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

FIVE DECADES OF HEALTHCARE SIMULATION

Sally C Brailsford

Southampton Business School
University of Southampton
Highfield
Southampton, SO17 1BJ, UK

Michael W Carter

Centre for Healthcare Engineering
5 Kings College Road
University of Toronto
Toronto, Ontario M5S 3G8, CANADA

Sheldon H Jacobson

University of Illinois
201 North Goodwin Avenue
Urbana, IL 61801, USA

ABSTRACT

In this paper we have not attempted to produce any kind of systematic review of simulation in healthcare to compete with the dozen (at least) excellent and comprehensive survey papers on this topic that already exist. We begin with a glance back at the early days of Wintersim, but then proceed, in line with the theme of this special track, to reflect on general developments in healthcare simulation over the years from our own personal perspectives. We include some memories and reflections by several pioneers in this area, both academics and healthcare practitioners, on both sides of the Atlantic. We also asked four current simulation modelers, who all specialize in healthcare applications but from very diverse perspectives, to reflect on their experiences. We endeavor to identify some common or recurring themes across the years, and end with a glimpse into the future.

1 INTRODUCTION

Healthcare has been a prolific application area for simulation modeling ever since the very early days of computer simulation. There are papers in healthcare operations research (OR) long predating the first Winter Simulation Conference, such as Bailey (1952) and Welch and Bailey (1954). Fries (1976) presents the first known bibliography of healthcare applications of OR: his review covers a total of 188 papers, several of which are applications of simulation that predate Wintersim, e.g. Fetter and Thompson (1965). More recent reviews, including those by two of the authors of this paper (Jun, Jacobson and Swisher (1999) and Brailsford et al. (2009)), testify to the continuing popularity of simulation as a modeling approach to tackle problems in healthcare. The key reasons for this were outlined by Davies and Davies (1994) and remain equally true today: no other modeling method is capable of capturing the unique combination of complexity, uncertainty, variability and the detailed focus on the individual that characterizes healthcare systems.

Jun et al. (1999) provide a highly-cited survey of discrete-event simulation in health care clinics. The majority of papers focus on operational issues, including patient service, patient throughput, and medical staff utilization. This focus has continued into the 21st century, including patient scheduling optimization and better use of health care resources such as physical space and all levels of medical personnel. One change that has occurred is the granularity of the health care environment that simulation models can now capture. Early work focused on generic patient scheduling or staff utilization modeling. More recent efforts

978-1-5386-3428-8/17/$31.00 ©2017 IEEE

have considered particular types of medical facilities (e.g., emergency rooms, surgical centers) or particular types and mixes of staff and facilities (e.g., coordination of nurse schedules with operating rooms). Emergency room (ER) modeling has attracted a significant amount of attention, given the large amount of uncertainty inherent in the operation of such facilities.

Brailsford et al. (2009) comment on the massive scale of the academic literature on healthcare simulation: for example, they found 1008 papers describing discrete-event simulation models of ERs. However, in common with previous reviews such as Fone et al. (2003) and dating back as far as Wilson (1981), they found that only a very small proportion (around 5%) of papers report practical implementation of the model results. This is a somewhat depressing feature of health-related OR, and raises the question of whether there is something different or special about healthcare systems compared with other areas such as defense or manufacturing industry, where successful implementations are plentiful.

2 WINTER SIMULATION CONFERENCE: A LOOK BACK

2.1 The early days

The first Wintersim, in 1967, did not have Proceedings. The 1968 conference did have Proceedings but did not include a healthcare applications track. However in 1969 there were three papers, and four in 1970, including a very interesting paper by Kennedy et al. which described a model for planning services for mental health care in alcoholism "*used by the North Carolina Department of Mental Health in their planning and budgeting process*" (Kennedy et al. 1970). This model was written in Fortran and required "*53,200 characters of disk storage*", whatever that means (bytes?). It is also worth noting that the authors comment that the project "*combined the talents of four personnel types*": clinical and social care staff working directly with alcoholics, researchers (modelers, psychologists and sociologists), senior decision-makers from the Department of Mental Health, and advisors from the state legislature. This was a very impressive team line-up, with all bases covered, which may well account for the fact that unusually, this was a model that was actually used in practice.

For the remainder of the 1970s the Health/Hospital Services track remained fairly small, but of course all the tracks were relatively small in the early days. There were no regular contributors or instantly recognizable names until 1977, when there was a paper by Charles Standridge, Charles Macal, Alan Pritsker, Harry Delcher and Raymond Murray which described a hybrid continuous/discrete model of the primary health care system in Indiana (Standridge et al. 1977). Hybrid simulation is clearly not quite such a new idea as we thought when we started the Hybrid mini-track in WSC'14, even though hybrid modeling software like AnyLogic was obviously not available in 1977.

2.2 Subsequent years

The 1980s were lean years for healthcare at WSC, even though the conference itself was growing, and it was not until the late 1990s and early 2000s that a significant number of papers began to appear in the Health track (sometimes named the "Hospital Services" or "Medical Administration and Services" track). Of course, over the years there have been many papers on healthcare applications in other tracks: for example, in WSC'16 the Hybrid track contained six papers on healthcare. One of the features of healthcare as an application area is that its complexity has often driven the need for new methodological research, and healthcare-related papers can be found in many different tracks. We have therefore not attempted to count the total number of WSC papers on healthcare applications, but Table 1 shows the number of papers in the track dedicated to healthcare applications (if there was one, and regardless of what it was actually called) over the past 50 years. The first Advanced Tutorial paper, *Advances and Challenges in Healthcare Simulation Modeling*, appeared in 2007 (Brailsford 2007) and the growth in this track from that point onwards is considerable: not that we claim any causal effect!

Table 1: Number of papers in the "Healthcare Applications" track at WSC.

