parallel simulation.[49] Also, the GPSS/H[50] provided dramatic improvements in execution speed and interactive debugging; both were major methodological advances. Simulation was also starting to be accepted across the disciplines; for example, a simulation department of the journal of Management Science was formed in 1978.[51] It should be pointed out, that although DES was well used in this decade, we have limited our discussion due to the lack of papers found relating to the future of DES specifically.

2.3.1. The future of simulation from the 1970s. During the 1970s, simulationists were prepared to take on grand challenges, and *world* modeling became a hot topic.[46,52] This enthusiasm for world modeling was soon tempered when the practical limitations (the credibility of results, model confidence and evaluation, and model documentation) became apparent; this resulted in a new focus on the more practical aspects of M&S like the development of V&V methods[26] and striking a balance between the ease of use of a simulation package and its flexibility.[53] In this decade, there was a significant expansion in DES and, by the end of this decade, it was predicted the future decade would experience a revolution in M&S and DES.[2]

2.4. The 1980s

In the DES world, there was an increased interest in manufacturing simulation, as seen by an increase in journal articles.[54] Although there had been massive enthusiasm for DES and M&S at the end of the previous decade, this enthusiasm began to wane in the 1980s; for example, the INSIGHT simulation language developed through the 1980s, and others, failed to be as successful as predicted.[53] Outside of DES, this decade was critical for the expansion of training simulations and there were also calls for standardization,[55] including interoperability and data standards. The use of DEVS expanded in this decade.[56]

2.4.1. The future of simulation from the 1980s. Within the DES world, the need to develop better animation became apparent.[53] Henriksen[57] pointed out the need for better graphical interfaces (a problem with the simulation that had persisted since the 1960s), and the need for better integration of simulation environments, which we, in modern times, would refer to as the interoperability and composability problems. Henriksen, also, observed that creating simulation was a more substantial and abstract problem than just computer programming. Another issue for the simulation community was that the simulation ''marketing environment is still top-heavy with buzzwords and technology descriptions'';[55] this problem still plagues the community today, even though there has been a change in the buzzwords used.[45]

Reitman[28] provided some discussion on the future challenges of simulation in his 1988 paper. He advocated for the future need for better parallelism, the ability to run a simulation in real-time, observing simulation through graphics (especially three-dimensional (3D) graphics), and better features to more easily build simulations, especially by unsophisticated users. Arguably, all these challenges have been met within the DES community. However, there are some of these challenges that have not been met, namely, ''a complex real-time model to be run and observed in real-time and at specific choke points to continue the real-time processing.''

2.5. The 1990s

The 1990s saw new possibilities for simulation being discussed and implemented, especially with the rise of 3D graphics and several commercial off-the-shelf (COTS) simulation packages entering the market.[58] These COTS were a significant advance for DES since they reduced the debugging time required.[59] Interoperability standards, like Distributed Interactive Simulation (DIS) and High-Level Architecture (HLA), emerged.[60] Crain et al.[59] argued that this emergence came about because one vendor could not supply all the software needed; however, it could just have occurred due to the desire to connect various disparate systems. The standards were not acceptable to everyone, resulting in the development of new ones, that is, Test and Training Enabling Architecture (TENA).

''Lower hardware costs, coupled with the virtually cost-free operation, potentially places simulation within reach of a much wider community of users'';[59] however, having access to a simulation language does not make you a modeler. This new ease of use opened up the use of simulations to study ''world-class'' problems, and the social sciences began to use simulation after it was championed as the future of research by the political scientist Robert Axelrod.[61] This eventually led to many journals and societies being formed, including the *Journal of Social Simulation and Artificial Intelligence* (JASSS) (http://jasss.soc.surrey.ac.uk) and the *Computational Social Science Society of the Americas* (CSSSA) (https://

computationalsocialscience.org/), both of which are still in existence today.

This era also saw the arrival of new terms, like ‘‘emergence,’’ to the simulation lexicography, although emergence had been seen, but unnamed, in historically famous simulations like Schelling’s[48] segregation model and Boids.[62] There was, however, confusion in the meaning of some of the terminologies. For example, the word ‘‘composability’’ is used to mean two interoperating simulations that had the same underlying concept present, while the word had previously been used to mean the simulation’s flexibility of configuration.[63] The difference in the usage of the word composability occurs due to the use of the word in different contexts.

This growth in terminology demonstrated that simulationists were beginning to think beyond the technical challenges and starting to discuss the more philosophical ones. This included the realization that simulations provide insight into the system; as stated by Crain et al.,[59] ‘‘it has seemed to me that the fundamental output of simulation models is, in fact, insight into the performance of the system.’’ Sterman[64] also realized that simulations are for understanding, not output. The idea of using simulation for insights goes back at least as far as 1978, in which Nygaard and Dahl[65] mention that understanding was derived from their SIMULA software implementation. This realization of the usefulness of simulations was especially crucial for the growth of ABM during this period.[66,67]

Two important journals on M&S and DES were established in this decade. First, the *ACM Transactions on Modeling and Simulation* (TOMACS), (1991 to present) and second, *Simulation Practice and Theory* (1993–2002), which continued as *Simulation Modeling Practice & Theory* till present.

Although simulation saw growth in the 1990s, it was not without its problems. One issue was that the random number generators (RNGs) used were plagued with problems.[68] However, by the end of the decade, new RNGs were created that overcame these problems, for example, Mersenne Twister.[69] Due to some of the simulation problems, more profound discussions about simulation philosophy arose in this decade.[70]

Another issue with the growth of simulation use was the mis-selling of simulation. As Crain et al.[59] pointed out, ‘‘overenthusiastic marketing tends to oversell the technology, and it is too easy to perpetuate a cruel hoax on the naive user.’’ This problem of simulation misuse still exists today.[71] Salt[29,72] collected a list of seven classes of mistakes (trifle-worship, belief in answers, connectionism, the black box mistake, methodolatry, the dead fish fallacy, and the Jehovah problem) that he saw in the practical development of simulations in his decades of experiences with M&S. Finally, computer simulation had existed for 40 years by the end of the millennium, and, as such, a simulation archive was announced at the 1998 WSC to preserve the historical record of simulations that had been created.[73,74]

2.5.1. The future of simulation from the 1990s.

At the beginning of the decade, Law[75] discussed the future of simulation. This discussion included making simulations easy-to-use by appointing a ‘‘no-programming approach’’ (what we now call a visual object-based approach). Law also discussed the need to introduce 3D visualizations into simulations. Later, Hollocks[17] pointed out that the simulation community efforts far exceeded Law’s predictions. For example, manufacturing simulation was made easier with the development of several COTS simulation packages, many of which are still around today, for example, Arena. In terms of visualization, Crain et al.[59] point out that ‘‘these days, we are probably animating more simulations that needn’t be animated than we are failing to animate simulation that should be.’’

Due to the enormous growth in the computer simulation community, which paralleled the increase in the personal computer market during this decade, there were more organizations within the simulation community and, eventually, more discussion on the community’s direction. Toward the end of the century, new challenges started to appear. These challenges included the need to better recognize the users’ needs.[76] Some of the challenges posed in this decade were a little further reaching, such as the development of consciousness within simulations.[77]

Patenaude[78] discussed some of the M&S challenges from a US Department of Defense (DoD) perspective. Some of these challenges were overcome, for example, creating physics-based simulations (see Unity3D for an example solution) and acceptance of M&S. However, many of the challenges persist in the modern era, for example, interoperability issues, funding, workforce development, and validation.

In summary, this decade saw the emergence of new terms; there was a significant advancement with the development of 3D graphics and COTS simulation packages. The usage of ABM grew too, which some consider an extension of DES.[41] Multiple challenges were identified, such as RNG problems and the misuse of simulation. Several challenges were identified, and, arguably, many of these challenges have been met by the community.

2.6. The 2000s

During the start of this century, it was recognized, by some, that DES focus had moved away from the ease of use toward connectivity.[17] This shift could be seen in the formalization of interoperability standards like Institute of

Electrical and Electronics Engineers (IEEE) Std 1516™ for HLA and IEEE Std 127™ for DIS. In 2003, the Simulation Interoperability Standards Organization (SISO) was recognized as the standards development organization by the IEEE. These standards are still supported by the DES and larger M&S Enterprise.

