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SIMULATION: THE PAST 10 YEARS AND THE NEXT 10 YEARS

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ABSTRACT

The *Journal of Simulation* is celebrating its tenth anniversary. The journal is published by The Operational Research Society of the United Kingdom. The society is the world's oldest-established learned society catering to the Operational Research profession, and one of the largest in the world, with 2,700 members in 66 countries. This panel session brings together four leaders of the simulation community to discuss significant advances in simulation over the last ten years, major simulation issues that still need to be addressed, and what can be accomplished during the next ten years. The first four authors of this paper are the panelists and the other three are editors of the *Journal of Simulation*.

1 INTRODUCTION

The *Journal of Simulation (JOS)* is one of eight publications of The Operational Research Society which is based in the United Kingdom. The society is the world's oldest-established learned society catering to the Operational Research profession, and one of the largest in the world, with 2,700 members in 66 countries. *JOS* was founded in 2006 with a focus on discrete-event simulation (see Taylor and Robinson 2006). From the beginning, *JOS* has published methodological and technological advances that represent significant progress toward the application of simulation modelling-related theory and/or practice. Particular interest has been paid to significant success in the use of simulation.

Over the last ten years, the scope of *JOS* has expanded (see Brailsford *et al.* 2009, Brittin *et al.* 2015, and Macal and North 2010 for some examples). Currently in *JOS,* the field of simulation includes the techniques, tools, methods and technologies of the application and the use of discrete-event simulation, agent-based modelling and system dynamics. The journal encourages theoretical papers that span the breadth of the simulation process, including both modelling and analysis methodologies, as well as practical papers from a wide range of simulation applications in domains including manufacturing, service, defense, health care and general commerce. It particularly seeks topics that are not “mainstream” in nature but interesting and evocative to the simulation community.

In order to celebrate the tenth anniversary of JOS, four major activities were planned. The first was a virtual issue of ten of the most important papers of the first ten years as determined by the founding editors Professor Simon Taylor (Brunel University) and Professor Stewart Robinson (Loughborough University). These articles can be found at the JOS website (http://link.springer.com/journal/41273).

The second activity involved having an invited paper in each 2016 issue from a leader of the simulation community. The first issue contained a paper from Professor Barry Nelson (Northwestern University), the second a paper from Dr. Charles Macal (Argonne National Laboratory), the third an article led by Professor Chun-Hung Chen (George Mason University), and the fourth a paper by Professor Markus Rabe (Technical University of Dortmund).

The third activity was a panel session at the 8th Simulation Workshop (SW16) which held April 11-13 in Stratford, Worcestershire, United Kingdom. SW16 was sponsored by the Operational Research Society, the INFORMS Simulation Society, and the Society for Modeling and Simulation International (SCS). The session entitled “Celebrating 10 Years of the Journal of Simulation” was moderated by Prof. Christine Currie (University of Southampton). The panelists were Prof. Simon Taylor (Brunel University), Prof. Stewart Robinson (Loughborough University), Prof. John Fowler (Arizona State University), and Prof. Sally Brailsford (University of Southampton).

The final celebratory activity is this panel session at the 2016 Winter Simulation Conference in Washington, D.C, USA. The session brings together four leaders of the simulation community to discuss significant advances in simulation over the last ten years, major simulation issues that still need to be addressed, and what can be accomplished during the next ten years. The panelists include Emeritus Prof. Russell Cheng (University of Southampton), Prof. Barry Nelson (Northwestern University), Dr. Charles Macal (Argonne National Laboratory), and Prof. Markus Rabe (Technical University of Dortmund). The panelists were asked to answer the following questions:

1. *What were the most significant advances that the simulation community made over the last ten years?*
2. *What are major issues that the simulation community still needs to address?*
3. *What will the simulation community be able to accomplish over the next ten years?*

The responses by the panelists for each question are given in the sections below.