1968	-	1978	2	1988	-	1998	7	2008	25
1969	3	1979	-	1989	3	1999	9	2009	27
1970	4	1980	-	1990	-	2000	7	2010	27
1971	4	1981	3	1991	3	2001	6	2011	26
1972	-	1982	-	1992	9	2002	-	2012	32
1973	3	1983	-	1993	2	2003	12	2013	32
1974	5	1984	2	1994	3	2004	13	2014	30
1975	4	1985	-	1995	6	2005	6	2015	25
1976	4	1986	-	1996	6	2006	9	2016	25
1977	3	1987	3	1997	3	2007	23	2017	TBC

3 SALLY BRAILSFORD: NURSE TURNED MODELER

3.1 I am old, but not that old

I was alive in 1952 when Norman Bailey published his famous paper on health OR, although I was only a few months old and therefore not a frequent reader of *The Lancet*. However, it was not until the late 1980s that I became an academic, returning to do a Masters following a mathematics degree in the early 1970s and then a career in nursing, so I have no personal experience of healthcare simulation prior to 1988. Hence my personal reflections only date back thirty years, rather than the 50 years that WSC has been in existence. Despite my relatively short career in healthcare simulation, the changes that I have seen since I developed my very first simulation model are immense, and arguably not all for the better.

I started my MSc at Southampton in 1987, a few years too late to have met or be taught by K.D. Tocher, Southampton's first Professor of OR. Tocher (known universally as Toch) died in 1981 at the early age of 60. He was undoubtedly one of the giants of simulation. In 1963 he published the *Art of Simulation*, the first textbook in discrete-event simulation (DES), cited by most PhD students in the 1980s but probably only actually read by a few of us. Tocher invented the three-phase method and developed the first DES package, the General Simulation Program (GSP). The Tocher Prize is now awarded every two years for the best paper in the *Journal of Simulation.* Ruth Davies was one of his PhD students, and Brian Hollocks, the keynote speaker in this track, wrote a paper in *JoS* about Tocher's life and work (Hollocks 2008). Hollocks records that *The Art of Simulation* had to be written a second time as the original and first proofs were lost in a fire at the publishers! I still actually have some of Tocher's original typescript papers in my office, which I rescued when the Maths Department was having a clear-out in the 1990s. Hollocks comments that "*Other innovative work included Activity Cycle (or Wheel) Diagrams, mixing discrete and continuous simulation, the notion of a visual interface to simulation, interactive models, and operational gaming—as well as an operating system. Other innovations, for example, simulation optimization, were anticipated but not (apparently) completed. Even this list omits further innovations and achievements, for example, Toch was the first industry-based visiting professor in a UK university*". (Hollocks 2008).

3.2 My early simulations: "code it yourself"

My first experience of simulation was my MSc coursework assignment. If anyone had told me at that point that I would spend the next 30 years of my life doing simulation, I would have fallen about laughing. In those days, students did not have access to user-friendly software with pretty graphics like the students of today. In the late 1980s at Southampton, we wrote our simulations in Pascal, using a library of routines (known as the "Lancaster system") for executing the three-phase method and performing housekeeping tasks like sampling from distributions, developed by John Crookes and his PhD students at Lancaster

University (Crookes et al. 1986). In fact Tocher had also worked with Crookes during a period as visiting professor of Mathematics at Lancaster, which presumably is why Southampton students were given the code. I have to say I struggled with this simulation assignment, mainly because I had zero background in programming and we had to develop and run our programs in the DOS operating system from a command line prompt. There was no facility for debugging and you had to interpret strange run-time error messages when (or if) the code compiled and the model executed, which in my case was not often. I totally forget what the task was that we were set, but I did not enjoy simulation one bit.

However, despite this inauspicious start, and somewhat against my better judgment, I then went on to use simulation for my dissertation project. I developed a small DES model for HIV infection, again coded from scratch in Pascal using the Crookes library. Somehow, my MSc dissertation grew into a PhD thesis, but this time my simulation model was coded in Borland Turbo Pascal, a Windows-based environment which was much more user-friendly and allowed for debugging and more rapid model development. Moreover, I was by now getting the hang of writing code. I was also using a different library of routines, developed by Ruth Davies although still essentially based on the Crookes code, called POST (Patient Oriented Simulation Technique: Davies and Davies 1994), which had the key benefit that it allowed entities to be in several places at once. This made the POST approach particularly suitable for healthcare modeling, because a patient entity could be simultaneously progressing through disease stages (modeled as a queuing network) and also actually queuing for treatment, or participating in some other activity such as a hospital stay. No other software at the time could handle this. In fact, by this time I was starting to enjoy writing code, and I particularly enjoyed having total control over the model logic and the flexibility this brought.

During this period I also did my first ever piece of consultancy. This project was nothing to do with healthcare: my role was to write a visualization of a port simulation, where a combination of automated guided vehicles (AGVs) and vast movable cranes called rail mounted gantries (RMGs) shifted containers around the port in complex sequences of moves. Another PhD student wrote the actual simulation, and my job was to take the numerical output from this model and turn it into an animation. I learned a very important lesson during this project, namely the power of visualization. I had initially used solid lines of different colors to distinguish between the RMG track and the roads used by the AGVs. However, when we showed the clients the model, they complained that the RMG track did not look like track, and said it should be depicted by cross-hatching, like the railroad lines in a child's drawing. He who pays the piper calls the tune, so I amended my visuals. It turned out that this was a key factor in the clients' acceptance of the model, far more important than all the statistical validation we also performed.