However, these standards were not recognized by some emerging simulation communities, who are developing their own ontologies and standards, for example, the Overview, Design concepts, Details (ODD) protocol for ABM[79,80] used in the ecological and social science communities. There was a divergence in ideas and ideology, which could be seen in the description of the approach for validating ABMs. There were some who regularly attended the WSC that advocated empirical validations of ABM,[81,82] whereas others were advocating a more hybrid approach, including face validation[83] (e.g., the use of subject matter experts), program slicing[84] (e.g., evaluation of the simulation's code to determine what causes the emergent results), and role-playing[85] (e.g., asking human participants to act the role of the simulation agents and comparing the outcomes). The divergence of the larger M&S Enterprise could be seen in the establishment of important, but focused, journals including, *Multiscale Modeling and Simulation* (2003), *Journal of Defense Modeling and Simulation* (2004), and *Simulation and Healthcare* (2006). Another journal that was established in this decade was the JOS (2006), which was established by the UK's Operations Research simulation community.

One of the significant changes to the M&S enterprise make-up was the rise of the healthcare simulation community. In 2001, the first International Meeting for Medical Simulation (IMMS), which would become the International Meeting for Simulation in Healthcare (IMSH), was held. There were over 2500 attendees, so not quite the 15,000+ that Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC) receives, but IMSH is still growing. Like social simulation, the rise in healthcare simulation was due to internal champions, namely, Kohn et al.[86] and her book *To Err is Human*. Previous to this rise, even though hundreds of DES healthcare simulations had been developed, only a handful got practically applied;[87] it should be noted that the rise of healthcare simulation was not due to DES, but training simulation.

The different factions of the DES community were not only divided by subject but also by country. By 2007, 40% of WSC attendees were from outside the United States.[88] The second part of the paper discusses this change in detail.

New simulation methodologies began to arise during this decade, for example, simulation optimization[89] and hybrid simulation.[90] Brailsford and colleagues[91,92] describe modern hybrid simulation as simulation involving DES, agent-based simulation, and/or systems dynamics, although a precise definition is in dispute. Arguably, the modern use of the term hybrid simulation was just a new form of combined simulation from the late 1970s.[59] With the rise of hybrid modeling, DES can no longer be considered in paradigm isolation.

2.6.1. The future of simulation from the 2000s. At the time, some authors were able to see that the DES users were changing;[17] this change in demographics was due to the lack of growth in the use of simulation for industrial applications and the growth of its use in social and healthcare applications. Taylor and Robinson[4] even questioned whether simulation practitioners (in general) should be software engineers, and the rise of different factions of simulation users would lead to ''more domain-specific software, with model re-use and ease of use for non-simulation specialists.'' This certainly is the case in the modern era, within the M&S enterprise, that is, simulation communities hosting their own conferences, that is, IMSH, I/ITSEC, and so on. The demand for ease of use and development of simulation led to new COTS being developed, including AnyLogic and Simul8 in 2000 and Simio in 2008.[53]

The start of the new millennium was an exciting time for being a discrete event simulationist. Macedonia[93] pointed out that ''Moore's law [double of computing power every year] was being outstripped and did not seem to come to an end, opening up great possibilities for simulation.'' This sentiment, combined with the advent of Joint Simulation Systems (JSIMS)—the most ambitious military simulations of all time, Joint Warfare Simulation (JWARS) and Joint Modeling and Simulation System (JMASS) led to much enthusiasm about simulation (eventually, JSIMS had severe cost overruns and other technical problems which lead to its decline). This enthusiasm led to several discussions on grand challenges for simulation, starting with a Standard Interoperability Workshop (SIW) during the fall of 2000. These workshops revealed several challenges for simulation, including a need for rapid simulation development, incorporating real human behavior in simulations (although this discussion was begun in DoD a decade earlier[94]), and the development of StarTrek—the next generation's holodeck,[95] where simulations would be indistinguishable from reality.[96] These challenges remain to the current day.

There were two follow-on workshops on grand challenges for simulation: the First International Conference on Grand Challenges for Modeling and Simulation (ICGCMS), which was held as part of the Society for Modeling and Simulation International Western Multiconference, 27–31 January 2001 in San Antonio, Texas, USA,[97] and Dagstuhl Seminar for Grand

Challenges in Modeling and Simulation, held 26–30 August 2002 in Dagstuhl, Germany.[98] The outcome of these workshops was a special issue of the journal *Simulation*. The special issue discussed several concerns of simulation, from the design of simulation architecture, which took advantage of high-performance computer microprocessors,[99] to the use of visualization in creating models.[100,101] The former has now been resolved, and the latter was not taken up by the community. Some challenges had disappeared, like the need to create orders-of-magnitude savings for solving manufacturing problems.[102]

Another concern from the special issue came from Mosterman and Vangheluwe,[103] who suggested that as simulations become "increasingly complex, subsystems models will necessarily become increasingly divergent in their dialects and representative formalisms. Holistic systems models that combine these individual subsystems models will require methods to bridge these dialects and formalisms." We would argue that this sentiment was the basis of hybrid simulation modeling, which has become popular in recent years.[91,104] However, there is no formally accepted definition of hybrid simulation,[90] so whether it encompassed these ideas is not clear.

The change in the demographics in the simulation enterprise led to significant changes within its make-up since there was no longer one dominant customer (i.e., DoD) controlling its funding fate. This sentiment was summed up by Loftin,[96] who said:

> the future of simulation will, in this author's opinion, be determined, not by a systematic, well-coordinated effort of a body of academic researchers, rather it will be determined by forces beyond the control of any individual or small group of researchers—world events and public demand for entertainment will play the predominant role in shaping the future of simulation.

The second half of the decade saw computational simulation turn 50 years old. Different predictions started to emerge, such as the idea that simulation would be an online service,[17,105] which had seen several attempts in preceding years (see https://fleet.vmasc.odu.edu/ and https://beta.cloudes.me/ for examples).

There were several concerns, with DES, from an academic point of view. Taylor and Robinson[4] identified the future major issues of DES in categories of technology, experimentation, applications, and practice through a survey with the JOS editorial board. Tolk[106] argued that more focus was needed on researching modeling and not just technical simulation challenges, which he continues to discuss to this day; this sentiment was supported by Pidd,[107] who pointed out that it did not matter how good the technology was if the underlying models were bad. Somewhat contrary to this statement, Taylor et al.[7] reviewed many simulation articles and argued most lack benefit to the real world; thus, the focus of academic M&S should be the application, not methodology. Simulation optimization suffered from both these problems, incorrect models and lack of application, because "an objective function must be formulated, which hindered the decision maker's ability to consider trade-offs that are not easily quantified."[51]

In summary, at the beginning of this century, the general focus of M&S enterprise continued to shift from ease of use to connectivity. New approaches for ABM validation were developed for new applications to social simulation. Simulation optimization saw improvements, and hybrid simulations were introduced. In this decade, the variety increased in the fields that simulation was being used for and where it was being used. As simulation applications in different fields expanded, there was much more enthusiasm about simulation. This decade predicted the future of M&S to the opening of great possibilities for simulation, especially with the advent of JSIMS (which eventually failed to achieve what was promised). As more groups started to use simulation in different fields of study, new software such as AnyLogic and Simul8 were developed. However, there were some challenges identified, such as the need for rapid simulation development. Several concerns of the simulation were identified from the design perspective to the use of visualization.

2.7. The 2010s

By 2016, the "simulation community covered a very broad church,"[108] and there had been exponential growth in the related M&S literature.[109] The diverging community also brought some new concerns because it was becoming difficult to know what the word *simulation* actually meant.[110] For example, Ören[111] found 400 definitions of simulation. Taylor et al.[110] suggested that simulation would become what those that defined themselves as simulationists did. Taylor also pointed out that just because a simulation was used in a new industry did not mean that it was used everywhere in that industry; for example, there were many medical training simulations, but only a few implemented healthcare DES ones. Severinghaus[112] pointed out that there had been non-technical problems, both legal and policy-related, in garnering widespread simulation adoption in the healthcare industry, for example, "it was actually easier to get data back in the 1970s than it is today."[113] However, this did not seem to have stopped the widespread adoption of medical training simulations.[87]

To embrace the demographic changes in the M&S enterprise, the WSC became international by being located in Berlin in 2012, and Gothenburg in 2018. It is scheduled to be in Singapore in 2022.[114] The Gothenburg conference had about 72.5% of non-USA attendees. The WSC also tried to embrace the new application areas with the introduction of mini-tracks.[114]

Agent-based Modeling and Simulation (ABMS) usage rose during this decade. ABMS became a core methodology,[97,110] but there were also concerns about the ability of Agent-Based Simulations (ABSs) to show benefits.[38,115] This concern was due to ABS being "tools for thinking"; its advantage lays "in the thinking it can inspire rather than quantitative prediction."[38] This view of "simulation to inspire thinking" was discussed earlier in the 1990s. It was argued that ABMS could be useful to the military community[116] although some had argued that ABMS had been used by the military for years.[80]

The decade saw a lot of new technology advances that were useful to the DES community. High-Performance Computing (HPC) rose in its usage in simulation during 2010.[117] Still, it was predicted that the HPC simulation research would need to transform itself to be useful for commercial analysis as it was "still the wild west."[117] We would argue that the scattering of DES across the disciplines could lead to a new "wild west" for the rest of the DES community due to the lack of having a single society for leadership. Other technological advancements included the development of persistent online simulation environments (https://improbable.io/) and the application of simulation optimization.[118] The advances of simulation have made simulation the "method of first resort."[119] The simulation archive was expanded in 2013 by North Carolina State University (NCSU) libraries to create a unique video oral history of computer simulation from 22 pioneers, which are now accessible online.[73]

2.7.1. The future of simulation from the 2010s. Showing the benefit and quality of simulations became the focus during the first part of the current decade, especially its ROI.[43,120] Taylor et al.[97] called for simulations to go through a review process similar to journal articles for publication. Arguably, the DoD Verification, Validation, and Accreditation (VV&A) processes could be used as a policy to resolve this challenge.[121] Collins[122] warned against the use of "cheap" alternative simulations that did not follow standards.