2 SIGNIFICANT ADVANCES OVER THE LAST TEN YEARS

With increased availability of computing resources, there have been a number of significant advances in the capabilities and use of simulation over the last decade. We asked the panelists the following question.

What were the most significant advances that the simulation community made over the last ten years?

2.1 Response by Russell Cheng

The 'simulation community' covers a very broad church, and as a single individual member of it, if I am one at all, I have studied only very specific and narrow aspects of simulation that are rather specialized, and probably not even in the main stream. If therefore I represent any part of the simulation community, it is only as one person of what is itself a tiny part of a massive whole. I therefore do not regard my comments as representative or being authoritative in any way.

Simulation is a quantitative tool applied with a very wide variety of uses. Winter Simulation Conference tracks tend, though not exclusively, to concern simulation in the more specific areas of operational research (OR) and industrial engineering (IE). My comments are in the main most relevant to these areas. However, as at one stage I spent much time working in ship-handling simulation, particularly on computer-generated imagery (CGI) side, I will make some comments in connection with CGI, even though it is not really connected with OR or IE.

Also I should say that my own training was in mathematics and statistics, and my interests in simulation tend to reflect this, involving the design and analysis of simulation experiments, the computer programming side, and advances in hardware design; with my interest being in the development of simulation tools. I will therefore have to remain mute on the application of such tools, which forms the practical side of simulation. In lay terms its application is far and away the most important side of simulation in terms of its impact, covering uses in healthcare, environmental, ecological and public services, economics, conflicts, astronomy, particle physics.

I will now turn to the first of the three questions. I have too little experience to offer anything other than a lay opinion on the first question. The use of simulation in trying to improve health care does seem to have grown, to the extent that an increasing number of hospital and healthcare authorities are becoming much more aware, and dare one say more committed to its use in improving healthcare provision. There is an increasing awareness that human behavior needs to be included in simulation models, and agent-based simulation is now well recognized as a powerful approach that can lead to useful modeling of emergent behavior.

On the technical side, the development of multiplatform tools, brought together and run interactively via the internet, is seeing increased recognition. This links in well with studies using 'big data' analytical tools where samples are now at the giga level,. A very interesting development in this regard is the construction of data driven simulation models, where the data itself is in effect the simulation model. There are also advances in facilitating model building using conceptual modeling, and also hybrid modelling incorporating system dynamics tools.

The only area I have real experience of is in CGI, though this perhaps predates the 10 year period of the question. In the period I was involved in powerful hardware was being developed that made it possible to develop good quality CGI that was affordable for ship-handling simulators (flight simulators had been well established well before but in systems a good magnitude more expensive than what ship-handling training could bear). The effect was dramatic and there was a quantum leap in improvement of the CGI implemented simulators for serious maritime training. At the time computer game visuals already looked very good, but these used a multitude of hardware tricks that could be deployed because the games were built round what was possible with the hardware and not the other way round. Genuine ship-handling simulation had to mimic the real maritime world, something the hardware simply could not do effectively until that time. Even so the computer code had to be very efficient to maintain adequate visual updating. An exciting time to be involved with CGI.

2.2 Response by Charles Macal

Agent-based modeling is a relatively new technique for simulation (Macal 2016). An agent-based model can be thought of as one composed of individual entities that have autonomous behaviors and are different from one another, having diverse characteristics and behaviors over a population. Over the past 10 years, the number and breadth of applications for agent-based modeling and simulation (ABMS) are truly remarkable. Applications range across virtually all disciplines in the natural, social and physical sciences as well as engineered systems and well beyond the usual ones for simulation in engineering, business, operations management, and similar fields. This is probably the greatest advancement in ABMS in the past 10 years, along with the development of various communities focused on ABMS in respective disciplines (Macal 2016). There has also been promising work establishing standards for ABMS models, whether the standards apply to documentation and explanation of ABMS in standard ways, or standards for processes for efficiently developing models, or standards for how agent-based models and their outputs can be explained to decision makers in such a way as to be accepted as important sources of information for their decision and policy making.