In the early 1990s, very few UK universities used commercial off-the-shelf (COTS) DES software for teaching. As I commented in my 2015 WSC paper (Brailsford 2015) it was only when SIMUL8 appeared during the late 1990's that students were widely exposed to software tools that they would use in their later careers. Mark Elder originally developed SIMUL8 for teaching when he was a junior lecturer at the University of Strathclyde in Scotland, but it is now a commercial product used all over the world. Back in the early 1990s, Mark took the brave step of leaving academia and setting up a company to turn the concept of a very cheap (or free) teaching tool into commercial reality: he had the insight to realize that a new generation of students who had grown up using SIMUL8 would then ask their future employers to buy it. Nevertheless, the early versions of SIMUL8 were simply too limited and restrictive to use for research, especially for people like myself who were accustomed to the total flexibility of writing our own code. The freedom of "code it yourself" meant that if some aspect of a problem situation required a particular non-standard logical rule or behavior, then you just encoded that rule or behavior, without worrying about how you might get round the constraints of a COTS package to deal with it. Although I welcomed the advent of SIMUL8 for teaching, I continued to write my own simulation code for research purposes until at least the turn of the new century. The downside of this was that animation was not normally possible, and a "text histogram" composed of horizontal lines of asterisks was probably the height of visual output at the time. This did have its drawbacks when working with hospitals or other healthcare professionals: today, many clients expect to see movie-like visualizations of their system.

3.3 Seeing the light: simulation is not just discrete-event simulation

Like most Master programs in the UK, Southampton's simulation course only covered DES and a little bit of Monte Carlo simulation. Since most students came from a mathematical or engineering background this seemed entirely natural to me. It was not until 2000 that I discovered that there were other simulation approaches, or "paradigms" – a word I had never even heard of until I moved from a Mathematics Department to a Business School in 1998. In 2000, the UK OR Society's Simulation Special Interest Group and the UK System Dynamics Society held a joint meeting at the University of Warwick, entitled "*Never the Twain Shall Meet*". At this meeting David Lane gave a talk about comparing DES with system dynamics (SD), and I had one of those lightbulb moments when I realized that SD could do many things that DES could not. SD can do far more than just continuous simulation. A paper that influenced me greatly was Lane et al. (2000) and I realized that systems, especially healthcare systems, could exhibit what Lane calls "dynamic complexity" for which SD is the ideal modeling approach, as well as "detail complexity", i.e. the features listed in the first paragraph of Section 1 that DES can deal with so well. In this paper, Lane used SD to study the effects of reducing hospital beds and concluded that "*using A&E waiting times alone to judge the effect of bed reductions is systemically naive. Developments in multiple performance indicators recapitulate an old idea: complex systems must be monitored using a corresponding variety of signals*." (Lane et al. 2000, p.529). One of the problems with simulating healthcare systems is that everything affects everything else.

However, SD was not widely used by OR modelers at the time and was rarely taught on MSc programs. The SD community had their own journals and their own conferences: SD papers were extremely rare in WSC. Following the Warwick meeting, David Lane and I jointly founded a new SIG called SD+, whose aim was to bring these two communities together. In 2008 I presented a paper at WSC entitled "*System Dynamics: what's in it for healthcare simulation modelers*?" (Brailsford 2008) and in fact there were three SD papers at this conference. In 2014, we decided to merge SD+ with the Simulation SIG, feeling that SD+ had done its job and achieved its objectives. The *Journal of Simulation*, whose original scope was limited to DES, now welcomes both ABS and SD papers, and the number of SD (and ABS) papers at WSC continues to grow.

3.4 Reflections

Looking back over my career, one thing that remains as true today as it did when I started out is the wide variety of attitudes to the use of simulation by healthcare professionals. I have come across a vast spectrum, ranging from evangelical people who think it is the answer to all the world's problems to people who are totally resistant and refuse to engage. The latter include both medical doctors, who think the only valid tool for experimentation is the randomized controlled trial, and managers who see simulation as a computer telling them how to do their job. Both need to be handled with care: the enthusiasts need to have their expectations managed realistically, whereas you often have to do a very good sales job to persuade people that simulation is simply a tool to help them do their job better. Sometimes you encounter both types in the same project, and this can feel like walking on a perpetual tightrope!

4 MIKE CARTER: OPTIMIZER TURNED SIMULATIONIST

4.1 Early days

I attended the University of Waterloo in Computer Science in 1966 because I wanted to be a programmer. In my third year, I discovered Operations Research, and changed my major to "Combinatorics and Optimization". From 1971-1978, I worked as a full time systems analyst at the University while taking graduate courses part time. In 1973, I did my first healthcare project during a scheduling course on an analytic solution to the number of nurses required to cover seven day shifts with mandatory weekends off. This was eventually published in Management Science in 1985. My first introduction to simulation occurred in 1974 when I was invited to teach an introductory course in simulation for architecture students. I had never taken simulation, so the first year, I was learning GPSS as I taught the course. It was 15 years later that I finally connected these two areas of research. Having obtained a doctorate in Mathematics from the University of Waterloo in 1980, my early work was mainly in scheduling and timetabling.

4.2 Healthcare Simulation

My career in simulation in healthcare really began in earnest around 1989. Professor Linda-Lee O'Brien-Pallas from the University of Toronto Faculty of Nursing called me to suggest that we apply for a $250K grant from the Ontario Incentive Fund and five Toronto teaching hospitals (SickKids, Toronto General, Toronto Western, Sunnybrook and Mt. Sinai). The hospitals were concerned about the trend at the time of nurses leaving Canada to jobs in the U.S. They felt that weekend work was a major irritation, and they hoped that by adjusting the Operating Room schedule, they could reduce weekend bed census and improve working conditions. Linda was a leading authority on nurse workload and I had done work on nurse scheduling. We hired John Blake, a graduate from Industrial Engineering at U of Toronto who had spent four years in the General Motors simulation team, and Linda McGillis-Hall, a nurse at SickKids who was working on her Master's. (John and Linda both later completed a doctorate. John is a professor in the IE department at Dalhousie University in Nova Scotia, and Linda is a professor in the Nursing Faculty in Toronto.) The key performance metrics revolved around bed census and the expected nursing workload in each ward of the hospital. We wanted to estimate required staffing levels.