Within the M&S enterprise, M&S concepts were being interpreted differently, which created communication challenges among the professionals of the field.[123,124] Given the diverse community of users, there was a need for more plug-and-play environments[125] so that "simulation will be applied more effectively if the user can focus on the decision, not the method."[126] There also remains the challenge of creating a more simulation-educated workforce.[127]

When it comes to the propagation of simulation, Sadagic and Yates[128] believed the issue was not quality-related but the need for better non-expert peer advertising for simulation adoption. Since both the agent-based and healthcare simulation communities rose from internal champions, this sentiment had historical backing. Sadagic and Yates[128] pointed out that the M&S enterprise needed individuals who were active in its promotion. Taylor et al.[110] pointed out that "building trustable stochastic models of large, complicated systems is one of the biggest challenges we face in M&S research" because simulations are built on uncertainty, and it is hard to sell uncertainty. These views were reinforced by Thaviphoke and Collins.[40]

Cheng et al.[108] suggested that using simulation for decision support would grow in the next decade, especially using simulation heuristics. They argued that the challenge was to show that M&S is an indispensable tool.

In the theme of modeling human behavior, Cheng et al. and Taylor et al.[97] suggested that research needed to be conducted into simulating behavior change in human agents; note that the "agent_zero" concept is a step to addressing this challenge.[129]

There was a continuation of the challenges highlighted in the previous decade. Taylor et al.[110] and Crosbie[35] discussed the technical challenges for input data, which had been a concern for simulation since Conway.[34] Tolk[130] continued his observation that M&S needed to develop its philosophical foundations; Roberts and Pegden[53] warned that there is no common foundational theory for DES.

Collins et al.[131] warned about the dangers of combining advanced techniques, like Artificial Intelligence (AI), into a simulation as it is challenging to understand whether the patterns observed in a simulation's outputs are reflective of the underlying systems or a consequence of the modeling complexity. This issue was especially important when trying to validate a simulation that used AI, as it is difficult to determine whether any unusual output is due to a mistake in the simulation coding.

There were some predictions for the focus of future simulations. Watkins et al.[132] pointed out the need to overcome the technical challenges of modeling megacities and weather effects (Hill and Tolk[60] also mention this challenge). They also pointed out the need for better integration of simulation into mobile technology. Cheng et al.[108] suggested that hybrid simulation and healthcare simulation would be the next big things; both have certainly grown over the last decade.[90] New areas predicted for simulation use included the hospitality industry, especially in conjunction with analytics.[133]

In this decade, there was an exponential growth in M&S literature, WSC became more international, and the application areas expanded significantly. Simulation also shifted from being considered the last option to be the premium choice of the decision-makers. There was a rise in the ABMS application, and it became a core methodology. As more groups began to use M&S, there were various interpretations of M&S concepts, which developed communication challenges among the user groups. In this decade, new technology advances were integrated into simulation such as HPC, online simulation environment, and simulation optimization. Also, the simulation archive was expanded with the oral history of a computer simulation, which became available online.

2.8. Summary of literature review

There have been many changes to the world of simulation over the last 60 years. These include the significant advancements in technology, but they also include a better understanding of DES. In the review of the changes of simulations over the decades, Nance and Sargent[22] suggest that the evolution of the focus of simulation was from system analysis to education and training to acquisition and system acceptance to research to entertainment. We would argue that the new focus is on diversification to non-traditional domains; we base this claim on the discussion given above.

Over the last 60 years, there have been many challenges and predictions made. Some of these ideas were realized relatively quickly, like those predicted by Law[75] and interoperability standards, while others remain unsolved, like determining the ROI of simulation.[43] Some of the challenges were more like wishes as it was infeasible they would be achieved in the modern era, for example, the creation of the holodeck[95] and development of consciousness in our simulations.[77]

One noticeable feature of the challenges provided to the community is that most of the human-based challenges were not resolved, like modeling real human behavior, and simulation use propagation. Over the years, the simulation community has focused on technology challenges as, ultimately, it is a lot easier to discuss the merits of GSP over GPSS or ABMS over DES than it is to discuss matters relating to the human condition. However, simulation has been described as a tool for inspiring thinking and, maybe, newly developed social simulations will help us understand and overcome some of the challenges that the DES community faces. Although we might not be able to solve some of the human-based challenges directly, we, as a community, might be able to create further developments that help in resolving those challenges, for example, making simulations easier to use.

In summary, the previous sections provided a brief review of DES over the last six decades. As the focus was on DES, many related areas were not touched upon, for example, output analysis,[114] although we did discuss general M&S topics where appropriate. Even with this limited scope, we did not cover, in detail, the development of DES in domains like manufacturing, transportation, or energy. We believe that such a comprehensive review would require a book, if not a series of books.

3. Bibliometric analysis

To supplement the literature review, we want to determine the trend in the number of publications being produced in peer-reviewed journals and to identify the primary producing countries of published articles to evaluate where new research is being conducted involving DES and M&S; this includes both their advancement and usage in research. Hence, a bibliometric analysis has been performed at the country level on only 13 English-language journals related to DES. The journals were chosen based on either their focus on DES or because they represent a key journal in a simulation specialization, which publishes DES studies; we do not limit our analysis to only DES-related papers within them, so a broader view of M&S is shown in our results. Other journals do exist which contain simulation papers within them; it would be interesting to investigate the propagation of simulation in these other related journals as future work. The following sections provide the data collection methods, data analysis, results, and discussion.

3.1. Data collection

Bibliometric data were collected from all articles published in the journals that were included in the physical literature review. The data consisted of information such as the author, article title, source, volume, pages, abstract, keywords, country, document type, and published year. The following is a list of the journals included in the analysis:

- *ACM Transactions on Modeling and Computer Simulation.*
- Communications in Statistics—Simulation and Computation.
- Computers and Operations Research.
- International Journal of Simulation Modeling.
- Journal of Artificial Societies and Social Simulation.
- Journal of Defense Modeling and Simulation.
- Journal of Simulation.
- Mathematics and Computers in Simulation.
- Multiscale Modeling and Simulation.
- Simulation.
- Simulation & Gaming.
- Simulation in Healthcare.
- Simulation Modelling Practice and Theory.

Although both the Proceedings of the WSC and the Proceedings of the I/ITSEC are heavily quoted in the prose section of this paper, due to access issues, they were not included in the bibliometric analysis. There are many sources of simulation information; however, we wanted to bound the sources that we considered. We chose the existing peer-reviewed journals due to their global accessibility and creditability. It would not be feasible to include all the simulation conference proceedings that have occurred over the years in our analysis, and it was not clear what exclusion criteria we should use. There are many simulation conferences; some tend to be regional (MODSIM and AlaSim), and some are no longer in existence (Autumn Simulation Conference). Also, there is a question of accessibility; for example, both the I/ITSEC and MODSIM conference proceedings are held on standalone online storage facilities, making meta-analysis difficult to achieve.

The Web of Science was used to obtain bibliographic data (Clarivate Analytics (2018) Web of Science http://apps.webofknowledge.com/). The Web of Science is a citation indexing service that provides access to some online databases that encompass over 80,000 books, 18,000 journals, and 180,000 conference proceedings. It should be noted that the Web of Science did not have a database that contained information about the *International Journal of Simulation and Process Modeling*. Therefore, it was not included in the bibliometric analysis.