2.3 Response by Barry Nelson

My comments relate to analysis methodology (AM) in simulation, which for me includes input modeling, experiment design and output analysis.

For a long time there was a big gap between research in optimization via simulation and the creation of algorithms that can be applied to difficult practical problems. That gap was narrowed substantially in the last ten years. This includes clever adaptions of ranking & selection techniques to become more efficient and scale up to larger problems; exploiting ideas from statistical learning; and focusing our attention beyond gradient estimation and toward the optimization algorithms in which the gradients are embedded. We have some really good solutions here.

I view the steady-state simulation problem in a single-processor environment to have been solved: we fully understand the bias-variance trade off, and we have robust estimators of the variance of the point estimators. Really powerful asymptotic analysis was key. Unfortunately, this was just in time for the entire problem context to be changed by highly parallel simulation (see section 4.3).

2.4 Response by Markus Rabe

While the rise of simulation application in production and logistics (P&L) in the 1980's and early 1990's has been characterized by the competition of tools and their philosophies, major progress in this respect cannot be recognized in the last decade. Many broadly used tools still root back to these early years and show continuous but non-disruptive improvements. A methodological novelty might be seen in tools that support different simulation technologies. However, application in the target area is rare (from a survey of 193 recent P&L-related papers , only seven report hybrid use of simulation).

Therefore, the major progress lies in accompanying technologies. These are as important (sometimes even more important) than the simulation technology itself, as they help to bring simulation into practice and to achieve credibility in its application.

A very significant basis for these developments has been the research of the Arbeitsgemeinschaft Simulation (ASIM) that has defined a procedure model for simulation studies in P&L applications (described in detail in German language in Wenzel et al. 2008 and Rabe et al. 2008). The core element of this procedure model has been adopted for the VDI Guideline 3633.1 (VDI 2014). Several extensions have built upon this model.

One of the major auxiliary developments is the detailed elaboration of the data acquisition and the related processes. In P&L, data play a very important role, and data processing can be expected to cover about half of the total study effort (Rabe and Hellingrath 2001). Therefore, the above-mentioned ASIM procedure model contains a specific path for data collection and data preparation (cp. Rabe et al. 2009). Building on this base, more detailed models for the information acquisition process have been developed (cp. Kuhnt and Wenzel 2010).

Furthermore, methods and tools to assist simulation use have been developed, mainly driven by the German automotive industry. Even if these tend to form just a collection of known methods, by bringing them into one unique environment with the underlying databases they bring great advantages in the efficient implementation of simulation (cp. Mayer and Mieschner 2015). The assistance covers, among other topics, preprocessing of input data, planning of experiments and validation in a client-server environment.

Also by the automotive industry (coordinated by the German automotive producers association VDA), new approaches towards unified simulation building blocks have been brought on the way. The resulting library in a common design and development of several competitive producers operates as a quasi-standard and is a great advantage in the quick and efficient application of simulation (cp. Mayer and Pöge 2010).

A very important step forward can be seen in procedures for verification and validation (V&V). This topic is obviously essential, as only V&V can lead to credibility of simulation models and the results achieved therewith (cp. Balci 1998). Based on previous work in the military sector (Brade 2003), a detailed procedure model has been elaborated by Rabe et al. (2008, 2009).

3 MAJOR ISSUES STILL TO BE ADDRESSED

While there were a number of significant advances in simulation over the last decade, there are still some major issues that need to be addressed. Therefore, we asked the panelists the following question.

What are major issues that the simulation community still needs to address?

3.1 Response by Russell Cheng

The second question is really a concomitant of the first. It seems to me that the single most important major issue is the development of human resource approaches and methodology which can be deployed to demonstrate to organizations that simulation should be considered an indispensable tool that is always part of a well-run organization, just as accountancy is recognized as a de-facto necessity of any well-run organization. We are still a long way off having simulation regarded in this way.