Due to computer storage limitations at the time, we created a separate model for each of the five hospitals. The models were slightly different but based on the same framework. Ironically, by the time we had completed the work almost three years later, the government was beginning a process of funding cuts to satisfy funding constraints, and no one really cared anymore about nursing attrition. However, each of the hospitals were very concerned about efficient, balanced bed utilization, so each of them used the model to address critical planning issues.

During this project, I came to realize how inefficient the hospitals were. Everyone was trying hard, but there was very little coordination, scheduling, planning or flow management. Moreover, in the early 1990's there were no researchers in Canada focused on process improvement in healthcare. I decided that things needed to change, and from that point on, I have devoted my research and my energy to making a difference.

Initially, I applied my knowledge in scheduling to operational level hospital problems, always working with clinical and administrative collaborators. But as I learned more, I realized that the real opportunities for major improvement lay at the system and policy level. Decision makers at senior levels have few quantitative tools available to help them understand the potential impact of their decisions. I decided that I wanted to focus my attention on either policy decision support modelling primarily using System Dynamics or operational models that could be applied to multiple hospitals generally as generic discrete event simulation tools. I have had literally hundreds of student projects over the years in health applications, most of which involved either discrete event or system dynamics models.

4.3 Reflections

It is often said that healthcare is 20 years behind other industries. My colleagues and students find it frustrating trying to apply their knowledge and models in an industry that is distinctly slow to innovate. However, I remain optimistic. When I look back even 30 years ago, I found a culture that was dominated by individuals applying their own expertise to specific patients. Today, it would be difficult to find anyone in healthcare who had not participated in a process mapping exercise to improve quality and efficiency. We are making slow progress. Healthcare leaders are now looking to quantitative "evidence-based" decision making. The culture is slowly evolving.

The big problem today is data quality and accessibility. Things are improving, but it is still difficult to get consistent, reliable system level patient information that facilitates research into policy questions. It is getting better, but there is still a long way to go.

5 SHELDON JACOBSON: METHODOLOGIST TURNED MODELER

5.1 Early days

As a graduate student at Cornell from 1983 to 1988, my interests in healthcare, let alone simulation healthcare, were nonexistent. Eventually taking my first simulation course from Lee Schruben, with people like Dave Goldsman before me, and Paul Sanchez's gentle encouragement, Lee became my dissertation advisor. As is typical when doing a simulation-focused PhD dissertation, the focus is on formulating and analyzing new methodologies, not designing new models. As such, my dissertation took on a probabilistic hue. In fact, the only simulation models in my dissertation were a variety of simple queueing models used to illustrate the analytical results that dominated the final work.

5.2 Healthcare

My first foray into healthcare simulation was pure serendipity. Serving on the faculty at Virginia Tech, I received a phone call from the office of RJ Kirk. RJ owned and operated General Injectibles and Vaccines (GIV), a distributor of medical products in Radford, Virginia. One of his subsidiary companies was Biological and Popular Culture, Inc. RJ, trained as lawyer, was a visionary entrepreneur with new ideas on how healthcare delivery should be managed. He also had an appreciation for operations research modeling and its value in identifying opportunities for process improvement. He believed that the optimal use of the time spent by high value physicians could be better managed with a more careful analysis of their work flow and how they managed their time. After hearing his ideas, it became clear that simulation could be used to gain insights into such office management issues. Given my limited modeling skills, I brought Osman Balci aboard to oversee the modeling effort, using an object-oriented approach based on his visual simulation environment (VSE) software (Swisher at al. 2001). GIV hired two of my graduate students (James Swisher and Brian Jun), who split their time working on this simulation project and towards their MS theses. In addition to the modeling, several simulation statistical techniques were employed to gain insights into the health care work environment, including batch means, fractional factorial designs, and simultaneous ranking, selection, and multiple comparisons (Swisher and Jacobson 2002). Note that the majority of this research was conducted between 1996 and 1999, many years before it was standard practice to model patient and medical staff work flow using simulation. Today, this is quite common, with many simulation software packages offering modules for such system analysis.

My second foray into health care simulation was also by serendipity. While attending the 1996 INFORMS meeting in Atlanta, I was approached by Robert Deuson, a visiting research scientist at the Centers for Disease Control and Prevention (CDC) in Atlanta. He outlined an optimization problem involving how to design pediatric formularies that incorporate multivalent combination vaccines. Although this situation did not currently exist in the United States, there were a number of such products being used around the world, which were under consideration for FDA approval in the United States. Bruce Weniger, a CDC staff member, realized the challenges the public health community would face with multiple, partially overlapping combination vaccines. In listening to Robert and Bruce, it was clear that the first approach to be taken employed integer programming. As such, I brought a colleague, Edward Sewell, onto the project. However, we eventually incorporated Monte Carlo simulation methods into our analysis to build vaccine price distributions, since consumers of vaccines rarely acted with certainty. Monte Carlo simulation allowed one to estimate such price distributions, and their impact on pediatric formulary designs (Jacobson and Sewell 2002). This research allowed us to combine discrete optimization and Monte Carle simulation in manner that exploited the strengths of each approach, providing practical insights in the health care domain. Once again, combining optimization and simulation in this manner was not as common as it is today, so this research provided a nice introduction to combining such methods.