The bibliographic data were collected by performing an advanced search of the Web of Science Core Collection using the ISSN numbers for each publication. The advanced search resulted in 23,163 records for the articles in the 13 journals. The ''Full Record'' for each search result was downloaded in BibTeX format.

The BibTeX files were imported into RStudio, an open-source integrated development environment for R, using the R package Bibliometrix;[134] this package is designed to enable the importing of bibliographic data from various Internet sources, and it contains functions that can be used to perform bibliometric analysis on that data. This package provides the ability to extract the published year, journal, and country from the BibTeX files.

It should be noted that a limitation in this analysis was the amount of information that could be extracted from the article records. The format of the bibliographic data was not consistent over the years and from journal to journal. Therefore, not all information was able to be extracted for the analysis. In particular, we were able to grab country information from only 35.6% of the published articles from our data in the 1970s. This percentage increased to 80.7% for the data in the 1980s and 81.0% for the data in the 1990s. This percentage further increased to 96% in the 2000s and 97.6% in the 2010s. Future work includes developing methods to extract these missing data. This limitation of data was also the reason why this analysis started in the 1970s. Since all articles were considered from all of the journals, the bibliographic analysis covers all topics that were deemed appropriate for the simulation journals, not just DES.

4. Results

The following sections provide the results of our analysis of bibliographic data and brief discussions on the results.

4.1. Total annual production

Figure 1 shows the total number of articles published in the 13 journals each year from 1968 through 2017. A gray vertical line identifies each decade. The annual production of published articles appears to be growing at an exponential rate (dotted line).

4.2. Production by country

In addition to looking at the total number of articles published each year for all the journals, an analysis was performed on the highest producing countries per decade. For comparison, within each decade, the member countries of the G7 (Group of Seven) were considered. The G7 is an informal forum of industrialized democratic countries with the seven largest advanced economies in the world (International Monetary Fund, https://www.imf.org/external/pubs/ft/weo/2017/02/weodata/weoselco.aspx?g=119&sg=All + countries + %2f + Advanced + economies + %2f + Major + advanced + economies + (G7)). Members include Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. The purpose of the G7 is to discuss issues on global economic governance, international security, and energy policy. The market share of publications in the analyzed journals of the G7 countries was significant in the early decades.

4.2.1. The 1970s. The top 15 article-producing countries during the 1970s are provided in Table 1. Of these countries, five are members of the G7, including the top three.

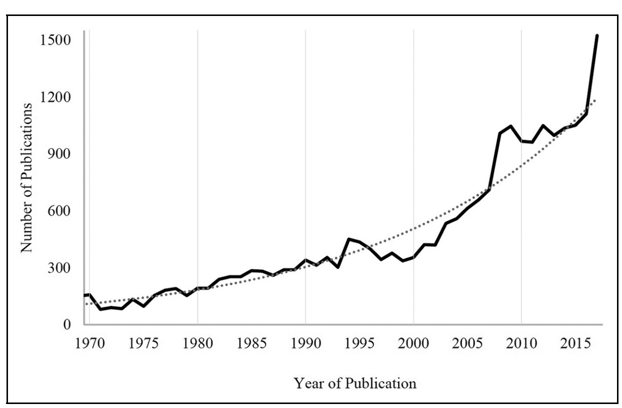

Figure 1. Annual total production (1968–2017).

Table 1. Production by country (1970s).

Country	Articles	Percentage
The United States	251	51.9%
Canada	58	12.0%
The United Kingdom	62	12.8%
Israel	22	4.5%
The Netherlands	15	3.1%
Australia	14	2.9%
Denmark	11	2.3%
India	8	1.7%
Sweden	8	1.7%
Italy	6	1.2%
South Africa	5	1.0%
Belgium	4	0.8%
Finland	3	0.6%
Germany	2	0.4%

Table 2. Production by country (1980s).

Country	Articles	Percentage
The United States	1255	61.3%
Canada	167	8.2%
Australia	76	3.7%
The United Kingdom	72	3.5%
Israel	47	2.3%
The Netherlands	45	2.2%
France	44	2.1%
Italy	35	1.7%
India	28	1.4%
Japan	27	1.3%
Finland	23	1.1%
Greece	22	1.1%
Switzerland	13	0.6%
Belgium	12	0.6%

The two missing are Japan and France (ranked 17 and 23, respectively). The G7's total market share of publications is 76.2%. An astute reader will notice that there are only 14 entries in both Tables 1 and 2. This is due to analysis reporting England and Scotland separately; as a result, they were combined (along with papers from Wales) to form the United Kingdom entry. The United States produced the most articles with 251, followed by Canada (count: 58) and the United Kingdom (count: 49). The United States produced over four times as many published articles as second-ranked Canada and contributed 51.9% of the total publications.

4.2.2. The 1980s. The top 15 countries for article production during the 1980s are provided in Table 2. The total number of G7 countries increased to six. France and Japan were included (7th and 10th, respectively), and Germany dropped to the 48th position. The market share of the G7 countries' publications remained high at 77.5%.

The United States was still ranked 1st with 1255 publications, followed by Canada (count: 167) and Australia (count: 76). There was a significant increase in the US' production of articles in comparison to other nations. The United States produced almost 7.5 times as many published papers as second-ranked Canada. The US percentage of total articles published increased from 51.9% to 61.3%.

4.2.3. The 1990s. The top 15 countries for article production during the 1990s are provided in Table 3. All of the G7 counties were in the top 15, with five occupying the top six spots. Their market share dropped from 77.5% to 61.9%.

The top three rankings remained unchanged, with the United States ranked 1st with 1132 publications, followed by Canada (count: 185) and Australia (count: 172). There was a massive decrease in the US's market share as it dropped from 61.3% to 38.2%. This was due to a slight decline in the US's production and a significant increase in publications from countries ranked below the top two. During the 1980s, only the United States and Canada had more than 100 publications. During the 1990s, Australia, France, UK, and Germany also had more than 100 papers.

Table 3. Production by country (1990s).

Country	Articles	Percentage
The United States	1132	38.2%
Canada	185	6.2%
Australia	172	5.8%
France	169	5.7%
The United Kingdom	111	3.7%
Germany	101	3.4%
Taiwan	90	3.0%
Japan	78	2.6%
India	74	2.5%
Korea	70	2.4%
Italy	56	1.9%
Spain	55	1.9%
The Netherlands	40	1.4%
Israel	38	1.3%
Belgium	37	1.2%

4.2.4. The 2000s. The top 15 countries for production during the 2000s are provided in Table 4. Again, all of the G7 countries were in the top 15, with three occupying the top five spots. The market share of the G7 countries dropped again, going from 61.9% down to 49.9%.

The United States was still ranked 1st with 1482 publications, followed by China (count: 359) and France (count: 326). Canada dropped to 4th while Australia dropped to

Table 4. Production by country (2000s).

Country	Articles	Percentage
The Unites States	1482	24.4%
China	359	5.9%
France	326	5.4%
Canada	318	5.2%
Taiwan	289	4.8%
Spain	284	4.7%
The United Kingdom	261	4.3%
Italy	245	4.0%
Germany	240	4.0%
Australia	173	2.8%
Korea	160	2.6%
Japan	157	2.6%
Greece	126	2.1%
Brazil	123	2.0%
Turkey	112	1.8%

Table 5. Production by country (2010s).

Country	Articles	Percentage
The United States	1691	19.2%
China	1036	11.8%
Spain	463	5.3%
France	460	5.2%
Italy	415	4.7%
Germany	353	4.0%
Canada	345	3.9%
Iran	297	3.4%
The United Kingdom	294	3.3%
Turkey	251	2.9%
India	232	2.6%
Taiwan	230	2.6%
Brazil	213	2.4%
Korea	185	2.1%
Australia	151	1.7%

10th position. There was another decrease in the US's market share as it dropped to 24.4%. This was due to all of the top 15 countries increasing publications, with all countries producing over 100, 9 countries over 200, and 4 countries over 300 articles.

As a side note, the number of international attendees to the WSC did not grow to more than 20% until 1998.[135] Also, AsiaSim (Asia Simulation Conference) started in 2001.

4.2.5. The 2010s. The top 15 countries for production during the 2010s are provided in Table 5. The number of G7 counties in the top fifteen dropped to six, with three occupying the top five spots. The G7 market share was reduced again and dropped from 49.9% to 41.6%. Note that even though only 8 years were considered, the numbers shown exceed the publications produced in other years.