3.2 Response by Charles Macal

Given the dynamism of the field, there are several research areas that show great promise for advancing the capabilities of ABMS to solve problems in the next 10 years, including: behavioral modeling, simulation analytics, hybrid modeling, and large-scale ABMS techniques and applications (Taylor et al. 2013, Tolk et al. 2015).

Behavioral Modeling. The behavioral modeling challenge for ABMS is to develop better representations of agent behavior and the methods that populate behavioral models with the requisite data. Advancements in behavioral economics and behavioral operations management have fueled interest in better models of behavior. Better models of agents are needed that describe how people actually behave in a variety of contexts. Agent-based models have moved beyond the normative rational actor model to include variations of the more descriptive bounded rationality model, in which agents' decisions and behaviors are tempered by realistic constraints on time, effort and attention, among other approaches

(Balke and Gilbert 2014). Causative agent behavioral models, based on insights from behavioral economics (Kahneman 2011) and cognitive sciences (Sun 2006) that include social and emotional factors could be essential elements of more predictive, and useful, agent-based models. For example, Epstein (2014) introduces a new theoretical entity, Agent_Zero, a conceptual software individual endowed with distinct emotional or affective, cognitive or deliberative, and social aspects, grounded in contemporary neuroscience that represents explicit causative factors underlying agent behaviors. New approaches using data analytics for inferring agent behaviors from data streams, social media and sensor networks (Kosinaki et al. 2013) demonstrate how behavioral attributes can be identified from digital records (Bengtsson et al. 2011).

Simulation Analytics. The simulation analytics challenge for ABMS is to develop the methods and tools, such as data analytics and statistical analysis techniques, for extracting meaningful information from simulation results. ABMS's gain in complexity is at the loss of analytical tractability and the ability to derive facts *a priori* about agent-based models, such as relating micro-level agent behaviors to macro-level system outcomes. Computational experiments must be cleverly designed in advance to efficiently obtain the data that can be used to understand model behaviors, sensitivities to parameters, and how uncertainties in input data and structural relationships (e.g., agent behaviors) are propagated to model outputs. The problem is compounded in a stochastic environment by uncertain parameters characterized by ranges and distributions. A single run of a stochastic agent-based simulation consisting of millions of agents moving through an urban environment and updating their states hourly for a period of 10 years, produces a terabyte of data. Doing many runs of a stochastic simulation or doing parameter explorations can require of thousands of ensembles of simulations that can only be done in distributed computing environments and managed by specialized workflow software. Data analytics approaches turned to simulation output data such as simulation analytics (Nelson 2016) will be needed.

Hybrid Modeling. The hybrid modeling challenge is to understand how agent-based modeling can be effectively used with other simulation and modeling techniques operating together in the same "hybrid" model in such a way that each technique addresses the part of the problem that it does best. The hybrid modeling challenge has both logical (how to link models together in way that makes sense) and mechanistic elements (how to link two existing models together that use disparate modeling tools). An example of a hybrid model consists of an agent-based model of a regional economy, in which agents generate economic activity according to their detailed behavioral models, linked to a system dynamics model that supplies the macroeconomic variables at the national level; the hybrid model captures the two-way linkages between the agent-based model and the SD model. ABMS toolkits have begun to incorporate hybrid-modeling capabilities.

Large-Scale Agent-based Modeling and Simulation. The large-scale agent-based modeling challenge is to efficiently and effectively simulate large-scale agent-based models, consisting of millions of agents, at the city scale, or even billions of agents, at the global scale. The computing challenge is to develop algorithms and software for distributing agent-based models, or their interacting components, on high performance computing, cloud computing, and other platforms (Collier at el. 2015). Workflows can be implemented that offer "simulation as a service" and ease the burden on the modeler of the mechanics of distributed computation (Ozik et al. 2016). Research challenges include how to dynamically balance simulation workloads, interact with running simulations, and efficiently collect model outputs for further analysis. A large-scale ABMS challenge is to engineer processes for efficiently developing synthetic populations of agents, whether agents represent actual people, which comes with the associated data access and privacy issues, or only surrogate agents that correspond to the population, but only in the aggregate to properly address anonymity requirements.