5.3 Reflections

The healthcare simulation footprint has grown over the past two decades. Jun et al. (1999) provided an overview of where the field was in 1999. Since that time, visualization in simulation software has made it easier for healthcare professionals to appreciate the value of simulation modeling. This has expanding the breadth of problems that have been addressed using simulation modeling. Optimizing the utilization of staff (nurses, physician) and facilities (rooms, space) has attracted a significant amount of attention. Any systems that involve the flow of objects naturally lend themselves to simulation modeling and analysis. The challenge from these efforts has been translating the conclusions of simulation studies into practical implementation. As is the case for many operations research modeling efforts, the objectives often focus around the optimal use of resources, through cost reductions, profit increases, and efficiency enhancements. However, in health systems, the objectives focus on enhancing the patient experience, through increasing patient safety, reducing patient waiting time, and increasing patient access to services. This creates a natural dilemma in how models capture the appropriate objectives in healthcare. Such a mismatch of objectives provides a fruitful direction for future research and implementation, which will better position simulation efforts to have greater impact in the field.

6 PIONEERS IN HEALTHCARE SIMULATION

6.1 Tom Closson [interview by Mike Carter]

One of the first people to use simulation in healthcare in Canada was Ben Bernholtz, a professor in Industrial Engineering at the University of Toronto from 1962 to 1979. Ben recognized the need to concentrate on a few key research areas including a strong focus on healthcare systems. He supervised a number of undergraduate projects in collaboration with Toronto Hospitals, and several of his students went on to careers in the healthcare industry. I asked Tom Closson, one of Ben's protégés, for his experiences with early simulation models. Tom graduated from Industrial Engineering at the University of Toronto in 1971. He spent his career in healthcare, culminating as CEO of the University Health Network in Toronto (the largest hospital network in Canada) followed by CEO of the Ontario Hospital Association. He is now semi-retired but still consulting and frequently speaking with young Industrial Engineers interested in healthcare.

In the summer of 1970 between third and fourth year in Industrial Engineering at UofT, Tom obtained a summer job in the Industrial Engineering Department of the Hospital For Sick Children (HSC) in Toronto with the plan of doing his thesis project there. The project involved analyzing the methods used at HSC for moving patients, supplies and lab specimens around the hospital with the goal of modifying them to optimize service levels and costs. The hospital had a decentralized system, with staff located in many departments spending a portion of their time performing this transportation function. Together with another UofT student, Stewart Park, Tom developed simulation models using Monte Carlo methods coded in Fortran and GPSS to determine the optimum manner of staffing a centralized department to perform this function. Because demand varied by time of day and day of week in a generally predictable manner, they simulated a staffing model that also varied by time of day and day of week to match the expected demand. They ran the model multiple times using sampled data to establish the ideal centralized staffing model to optimize service levels and costs. The results were written up as their thesis project and were presented to the senior management team at HSC.

Upon graduating in 1971, Stewart and Tom went to work elsewhere. However, Tom returned to work at HSC in 1973 and was asked to implement a centralized transportation service. He did not collect any new data, as he assumed that the original data and modelling results would suffice. The new service was implemented and performed in a manner that was very close to what the simulation model predicted. Looking back, Tom felt that simulation was a good choice because of its flexibility in addressing the complexity of the real world. He commented that it would be an even better choice today because there are better simulation tools now, and data to feed these tools is more readily available in organizations' computer systems.

6.2 Mark Hundert [interview by Mike Carter]

Mark Hundert graduated from the University of Toronto in 1971, the same year as Tom Closson. His undergraduate thesis project was titled "System Analysis of the Radiology Department of the Wellesley Hospital". The hospital was looking for ways to improve operations and reduce the costs of the radiology department. Patient volume was increasing at a rate of 10% per year, and the hospital was hoping to avoid a perceived need to add five additional X-ray rooms in order to decrease patient waiting time, balance the daily patient load, facilitate better patient handling and decrease "man-hours" of work required (in 1971, workload was still called man-hours).

Mark created a simulation model using GPSS. He remembered carrying around a pretty large card deck, but didn't recall any issues in getting sufficient computing power to process the program. Wellesley Hospital had an Industrial Engineering Department, so they were open to IE techniques. The radiology department was intrigued and very supportive of the work: Mark thought they were amused by what he was doing, and pleased that someone was trying to address their problem. In order to establish service times, the department organized a work measurement process which involved time stamping everything they did for a month. The hospital used the findings of the study to change its approach to patient scheduling and scheduling of clinics (mainly fracture clinics) that created most of the demand for radiology services, and also to change its approaches to work processing. The hospital was very appreciative and Mark recalled being given a very high grade for his work on the project…..so from his perspective it was a very successful exercise.

After graduation, Mark did a Master's in Industrial Engineering at Northwestern University, supervised by Bill Pierskalla. After completing the Master's in 1973, Bill connected Mark with a position at Medicus Systems Corp. in Chicago. One of his first projects at Medicus was a nursing home simulation model for the Illinois Department of Public Health. The project was sponsored and funded by the Bureau of Health Services Research of the Health Resources Administration of the US Department of Health Education and Welfare. One of the most difficult areas in the regulation of nursing homes involved assessing the adequacy of a facility's staff to meet the needs of its residents. Regulatory standards for nurse staffing (at that time) were extremely vague; it was doubtful that they were adequate to ensure appropriate care for residents of nursing homes. The Senate Subcommittee on Long Term Care stated the problem even more strongly: "*Most leading authorities concluded at subcommittee hearings that the new (Medicare and Medicaid) standards are so vague as to defy enforcement*." A concomitant concern was the rapidly increasing costs associated with care provided by long term care facilities. The dramatic increase in the number of publicly supported nursing home residents with the advent of the Medicare and Medicaid programmes made it increasingly evident that a means of controlling the cost of nursing home care was necessary.

This interest led to the development of the Nursing Home Simulation Model (Hundert and Feldman 1977). The specific objectives for the model were to provide a means for articulating the nursing care requirements of each classification of nursing home residents and translating those needs into specific regulatory standards for staffing levels in nursing homes, and to provide a means for understanding the necessary cost of care in nursing homes as a basis for reimbursement for long term care. The model was developed in both Fortran and Simscript. Mark didn't remember why they developed two different models, but Medicus took over the contract from CACI who had used Simscript to develop a model that didn't work. Mark assumed that the programmers and advisers that they used from Northwestern felt that Simscript (at the time) was not robust enough to support the modelling objectives of the client, and so they decided to develop a more robust Fortran version of the model. In subsequent work, Mark used the Fortran version, so presumably he agreed with this view.