The United States was still ranked 1st with 1691 publications, followed by China (count: 1036) and Spain (count: 463). There was another decline in the US's market share as it dropped from 24.4% to 19.2%. This was due to China's significant increase in production with over 1000 published articles. The gap between the United States and China decreased from 18.5% in the 2000s to just 7.4%.

It is interesting to note that Iran is now included in the top 15. It increased its publication from 54 published articles in the 2000s (ranked 23rd) to almost 300. Iran is currently on the US State Department's list of State Sponsors of Terrorism. Future work will include looking into simulations that are being studied by Iran.

4.2.6. 2017. We also looked at the total production during 2017 to see how the countries ranked in the final year of our analysis (Table 6). The number of G7 countries remained at six in the top 15, but their market share dropped again. It dropped to 36.3%. This was roughly half in comparison to the 1970s and 1980s.

Table 6. Production by country (2017).

Country	Articles	Percentage
The United States	259	17.2%
China	198	13.1%
France	84	5.6%
Iran	83	5.5%
Italy	63	4.2%
India	61	4.0%
Turkey	60	4.0%
Brazil	54	3.6%
Germany	48	3.2%
Canada	47	3.1%
Spain	46	3.0%
The United Kingdom	35	2.3%
Korea	32	2.1%
Taiwan	31	2.1%
The Netherlands	25	1.7%

It is interesting to note that China reduced the gap with the United States and is still ranked second being only 4.1% behind the United States. Also, Iran moved up to 4th position with a production percentage of 5.5%. India and Turkey have also increased their production of articles and are ranked 6th and 7th, respectively.

In contrast to the rising nations not in the G7, Germany, Canada, and the United Kingdom dropped to 9th, 10th, and 12th ranking, respectively. Their market share dropped from 11.2% to 8.6%.

With respect to the WSC, according to Goldsman et al.,[135] the United States has the most papers ever produced by a factor of 20; Germany, the United Kingdom,

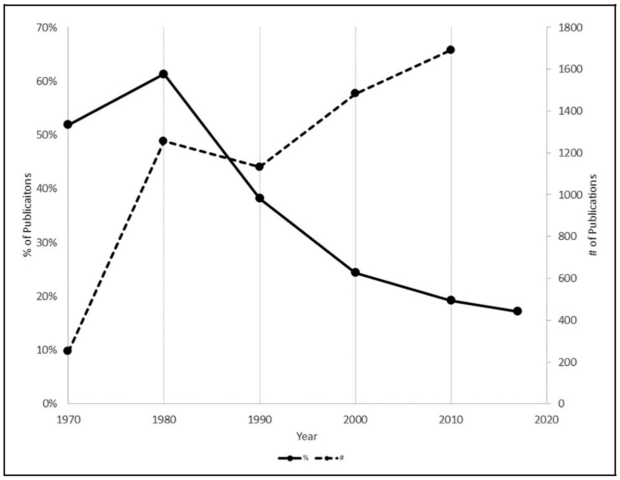

Figure 2. The US publication contribution (1970–2017).

and Canada next. What is interesting is that top simulation paper-producing countries like China and Iran (only eight papers) are not reflected in WSC. About 30 countries per year go to WSC, and a total of 72 countries have ever attended WSC.

4.3. Summary of bibliometric analysis

The results from the bibliometric analysis indicate both an increase in the number of publications over the decades as well as a decline in the percentage of publications with US authors. This change is summarized in Figure 2.

As previously mentioned, we do not claim to provide a complete history of M&S or even a complete history of DES. The history we have provided was to give the ''future of simulation discussions'' in each section enough context to be meaningful.

5. Conclusion

This paper has looked at the evolution of simulation, specifically DES, over time, especially with regard to the challenges set in each of the past six decades. This was done using two approaches, namely, a prose discussion on the literature and a quantitative analysis of the metadata of the literature; this metadata was the authors' country of origin and the year the article was published. Before any general conclusions are given, it is essential to note that only English-language articles were considered in this paper. This bias toward English might explain some of the results discussed, for example, the rise of globalization has led to a broader acceptance in non-English speaking countries' academics to publish in English-language journals. The authors feel justified that their conclusion stands, even with this limitation, due to the dominance of the English-language journals in academia since the Second World War.[136]

The quantitative analysis indicates that the M&S demographic is changing both in terms of authors' nationality and the academic discipline from which they hail. There were very few articles on the challenges and future of DES, that acknowledge this change in demographics within the DES community and the M&S enterprise. The reason for this lack of discussion is unclear as the community is accommodating this change, for example, holding WSC outside the United States. However, these demographic changes will, we believe, deeply change the future of M&S, and DES, and, as such, are worthy of future discussion.

The spread of simulation, both across countries and across academic domains, is concerning because of the potential disconnect within the M&S enterprise that might arise. There are many people now building their careers in simulation who have never heard of DEVS (or maybe even DES), such as those in the computational social science community. This creates new problems regarding what it means to be a simulationist and how to certify those that call themselves such. However, the new ideas generated by these new communities, hopefully, will outweigh this loss of cohesion.

DES has benefited over the years from the technological changes in our societies, for example, the rise of the personal computer and computer programming advancements. However, simulationists should be reminded that these technology changes were not created for simulation, and the DES community has just been beneficiaries of it. For example, Unity 3D is used in many simulations, but Unity Technologies made it for the gaming industry and not for simulation. Even the recent rise of simulation in the social sciences and healthcare domains was due to champions in those domains and not simulationists. Non-simulationists have found ways to overcome the challenges that the simulation community faces; for example, the computer gaming industry has dealt with issues that are like the simulation interoperability challenges in their development of massive multiple online games (MMOGs) without using simulation standards. Recently, Improbable, a computer game start-up, has created immense persistence online simulated environments with their SpatialOS platform resulting in receiving $550 million in investor funding (http://improbable.io). It has been a long-time since a simulation project could dream of that kind of investment. As we strive toward DES reaching a wider audience,[40] maybe its future is held in the hands of the non-specialist.[4]

This paper discusses many challenges of DES and M&S as a whole, some that have been met and some which continue to plague the community, for example, the mis-selling of simulations[59] and determining its ROI.[43] Some DES challenges have been with us from the beginning, such as Conway[34] pointing out that DES is better suited to exploration and not replication; while others have emerged over time, like the splintering of the community into uncoordinated subcommunities, which has led to communication issues.[124] Some argue the need for the community to move away from its technical focus to more practical application,[7] or greater understanding of modeling.[107]

Of the DES challenges discussed throughout the decades, there has been a repeated challenge for the community to incorporate accurate human behavior modeling in simulations; it seems naive to assume that simulationists would resolve this problem when social psychologists have not been able to do so in the hundred years that their subject has existed. However, with the social sciences and humanities communities embracing simulation, maybe progress on this challenge will happen soon.

Some call for the DES community to look inwards to its theoretical foundations;[130] we would argue that the simulation community needs to look outwards if it wants to understand its direction better. Returning to Conway's[34] first paper on the future of simulation: ''particularly during these formative years for [simulation], it is vital that its practitioners exchange information and experience on every aspect of its use so that previous mistakes will be less frequency repeated.'' We hope that the traditional DES community is ready to embrace the new communities that are arising and follow Conway's advice.

This study only considered a fraction of M&S material that has been generated over the last 60 years. Even by limiting ourselves to only the DES viewpoint (discussion papers in the peer-reviewed literature), there is still a likelihood that major gaps are present. But that is the point of this paper! The body of practice of DES is fragmented and we hope the reader now sees that the resultant incoherence of knowledge is expanding, not contracting. We suspect that DES is now in the hands of thousands of developers and users with only pockets of leadership and management, like DoD and WSC, present. We must accept this new reality, and we, the traditional M&S community, must adjust to it.