3.3 Response by Barry Nelson

While we have gotten more rigorous, we have also tended to get a bit farther away from simulation practice. Reconnecting with practice and thinking about technology transfer would be in our interest; see Nelson (2016a).

Although there have been significant advances in optimization via simulation, the incorporation of stochastic constraints still stands out as a practical feature for which we do not have well-accepted solutions. Nelson (2013) outlines the difficult issues.

3.4 Response by Markus Rabe

A major issue still to be addressed is to transfer the above-mentioned procedure model for V&V into daily use. The model is today under discussion for a VDI guideline (3633.13) to cover V&V in the P&L simulation. While the procedure model is recognized as being well-structured and mostly complete, it is also suspected to be too work-intensive for many typical P&L applications and to offer not enough support in focusing it in a pragmatic way. Therefore, research is required to bring this model into practice with pragmatic guidelines. The need for such development is obvious: while V&V is absolutely essential for credibility of a simulation study, in an investigation of recent papers on P&L simulation topics (mainly from the ASIM Dedicated Conferences on Simulation in Production and Logistics and the Winter Simulation Conferences), 170 out of 193 contributions did not even mention validation at all.

While simulation experiments in the past have mostly been designed by the “intelligent engineer”, there is a request for automatic systems that propose “good” solutions. The discussion of the combination of simulation and optimization has, therefore, gained more and more importance. Especially in Germany, there has been significant systematization by ASIM (März et al. 2011) and VDI in its guideline 3633.12 (VDI 2016). As a side effect, the call for optimization also leads to the need of more efficient simulation tools that just enable processing more runs in shorter time. This might also lead to more simple and specialized tools in comparison to the powerful but sometimes slow “use for everything” applications that dominated the market in the past.

While tools to assist in simulation studies might find further improvements, there is a growing need to get results even in earlier states where data are still incomplete or aggregated. Therefore, there is a demand for integrated solutions that provide different solution technologies like discrete event simulation, continuous applications (sometimes called mesoscopic simulation), and even non-simulation calculation schemes for quick analyses on draft and aggregated data. Integration of such technologies in assisting systems will bring great advantages and foster the application of such systems and, in consequence, simulation technology.

With the goal of cost-efficient simulation application, there is also a need for common and broad development of building blocks, potentially based on the successful VDA activities. In analogy to the rising open source communities, a simulation development community with common use and contribution to public building blocks would bring a tremendous step forward and even allow for conducting simulation studies that take too much time today for delivering results in due time, according to the investment decision milestones.

4 WHAT WILL BE ACCOMPLISHED IN THE NEXT TEN YEARS

The section above provided some of the panelists’ thoughts on major issues that still need to be addressed, so we asked them the following question about the future.

What will the simulation community be able to accomplish over the next ten years?

4.1 Response by Russell Cheng

With regard to the third question, I am personally most interested in how parallel programming might develop. Significant improvement in hardware design has already occurred in the development of general purpose graphics processor units (GPGPU) incorporating several thousand thread processors. Improved hardware design that leads to the removal of memory access bottlenecks, would signal the possibility of serious use of GPGPUs for more mainstream simulation modelling and output analysis, the latter possibly carried out using general purpose resampling methods which are highly amenable to parallelization

Fast simulation models are attractive because they can be used as a tool in real time decision taking. The idea links in with simulation optimization, where model performance is dependent on the setting of design variables. To achieve good system performance, the model is run a large number of times at different design variable settings to find the best alternative. If it can be done in real time, this would open up the use of simulation to inform real-time actual decision making. There are many possible applications. Some places where this approach has been tried include: vehicle traffic control, military conflict scenarios, real time tactics in motor racing, oil exploration.