The results were used by the Illinois Department of Health as a guide for setting staffing standards and reimbursement levels for nursing homes in Illinois. Subsequently, in the early 1980's the model was discovered by David T. Marks, a State Prosecutor in Galveston Texas who was angered by the neglect of residents in Texas Nursing Homes. In one grievous instance a resident died from neglect (malnutrition, pressure sores, etc.) The prosecutor decided to bring murder charges against the nursing home chain that owned the facility where the patient died. The prosecutor used the simulation model to demonstrate that the staffing levels employed by the nursing home could not possibly have provided the care needed by the residents. The findings were used as part of the evidence in the trial (People.com 1983). This was surely one of the most unusual applications of simulation modeling!

6.3 Walton Hancock and Robert Storer [interview by Mike Carter]

In 1970, Walton (Walt) Hancock, who was chair of the IOE Department and director of the Human Performance Laboratory at the University of Michigan, was studying ways to minimize hospital costs and became interested in whether the flow of patients was optimal. In order to learn more about patient flows and hospital management, he moved his primary office to the School of Public Health, where there was a hospital administration graduate program. There he joined John Griffin, the director of the program, and others in the School of Public Health to develop stochastic flow systems that achieved maximum occupancy once the number of beds to be staffed were properly determined. In 1974, one of Hancock's first IOE PhD students working in hospital systems engineering, James Martin, joined Griffin and Hancock in the School of Public Health as an assistant professor. In 1976, Griffin, Hancock, and Fred Munson published the first book on the topic, Cost Control in Hospitals, which was lauded for its use of case studies showing that a data-driven systems approach could effectively reduce the cost of many different types of hospital operations. With the advent of mini computers in the '70s, and with funding from a National Institutes of Health (NIH) grant, they developed a computer simulation designed to allow hospitals to maintain much higher occupancies, and at the same time provide for unexpected emergency arrivals. The first successful implementation of this simulation resulted in a six percent increase in patient occupancy with an increase in budget of only $10,000 annually in a large hospital. This was a time when NIH officials were promoting translational research. The project director of NIH encouraged Hancock to start a company to implement the Admission Scheduling and Control System (ASCS) in other hospitals. Hancock successfully implemented the ASCS in 20 hospitals.

Professor Robert (Bob) Storer (now at Lehigh University) was an undergraduate at University of Michigan in the 1970's. Bob worked in Walt's research group as an undergraduate IE student at Michigan around 1976. He remembers working with Walt's graduate students including Paul Fuhs, Rick Hamilton and Ken Hawley. Walt also had a colleague and former student named Jim Martin from the School of Public Health who was involved as well. Bob recalls that the work they were doing was funded by one or more of the big automobile manufacturers. Their motivation was that (even back then) their employee healthcare coverage represented a very significant part of their cost structure. The work they did ended up getting implemented at several hospitals in the Detroit area.

The basic idea was based on the observation that the hospital census varied significantly over the days of the week. The research aimed to reduce cost by keeping the census uniformly high throughout the week. Two basic types of patients were observed: scheduled patients and emergency patients. Walt proposed a third class named something like "Call-in patients". These were elective patients that could be called up on (relatively) short notice and told to come to the hospital for their care. These patients were thus used to "fill the gaps" in census. The team developed a big simulation model written in Fortran to determine better ways to schedule patients, and in particular rules the hospital admissions staff could follow to decide how many call-in patients to summon each day in order to keep the census high.

As an undergraduate, Bob spent most of his time running different cases through the simulation to help build the rules. He says they were blessed, relative to other students at the time, with "DecWriters" (like teletypes only a bit faster) to do this work on. Part of the simulation input analysis entailed building patient length of stay models. At first, they tried relying on physician estimates, but these turned out to be terrible predictors. They then turned to building models based on patient attributes, diagnosis, etc. Bob still recalled being shocked (at least at the time…not any more) that one of the most significant variables was day of admission. Physicians would routinely discharge patients on Friday to avoid weekend rounds if they could. *Plus ça change …*

6.4 Ray Paul [interview by Sally Brailsford]

Ray Paul, Professor Emeritus at Brunel University London, is one of the UK's best known simulation experts and is very well known to the WSC community. His last post before taking early retirement in 2003 with Parkinson's disease was as Dean of the Faculty of Technology and Information Systems at Brunel. His honors within the field of simulation include being ranked 21st in the world amongst experts in simulation systems by eH-index (2009); being awarded the title of Companion in Operational Research by the UK Operational Research Society (2009); and winning the 2008 ACM SIGSIM Distinguished Contributions Award. Ray's contributions to the field include more than 350 refereed journal articles and several textbooks, and he has supervised the remarkable number of 55 PhD students. He was a moving force in the founding of the *Journal of Simulation*, and he served as Editor of the *European Journal of Information Systems* for 12 years.

Ray described a simulation project he undertook in the 1980s for the UK Department of Health. The model, a DES called CLINSIM developed in Simscript, was intended for generic use by any hospital outpatient clinic as it could (in theory) be tailored for any setting. Ray called it an "iceberg project" because although on the face of it, the model specification was fairly simple, there was an enormous amount of complexity beneath the surface. There was also a political dimension: his was in fact the third attempt to develop such a model and the project, which had been commissioned as a result of a ministerial request to "do something about clinic wait times", was already behind schedule before Ray even started work as two previous attempts by graduate students had failed. One feature that turned out to be particularly challenging to model was to assign patients randomly to any queue: it seems curious today that this should be so difficult! Although the model was intended for widespread use, and would be provided to hospitals free of charge, it was in fact only ever used once, in Leeds General Hospital where there was (very unusually) an enthusiastic analyst with some knowledge of OR. The model showed that the mean patient waiting time could be reduced from 1 hour 40 minutes to 20 minutes, using no extra resources. However the model was never used anywhere else: maybe because it was free?