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ORCID iD

Andrew J Collins https://orcid.org/0000-0002-8012-2272

References

1. NATO Modelling and Simulation Group (NMSG). *M&S resource discovery and access*. Brussels: North Atlantic Treaty Organization (NATO), 2016.
2. Robinson S. Discrete-event simulation: from the pioneers to the present, what next? *J Oper Res Soc* 2005; 56: 619–629.
3. Gordon G. The development of the general purpose simulation system (GPSS). In: Wexelblat RL (ed.) *History of programming languages*. New York: ACM, 1978, pp. 403–426.
4. Taylor SJE and Robinson S. So where to next? A survey of the future for discrete-event simulation. *J Simul* 2006; 1: 1–6.
5. Nance RE. A history of discrete event simulation programming languages. In: Bergin TJ and Gibson RG (eds) *History of programming languages—II*. New York: ACM, 1996, pp. 369–427.
6. Sharma M. Simulation models for teacher training: perspectives and prospects. *J Educ Pract* 2015; 6: 11–14.
7. Taylor SJE, Eldabi T, Riley G, et al. Simulation modelling is 50! Do we need a reality check? *J Oper Res Soc* 2009; 60: S69–S82.
8. Araten M, Hixson HG, Hoggatt AC, et al. The winter simulation conference: perspectives of the founding fathers. In: *Proceedings of the 1992 winter simulation conference* (ed J Swain, D Goldsman, RC Crain, et al.), Arlington, VA, 13–16 December 1992, pp. 37–62. Piscataway, NJ: ACM.
9. Metropolis N and Ulam S. The Monte Carlo method. *J Am Stat Assoc* 1949; 44: 335–341.
10. Cooper NG, Eckhardt R and Shera N. *From cardinals to chaos: reflection on the life and legacy of Stanislaw Ulam*. Cambridge: Cambridge University Press, 1989.
11. Tippett LHC. *Random sampling numbers*. Cambridge: Cambridge University Press, 1927.
12. L'Ecuyer P. History of uniform random number generation. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 202–230. New York: IEEE.
13. Hollocks BW. A history of simulation development in the United Kingdom. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, p. 4. New York: IEEE Press.
14. Conway RW, Johnson BM and Maxwell WL. A queue network simulator for the IBM 650 and Burroughs 220. *Commun ACM* 1959; 2: 20–23.
15. Conway RW, Johnson BM and Maxwell WL. Some problems of digital systems simulation. *Manage Sci* 1959; 6: 92–110.

16. Hurd CC. A note on early Monte Carlo computations and scientific meetings. *Ann Hist Comput* 1985; 7: 141–155.
17. Hollocks BW. Forty years of discrete-event simulation—a personal reflection. *J Oper Res Soc* 2006; 57: 1383–1399.
18. Forrester JW. *Industrial dynamics*. Cambridge, MA: The MIT Press, 1961.
19. Tocher KD and Owen DG. The automatic programming of simulations. In: *Proceedings of the 2nd conference of the international federation of operational research societies (IFORS)* (ed J Banbury and J Maitland), Aix-en-Provence, 1960, pp. 50–68. London: English Universities Press.
20. Gordon G. A general purpose systems simulation program. In: *Proceedings of the December 12–14, 1961, eastern joint computer conference: computers-key to total systems control*, Washington, DC, 12–14 December 1961, pp. 87–104. New York: ACM.
21. Tocher KD. *The Art of Simulation*. London: English Universities Press, 1963.
22. Nance RE and Sargent RG. Perspectives on the evolution of simulation. *Oper Res* 2002; 50: 161–172.
23. Schriber TJ. *Simulation using GPSS*. New York: Wiley, 1974.
24. Kiviat PJ. *Digital computer simulation: modeling concepts*. Report no. RM-5378-PR, August 1967. Santa Monica, CA: Rand Corporation.
25. Fishman GS and Kiviat PJ. The statistics of discrete-event simulation. *Simulation* 1968; 10: 185–195.
26. Sargent RG and Balci O. History of verification and validation of simulation models. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 1–16. New York: IEEE Press.
27. Naylor TH, Finger JM, McKenney JL, et al. Verification of computer simulation models. *Manage Sci* 1967; 14: B92–B106.
28. Reitman J. A concise history of the ups and downs of simulation. In: *Proceedings of the 1988 winter simulation conference* (ed M Abrams, P Haigh and J Comfort), San Diego, CA, 12–14 December 1988, pp. 1–6. Washington, DC: IEEE.
29. Salt JD. The seven habits of highly defective simulation projects. *J Simul* 2008; 2: 155–161.
30. Dahl O-J and Nygaard K. SIMULA: an ALGOL-based simulation language. *Commun ACM* 1966; 9: 671–678.
31. Bell PC and O'Keefe RM. Visual interactive simulation—history, recent developments, and major issues. *Simulation* 1987; 49: 109–116.
32. Wegner P. Concepts and paradigms of object-oriented programming. *ACM SIGPLAN OOPS Mess* 1990; 1: 7–87.
33. Schriber TJ, Reitman J, Ockene A, et al. History of the winter simulation conference: origins and early years (1967–1974). In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 40–49. New York: IEEE.
34. Conway RW. Some tactical problems in digital simulation. *Manage Sci* 1963; 10: 47–61.
35. Crosbie R. Grand challenges in modeling and simulation. *SCS M&S Magazine*, January 2010, vol. 1, pp. 1–8.
36. Wagner HM. *Principles of operations research, with applications to managerial decisions*. Englewood Cliffs, NJ: Prentice Hall, 1969.
37. Siebers P-O, Macal CM, Garnett J, et al. Discrete-event simulation is dead, long live agent-based simulation! *J Simul* 2010; 4: 204–210.
38. Hoad K and Watts C. Are we there yet? Simulation modellers on what needs to be done to involve agent-based simulation in practical decision making. *J Simul* 2012; 6: 67–70.
39. Brailsford S. Discrete-event simulation is alive and kicking! *J Simul* 2014; 8: 1–8.
40. Thaviphoke Y and Collins AJ. Simulation for the common man: how do we make M&S accessible? In: *Proceedings of the MODSIM world 2019 conference* (ed N Drucker and S Werner), Norfolk, VA, 22–24 April 2019, pp. 1–7. National Training & Simulation Association (NTSA).
41. Law A. *Simulation modeling and analysis*. 5th ed. New York: McGraw Hill Science/Engineering/Math, 2015.
42. Smith K and Sheaham R. Training by simulation-past-present-future. In: *Proceedings of the Naval Training Device Center (NTDC) and industry conference*, 1968, pp. 218–225. Orlando, FlL: Naval Training Device Center (NTDC).
43. Oswalt I, Feinberg J, Cooley T, et al. Calculating return on investment for US Department of Defense modeling and simulation. *M S J* 2012; Fall: 4–15.
44. Collins AJ, Knowles Ball D and Romberger J. Exploring the ''Whys'' of simulation visualization. In: *Proceedings of the MODSIM world conference and expo 2014*, Hampton, VA, 15–17 April 2014.
45. Collins AJ, Knowles Ball D and Romberger J. Simulation visualization issues for users and customers. In: *Proceedings of the 2015 spring simulation multiconference*, Alexandria, VA, 12–17 April 2015.
46. Sargent RG, Roth PF and Schriber TJ. History of the winter simulation conference: Renaissance period (1975–1982). In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 50–59. New York: IEEE.
47. Zeigler BP, Praehofer H and Kim TG. *Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems*. San Diego, CA: Academic Press, 2000.
48. Schelling TC. Dynamic models of segregation. *J Math Sociol* 1971; 1: 143–186.
49. Fujimoto RM, Bagrodia R, Bryant RE, et al. Parallel discrete event simulation: the making of a field. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, p. 16. New York: IEEE Press.
50. Henriksen JO. *Building a better GPSS: a 3:1 performance enhancement*. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE), 1975.
51. Nelson BL. 50th anniversary article: stochastic simulation research in *Management Science. Manage Sci* 2004; 50: 855–868.
52. Forrester JW. *World dynamics*. Cambridge, MA: Wright-Allen Press, 1971.