4.2 Response by Charles Macal

Of the possibilities discussed above, probably the most important area for the next 10 years of ABMS development is to have better models of behavior, but more specifically and importantly better models of *behavior change* that can be implemented in ABMS, based on the rapidly advancing fields of quantitative social and behavioral sciences, blended with normative and descriptive modeling perspectives, as well as the neurosciences that are revealing new insights into how people will respond to various situations (which can be encoded as individual agent states) as well as interventions designed to affect and nudge behavior and populations toward better social outcomes.

4.3 Response by Barry Nelson

In Nelson (2016b) I identified AM problems for the next ten years in three categories: simulation analytics; parallel simulation; and simulation to support decisions. These arise from acknowledging three fundamental features of the current environment in which simulation is practiced:

1. "Data storage is cheap and effectively unlimited, which means that we can exploit more of the simulation-generated data than we typically do today.
2. Parallel simulation is becoming easy to do, and any simulation experiment that requires multiple replications or multiple scenarios can benefit dramatically from parallel simulation.
3. More and more current and potential simulation users are interested in risk analysis, prediction and control, rather than in system design."

By *simulation analytics* I mean digging deeper into the behavior of simulated systems by retaining complete sample path information from all replications and scenarios simulated. This would allow us to not only say which system has the best long-run average performance, but *why* it performs better, and move us in the direction of using simulation for system *control* rather than just design.

Massively parallel simulation is valuable any time we make replications or simulate multiple scenarios (as in optimization via simulation). But parallelizing our methods is not straightforward: There are biases introduced when outputs return from the processors in an order different from what they were requested. Many of our algorithms for output analysis assume a single processor (e.g., one long run in a steady-state simulation) or achieve number-of-outputs efficiency by lots of coordination (e.g., ranking & selection procedures with elimination). Using a single processor or frequently coordinating multiple processors is silly in a massively parallel environment. I expect to see many advances in this area.

In AM research we have tended to focus on measuring estimator error, while practical decisions are more often based on risk. *Simulation to support decisions* is essential for us to remain relevant. We should (and I think will) help users understand risks associated with system behavior, and also broaden our concept of "risk" to include *model risk*, not just stochastic output risk. Data analytics has emphasized the importance of prediction rather than estimation; I believe simulation users will be looking for the same change in emphasis from us.

4.4 Response by Markus Rabe

A prognosis for a decade is more than difficult – things don't tend to come as expected, especially in heterogeneous areas like simulation. Just as an example, the expectations of many experts on distributed simulation in P&L (cp. Straßburger und Schulze 2008) have turned to be mostly wrong.

Nevertheless, one issue that can honestly be expected to see a very good progress in the next decade is the integration of simulation and optimization technologies. As the optimization in P&L applications nearly always means the application of heuristics, the term simheuristics has been brought into discussion (Juan et al. 2015). Many papers (also mirrored by the main conferences that address simulation in P&L, like ASIM and WSC) address simheuristics either explicitly or implicitly. Several research groups are developing new methods and applications. Just to name a few samples, there are interesting developments in Barcelona (cp. Gruler et al. 2015), Dortmund (cp. Rabe and Dross 2015), and Munich (cp. Uhlig and Rose 2015).

Some further developments seem also to be promising. The broad attention that V&V has achieved, especially in Europe, leads to expectations of achieving practical and broadly followed V&V procedures and accepted guidelines. There are also approaches visible towards very fast simulation tools. Research on mesoscopic simulation is conducted by some groups, and the demand from the market might accelerate such development.

Other developments raise less expectations. Just as one example, 3D technologies are in a very good fashion and are even improving. However, the demand from the market for having perfect 3D in their simulation applications is low and enterprises do not show the intention to intensify its use (Schmitz and Wenzel 2013).

5 CONCLUDING COMMENTS

The *Journal of Simulation* strives to serve all of the subsets of the broader simulation community that regularly participate in the Winter Simulation Conference. Based on the outstanding panelists, we are confident that this panel session will stimulate many conversations amongst the simulation community.

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