Ray reflected on changes over the years. He was skeptical about the increasing use of animation, visuals and other supposedly user-friendly features which, in his words, "encourage people not to think". He believes that as a community, we should be getting more out of simulation models than we do. Rather more controversially, he feels that the area where simulation has developed the least is in statistics – there has been no progress since the 1980s apart from theoretical mathematical advances, very few of which have translated into improved modeling tools for the simulation practitioner.

Ray considers one of his greatest achievements to be the development of the software tool VS7, for which he was the system architect: the actual code was written by his students. VS7 was a program generator based on activity cycle diagrams (ACDs) and was developed for teaching purposes. Students created an ACD on screen, and the software then automatically generated the simulation code. Ray has written many WSC papers over the years on the use of ACDs and other diagramming approaches, and he still feels there is further value to be gained from them which people do not fully exploit. VS7 demonstrated the potential links between research, teaching and the "real world": it was the first simulation teaching tool that did not require students to write code, and it paved the way for SIMUL8, software that was also originally aimed at students. Nevertheless, Ray thinks that students still need to know how to write code!

6.5 Ruth Davies [interview by Sally Brailsford]

Ruth Davies, Professor Emeritus at the University of Warwick, is another of the UK's best known simulation experts, particularly for her work in healthcare. She is equally well known to the WSC community and is internationally renowned for her ground-breaking work in developing POST (Davies and Davies, 1994). In addition to working on end-stage renal failure, diabetic retinopathy and coronary heart disease, she has also led a major project on combining DES with Lean methodology. Like Ray Paul, she retired early due to ill-health but she has always been one of the strongest influences on my own work.

Before moving to Warwick, she worked at Southampton for many years and I was her post-doc on the above-mentioned diabetic retinopathy project.

Ruth was involved in several OR projects at Kings College Hospital in London between 1971 and 1973. One of these was for the Renal Unit at Dulwich Hospital, which was in the Kings College Hospital Group. A senior administrator at Dulwich had seen a report of an article in the BMJ (Farrow et al. 1971) and suggested that she could do something similar for them. This work described a Markov model. She did some work on this in 1972-3 but left to work at the South West Regional Hospital Board in 1974. In 1976 she got a job at Reading University, and published a paper on the work at Dulwich (Davies 1978). Ruth recalled that there were no software tools at the time to do the modeling, which was a major difficulty. She felt her results influenced people's thinking, but not their routine selection and treatment of patients.

Later on (1980-84) she continued the renal work for her PhD, using simulation, initially under the supervision of K.D. Tocher at Southampton. The client was Fratton Hospital in Portmouth and she spent a considerable amount of time talking to staff and collecting data. For some time previously Tocher had been thinking that the three phase method should be computerized, and this formed the basis of Ruth's research topic. Toch suggested that she should use a Fortran pre-processor called Ratfor, which had been designed and implemented by Brian Kernighan at Bell Telephone Laboratories in 1974 (Kernighan and Plauger 1976). However, there were problems with the software and moreover it ran on the university's mainframe computer where you would only get one run a day, or two if you were lucky. Ruth found things were moving very slowly.

Sadly Toch died in 1981 but Ruth, together with Toch's other PhD student Bob O'Keefe, continued her doctoral study under the supervision of John Crookes at Lancaster (although they were both nominally still based at Southampton). They used Crookes' Pascal code for the three-phase method, implemented on an early Apple micro-computer. Ruth was able to advance much more successfully with this, although she found that the basic three phase approach had to be modified to accommodate the renal problem and she wrote a lot of new code herself. Looking back now, she says that the computer was incredibly slow although a lot better than what had gone before. It took hours to do one run, never mind several repetitions. Nevertheless, this early work paved the way for POST and its many later successful applications to other healthcare problems.

Ruth said that one of the reasons that OR seemed possible in this particular area of health (end-stage renal failure) was because doctors thought they knew exactly how many people got ill and exactly what treatments were available. It was certainly an easier problem to structure than most other areas of health care. However, there were still problems, many of which are shared by other areas of patient care and many of which remain true today. Initially hardware was an issue, and even though computers are now very much faster more suitable software is still needed. Ruth said that the development of Tocher's three phase discrete event simulation was a great step forward in terms of problem structuring but even so, it has severe limitations in the structure of most health service problems. There are no simulation methods that are generally suitable for patient problems. For example, people are not widgets and have minds of their own, which affects the simulation progress.

With advances in medicine since the 1970s, and an ageing population, the numbers of people needing treatment for renal failure increased vastly as time went by. More people in the age group she had looked at were referred for treatment, so the initial figures were an underestimate. Moreover, originally people over the age of 60 were not considered eligible for treatment, but this maximum age limit was later removed. A large number of people whose lives were saved continued to need care and treatment: this obviously included people on kidney machines, but also those whose transplants had failed. As a result, there were ever increasing numbers of (older) patients, who, in due course, had other problems and needed other treatments.

Ruth said that many exciting problems still remain to be addressed by healthcare modelers. Better software is needed, suitable for describing people's movements between home and different types of institutions, taking into account the availability of key resources: i.e., the speed and direction of individuals' movements are affected by resource provision and availability. She said (and I agree!) that it is always difficult not to develop models that get too complicated, but the best way forward may be to use new software to follow some major illness groups such as heart disease.