53. Roberts SD and Pegden D. The history of simulation modeling. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 1–16. New York: IEEE Press.
54. McGinnis LF and Rose O. History and perspective of simulation in manufacturing. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 385–397. New York: IEEE Press.
55. Courtice A. The next step ... emerging issues and implications for the implications for program management in the acquisition of training systems in the air force. In: *Proceedings of the interservice/industry training systems conference (I/ITSC)*, 1986, pp. 97–105. Orlando, FL: National Training & Simulation Association (NTSA).
56. Zeigler BP. Hierarchical, modular discrete-event modelling in an object-oriented environment. *Simulation* 1987; 49: 219–230.
57. Henriksen JO. The integrated simulation environment (simulation software of the 1990s). *Oper Res* 1983; 31: 1053–1073.
58. Nance RE and Overstreet CM. History of computer simulation software: an initial perspective. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 243–261. New York: IEEE.
59. Crain RC, Sussman JM, Schriber TJ, et al. The winter simulation conference: celebrating twenty-five years of progress. In: *Proceedings of the 24th conference on winter simulation*, Arlington, VA, 13–16 December 1992, pp. 3–33. Piscataway, NJ: ACM.
60. Hill RR and Tolk A. A history of military computer simulation. In: Tolk A, Fowler JW, Shao G, et al. (eds) *Advances in modeling and simulation*. Cham: Springer, 2017, pp. 277–299.
61. Axelrod R. Advancing the art of simulation in the social sciences. In: Conte R, Hegselmann R and Terna P (eds) *Simulating social phenomena*. Berlin; Heidelberg: Springer, 1997, pp. 21–40.
62. Reynolds CW. Flocks, herds and schools: a distributed behavioral model. In: *Proceedings of the 14th annual conference on computer graphics and interactive techniques*, Anaheim, CA, 27–31 July 1987, pp. 25–34. New York: ACM.
63. Tolk A, Diallo SY, Padilla JJ, et al. How is M&S interoperability different from other interoperability domains? In: *Proceedings of the 2011 spring simulation interopability workshop (SIW)*, Boston, MA, 4–8 April 2011, pp. S11–S105. Simulation Interoperability Standards Organization (SISO).
64. Sterman J. *Business dynamics: systems thinking for a complex world*. Boston, MA: Irwin/McGraw Hill, 2000.
65. Nygaard K and Dahl O-J. The development of the SIMULA languages. In: Wexelblat *RL (ed.) History of programming languages*. New York: ACM, 1978, pp. 439–480.
66. Epstein JM and Axtell R. *Growing artificial societies: social science from the bottom up*. Washington, DC: Brookings Institution Press, 1996.
67. Epstein JM. Why model? *J Artif Soc Soc Simulat* 2008; 11: 12.
68. Kuhl ME. History of random variate generation. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 231–242. New York: IEEE.
69. Matsumoto M and Nishimura T. Mersenne twister: a 623-dimensionally equidistributed uniform pseudo-random number generator. *ACM T Model Comput S* 1998; 8: 3–30.
70. Kleindorfer GB and Ganeshan R. The philosophy of science and validation in simulation. In: *Proceedings of the 25th conference on winter simulation*, Los Angeles, CA, 12–15 December 1993, pp. 50–57. New York: IEEE.
71. Knowles Ball D and Collins AJ. Simulation visualization rhetoric and its practical implications. In: *Proceedings of the 48th annual meeting of southeastern chapter of INFORMS*, Myrtle Beach, SC, 4–5 October 2012, pp. 584–591.
72. Salt JD. Simulation should be easy and fun! In: *Proceedings of the 25th conference on winter simulation* (ed GW Evans, M Mollaghasemi, EC Russell, et al.), Los Angeles, CA, 12–15 December 1993, pp. 1–5. New York: ACM.
73. Nance RE and Thayer GA. The computer simulation archive: development and current contents. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 330–341. New York: IEEE.
74. Sargent RG and Wilson JR. Creation of the computer simulation archive. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 324–329. New York: IEEE.
75. Law AM. Simulation software for manufacturing applications: the next few years. *Ind Eng* 1990; 22: 14–15.
76. Banks SB and Stytz MR. User modeling for distributed virtual environment intelligent agents. In: *Proceedings of the modeling, simulation, and visualization for real and virtual environments*, Orlando, FL, 5–9 April 1999, pp. 118–127. Bellingham, WA: International Society for Optics and Photonics.
77. Clarke T. Simulation's ultimate challenge. In: *Proceedings of the interservice/industry training, simulation and education conference (I/ITSEC)*, Orlando, FL, 1998, pp. 1–6. Arlington, VA: National Training & Simulation Association (NTSA).
78. Patenaude A. *Study on the effectiveness of modeling and simulation in the weapon system acquisition process*. Washington, DC: Office of the Secretary of Defense, 1996.
79. Grimm V, Berger U, Bastiansen F, et al. A standard protocol for describing individual-based and agent-based models. *Ecol Model* 2006; 198: 115–126.
80. Collins A, Petty M, Vernon-Bido D, et al. A call to arms: standards for agent-based modeling and simulation. *J Artif Soc Soc Simulat* 2015; 18: 12.
81. Hill RR, Champagne LE and Price JC. Using agent-based simulation and game theory to examine the WWII Bay of Biscay U-boat campaign. *J Def Model Simul* 2004; 1: 99–109.

82. Champagne LE and Hill RR. Agent-model validation based on historical data. In: *Proceedings of the 2007 winter simulation conference*, Washington, DC, 9–12 December 2007, pp. 1223–1231. New York: IEEE Press.
83. Klügl F. A validation methodology for agent-based simulations. In: *Proceedings of the 2008 ACM symposium on applied computing*, Fortaleza, Brazil, 16–20 March 2008. New York: ACM.
84. Gore R and Reynolds PF Jr. INSIGHT: understanding unexpected behaviours in agent-based simulations. *J Simul* 2010; 4: 170–180.
85. Ligtenberg A, Van Lammeren RJ, Bregt AK, et al. Validation of an agent-based model for spatial planning: a role-playing approach. *Comput Environ Urban* 2010; 34: 424–434.
86. Kohn LT, Corrigan JM and Donaldson MS. *To err is human: building a safer health system*. Washington, DC: National Academies Press, 2000.
87. Brailsford SC, Harper PR, Patel B, et al. An analysis of the academic literature on simulation and modelling in health care. *J Simul* 2009; 3: 130–140.
88. Barton RR, Joines JA and Morrice DJ. History of the winter simulation conference: period of growth, consolidation, and innovation (1993–2007). In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 87–99. New York: IEEE.
89. Fu MC and Henderson SG. History of seeking better solutions, AKA simulation optimization. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 131–157. New York: IEEE.
90. Eldabi T, Balaban M, Brailsford S, et al. Hybrid simulation: historical lessons, present challenges and futures. In: *Proceedings of the 2016 winter simulation conference* (ed TMK Roeder, PI Frazier, R Szechtman, et al.), Washington, DC, 11–14 December 2016, pp. 1388–1403. New York: IEEE.
91. Brailsford SC, Eldabi T, Kunc M, et al. Hybrid simulation modelling in operational research: a state-of-the-art review. *Eur J Oper Res* 2019; 278: 721–737.
92. Eldabi T, Brailsford S, Djanatliev A, et al. Hybrid simulation challenges and opportunities: a life-cycle approach. In: *Proceedings of the 2018 winter simulation conference (WSC)* (ed M Rabe, AA Juan and N Mustafee), Gothenburg, 9–12 December 2018, pp. 1500–1514. New York: IEEE.
93. Macedonia M. Computing and the future of simulation. *Simulation* 2001; 76: 290–292.
94. Pew RW and Mavor AS. *Representing human behavior in military simulations*. Washington, DC: National Academies Press, 1998.
95. Macedonia M. In search of the grand challenge. *Simulation* 2001; 76: 96–97.
96. Loftin RB. The future of simulation. In: *Proceedings of the human factors and medical workshop, NATO Research and Technology Organization (RTO)*, 1 June 2006, paper no. KN3-1-4. Brussels: North Atlantic Treaty Organization (NATO).
97. Taylor SJ, Khan A, Morse KL, et al. Grand challenges for modeling and simulation: simulation everywhere—from cyberinfrastructure to clouds to citizens. *Simulation* 2015; 91: 648–665.
98. Fujimoto R, Lunceford WH, Page EH, et al. Grand challenges for modeling and simulation. In: *Proceedings of the Dagstuhl seminar*, 2002. Schloss Dagstuhl, https://www.dagstuhl.de/en/program/calendar/semhp/?semnr=02351
99. Eeckhout L and De Bosschere K. Speeding up architectural simulations for high-performance processors. *Simulation* 2004; 80: 451–468.
100. Fishwick PA, Davis T and Douglas J. Model representation with aesthetic computing: method and empirical study. *ACM T Model Comput S* 2005; 15: 254–279.
101. Roman PA. Garbage in, Hollywood out! In: *Proceedings of the simulation conference and exhibition (SimTecT'2005)*, Sydney, NSW, Australia, 10–12 May 2005, pp. 1–5.
102. Fowler JW and Rose O. Grand challenges in modeling and simulation of complex manufacturing systems. *Simulation* 2004; 80: 469–476.
103. Mosterman PJ and Vangheluwe H. Computer automated multi-paradigm modeling: an introduction. *Simulation* 2004; 80: 433–450.
104. Mustafee N, Powell J, Brailsford SC, et al. Hybrid simulation studies and hybrid simulation systems: definitions, challenges, and benefits. In: *Proceedings of the 2015 winter simulation conference* (ed L Yilmaz, W Chan, I Moon, et al.), Huntington Beach, CA, 6–9 December 2015, pp. 1678–1692. New York: IEEE Press.
105. Pidd M and Carvalho A. Simulation software: not the same yesterday, today or forever. *J Simul* 2006; 1: 7–20.
106. Tolk A. What comes after the semantic web—PADS implications for the dynamic web. In: *Proceedings of the 20th workshop on principles of advanced and distributed simulation*, Singapore, 24–26 May 2006, pp. 1–8. New York: IEEE Computer Society.
107. Pidd M. Why modelling matters. In: *Proceedings of the 2008 winter simulation conference* (ed SJ Mason, RR Hill, L Mönch, et al.), *Miami, FL*, 7–10 December 2008, p. 10. New York: IEEE Press.
108. Cheng R, Macal CM, Nelson B, et al. Simulation: the past 10 years and the next 10 years. In: *Proceedings of the 2016 winter simulation conference* (ed TMK Roeder, PI Frazier, R Szechtman, et al.), Washington, DC, 11–14 December 2016, pp. 2180–2192. New York: IEEE Press.
109. Powers MJ, Sanchez SM and Lucas TW. The exponential expansion of simulation in research. In: *Proceedings of the 2012 winter simulation conference* (ed C Laroque, J Himmelspach, R Pasupathy, et al.), Berlin, 9–12 December 2012, pp. 1–12. New York: ACM.
110. Taylor SJE, Chick SE, Macal CM, et al. Modeling and simulation grand challenges: an OR/MS perspective. In: *Proceedings of the 2013 winter simulation conference* (ed Pasupathy R, Kim S-H, Tolk A, et al.), Washington, DC, 8–11 December 2013, pp. 1269–1282. New York: IEEE.
111. Ören T. A critical review of definitions and about 400 types of modeling and simulation. *SCS M&S Magazine*, 3 July 2011, vol. 2, pp. 142–151.

112. Severinghaus R. Simulation in healthcare—what is holding us back. In: *Proceedings of the interservice/industry training, simulation & education conference (I/ITSEC)*, Orlando, FL, 3–6 December 2012, pp. 1–11. Arlington, VA: National Training & Simulation Association (NTSA).
113. Brailsford SC, Carter MW and Jacobson SH. Five decades of healthcare simulation. In: *Proceedings of the 2017 winter simulation conference* (ed Chan WKV, D'ambrogio A, Zacharewicz G, et al.), Las Vegas, NV, 3–6 December 2017, pp. 365–384. New York: IEEE.
114. Alexopoulos C, Joines JA and Kuhl ME. History of the winter simulation conference: modern period (2008–2017). In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 100–114. New York: IEEE.
115. Hamill L. Agent-based modelling: the next 15 years. *J Artif Soc Soc Simulat* 2010; 13: 7.
116. McCourt R, Ng K and Mitchell R. An agent—based approach towards network—enabled capabilities—I: simulation validation and illustrative examples. *J Def Model Simul* 2013; 10: 313–326.
117. Ahmed K, Liu J, Badawy A-H, et al. A brief history of HPC simulation and future challenges. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 419–430. New York: IEEE Press.
118. Niño-Pérez E, Rivera-Collazo CA, Cabrera-Ríos M, et al. Iterative multicriteria simulation and prototyping optimization in manufacturing. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, pp. 481–492. New York: IEEE.
119. Lucas TW, Kelton WD, Sánchez PJ, et al. Changing the paradigm: simulation, now a method of first resort. *Nav Res Log* 2015; 62: 293–303.
120. Collins AJ, Meyr D, Sherfey S, et al. The value of modeling and simulation standards. In: *Proceedings of the 2012 autumn simulation multi-conference*, San Diego, CA, 28–31 October 2012, paper no. DMMS1. The Society for Modeling & Simulation International (SCS).
121. Department of Defense (DoD). *Instruction: DoD modeling and simulation (M&S) verification, validation and accreditation (VV&A)*. Washington, DC: DoD, 2009.
122. Collins AJ. Which is worse: large-scale simulations or the 80% solution? *SCS M&S Magazine*, 2012, pp. 27–38. https://www.scs.org/wp-content/uploads/2016/12/2012-04-Issue10-3.pdf
123. Tanaka A, Julian D, Mattingly P, et al. Validation for simulators: it's all about perspective. In: *Proceedings of the interservice/industry training, simulation and education conference (I/ITSEC)*, Orlando, FL, 28 November–2 December 2016, pp. 1–11. Arlington, VA: National Training & Simulation Association (NTSA).
124. Thaviphoke Y and Collins AJ. Applying SODA to the modeling and simulation accessibility problem. In: *Proceedings of the 2019 IISE annual conference* (ed HE Romeijn, A Schaefer and R Thomas), Orlando, FL, 18–21 May 2019, pp. 1–6. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE).
125. Gritton JMK, Kotick DM, Fraas GR, et al. Washington, we have a problem: the foundation for live virtual constructive (LVC) exercises requires fixing? In: *Proceedings of the interservice/industry training, simulation and education conference (I/ITSEC)*, Orlando, FL, 28 November–2 December 2016, pp. 1–15. Arlington, VA: National Training & Simulation Association (NTSA).
126. Nelson BL. ''Some tactical problems in digital simulation'' for the next 10 years. *J Simul* 2016; 10: 2–11.
127. Hill RR, Tolk A, Hodson DD, et al. Open challenges in building combat simulation systems to support test, analysis and training. In: *Proceedings of the 2018 winter simulation conference (WSC)* (ed M Rabe, AA Juan and N Mustafee), Gothenburg, 9–12 December 2018, pp. 3730–3741. New York: IEEE.
128. Sadagic A and Yates FA Jr. Large scale adoption of training simulations: are we there yet? In: *Proceedings of the interservice/industry training, simulation and education conference (I/ITSEC)*, Orlando, FL, 30 November–4 December 2015, pp. 1–12. Arlington, VA: National Training & Simulation Association (NTSA).
129. Epstein JM. *Agent_zero: toward neurocognitive foundations for generative social science*. Princeton, NJ: Princeton University Press, 2014.
130. Tolk A. Learning something right from models that are wrong: epistemology of simulation. In: Yilmaz L (ed.) *Concepts and methodologies for modeling and simulation*. Berlin; Heidelberg: Springer, 2015, pp. 87–106.
131. Collins A, Sokolowski J and Banks C. Applying reinforcement learning to an insurgency agent-based simulation. *J Def Model Simul* 2014; 11: 353–364.
132. Watkins J, Tamash T and Campbell C. Future simulation paradigms and synthetic natural environments. In: *Proceedings of the interservice/industry training, simulation and education conference (I/ITSEC)*, Orlando, FL, 28 November–2 December 2016, pp. 1–11. National Training & Simulation Association (NTSA).
133. Gendron J, Gendron B and Weisel E. Hospitality, big data, and restaurateurs: does simulation have a seat at the table. In: *Proceedings of the MODSIM world conference*, Norfolk, VA, 24–26 April 2018, pp. 1–11. National Training & Simulation Association (NTSA).
134. Aria M and Cuccurullo C. *bibliometrix*: an R-tool for comprehensive science mapping analysis. *J Informetr* 2017; 11: 959–975.
135. Goldsman D, De Almeida Costa M and Goldsman P. The countries of the participants in the winter simulation conference. In: *Proceedings of the 2017 winter simulation conference* (ed WKV Chan, A D'ambrogio, G Zacharewicz, et al.), Las Vegas, NV, 3–6 December 2017, p. 5. New York: IEEE Press.
136. Gordin MD. Introduction: hegemonic languages and science. *Isis* 2017; 108: 606–611.

Author biographies

Andrew J Collins is an assistant professor at Old Dominion University in the Department of Engineering Management and Systems Engineering. He has a PhD in Operations Research from the University of Southampton, and his undergraduate degree in Mathematics was from the University of Oxford. He has published over 90 peer-review articles. He has been the Principal Investigator on projects funded to the amount of approximately US$7 million. Dr Collins has developed several research simulations including an award-winning investigation into the foreclosure contagion that incorporated social networks. His website and full resume are at www.drandrewjcollins.com.

Farinaz Sabz Ali Pour is an Adjunct Assistant Professor at Old Dominion University in the Department of Engineering Management and Systems Engineering. She has a PhD in Systems Engineering from Old Dominion University. Her main research interests include Modeling & Simulation, Systems Engineering, and Risk Management. Her email is fsabz001@odu.edu.

Craig A Jordan is a lead project scientist at the Virginia Modeling, Analysis, and Simulation Center (VMASC) which is part of Old Dominion University. His primary research focus is on the development of artificial twins of physical systems. His work involves the use of qualitative and quantitative data in simulations to gain a better understanding of the system and guide policy decisions. He holds an MS degree in Modeling and Simulation from Old Dominion University and a BS degree in Civil Engineering from the University of Connecticut. He is also a licensed professional civil engineer.