7 A VIEW FROM THE YOUNGER GENERATION

In addition to interviewing these pioneers, we also contacted four younger people who are currently actively engaged in the practice of healthcare simulation, from four very different perspectives. Claire Cordeaux heads up the healthcare consulting branch of SIMUL8 Corporation; Todd Hushka is Principal Health Systems Analyst at the Mayo Clinic Kern Center for Science of Health Care Delivery; Sachin Pendharkar is a physician specializing in sleep disorders at the Foothills Medical Centre in Calgary, Alberta; and Vikram Tiwari is Assistant Professor of Anesthesiology and Biomedical Informatics at the Vanderbilt University School of Medicine, Nashville, TN. We asked them all to describe how they got involved in simulation; to reflect on what has changed the least and the most in their careers to date; the benefits and challenges of using simulation in healthcare; and what they see as the most exciting future developments.

7.1 Claire Cordeaux

Claire's Bachelor degree was in modern languages, and she spent the first part of her working life in public sector management. In 2002 she started work at a Strategic Health Authority in the UK National Health Service (NHS), responsible for planning health strategy for a population of 5 million. She assumed that there would be a well-trodden path to understand the impact of new government policies and local aspirations on healthcare demand and resource, and was rather surprised to find that was not the case. This led to a collaboration with Dr Norman Pinder, Medical Director, and Tony Ranzetta, ex CEO of various healthcare organizations, on a project to develop a specification for a modeling tool to aid strategic planning by identifying any unanticipated consequences in advance of implementation. SIMUL8 Corp offered to help develop this tool, and the simulation software *Scenario Generator* (described by Sally Brailsford as "*a DES with a system dynamics wraparound*") was born. The NHS set up a license agreement with SIMUL8 for the tool, and Claire left the NHS to head up the healthcare team at SIMUL8, where she is now Director of Healthcare.

She believes that today there is a greater requirement for evidence based operational change in healthcare than ever before, and this drives demand for simulation. The sophistication of models and their ability to tell the story about disease, clinical, organizational and patient behaviors is very powerful and is supporting adoption of new best practices. Models are being used and reused by different organizations worldwide, with real success. However in her experience it is still hard to get wide scale adoption of simulation in healthcare organizations. It is often led by an individual and their chances of promotion, once they have solved some problem with simulation, are pretty high – leaving the organization needing to rebuild capacity and without a champion. Organizations that have established teams seem to do better and can sustain the use of simulation tools internally.

Claire remains proud of the success of *Scenario Generator*. She said it is not often that you get a chance to realize an idea and then see it disseminated globally! Since that point, highpoints have been when she has been able to distill a key value from a simulation which can be shared with multiple healthcare organizations that have the same problem, for example SIMUL8's work with NHS England on alternative care models for people living with multi-morbidity. She commented that healthcare has (in spades!) all the components that simulation is good at: complexity, variation, increasing demand for scarce resources, and time sensitivity: patient outcomes deteriorate if they don't get the right care at the right time. She believes the most exciting development over the next decade will be the increasing quality and real-time availability of data, which should make building and updating of simulations much easier and will produce results that support continuous improvement of health systems.

7.2 Todd Huschka

Todd has worked at the Mayo since 1996, initially as a medical statistician but since 2006 as an OR expert. In the last decade he has developed many simulation models for the Mayo and has presented several of these at WSC. For example, Dumkrieger, Huschka and Stubbs (2014) describe a simulation to study the impact of reducing the maximum age at which blood could be transfused. The current standard was 40 days, and the model looked at what would happen to the availability of blood if the shelf life was reduced to 14, 21, or 28 days. While the 40 day standard has not changed, the simulation showed that the Mayo's inventory policy at the time was too conservative. The results showed that changing the inventory policy had the dual benefits of saving a considerable amount of money in inventory costs as well as reducing the average age of blood transfused, without any negative impact on patient care.

The first big simulation model Todd worked on was for the Mayo Pain Clinic (Huschka et al. 2008, Huschka et al. 2012). The clinic had recently planned an expansion, and while Todd's group was not involved with the initial floor design they built a model to help clinic staff understand how the new practice would work in real life: they were able to advise about staffing levels and how best to schedule patients. They also identified a scheduling issue that the clinic had not considered.

Todd commented that the biggest change he had seen over his career was in the power of the desktop computer. When he started out the thought of performing simulation on a personal computer was out of the question. Today it is commonplace, and he said that if anything the ease of doing simulation has resulted in some thinking that everything should be simulated. However one thing that has not changed is the difficulty of getting good time-stamped data. While RFID technology looks a promising way to get such data, we are not there yet: it is expensive to install and does not capture every step in the patient experience. Most time data are still collected manually, but although such data are biased, fortunately they tend to be biased in a consistent way and are still useful.

Todd said that almost every project has the same challenge: you think that you have identified all the important aspects of a system, but once you start to validate your model with hospital staff, it becomes clear that something has been left out. Often what seems like a very small aspect of a system ends up having a large downstream effect. On the bright side, this iterative aspect of building the model also helps sell the value of doing simulation modeling in the first place. Like Claire, he believes the most exciting development over the next decade will be real-time data collection, in particular using RFID technology. Right now RFID just puts a patient in a specific location, but when it is eventually linked to what is being done to patients, the system improvement possibilities are endless.

7.3 Sachin Pendharkar

As a practicing physician with a medical background, Sachin is arguably the most unusual simulation modeler of all our interviewees. Towards the end of his medical training in Toronto, he became interested in quality improvement and had been involved in a couple of small projects to improve patient care and the experience of medical residents. Shortly after starting his clinical training in pulmonary medicine in Calgary, he met Dr. Ward Flemons, a senior pulmonologist who was also the vice-president of quality and safety for the Calgary Health Region. Dr Flemons identified operations management and queueing theory as disciplines to which he had been exposed in his role and gave Sachin a few papers to read that sparked his interest in pursuing further study. He audited a couple of operations management courses in his final clinical year and subsequently met Tom Rohleder and Diane Bischak at the Haskayne School of Business. He had decided to pursue sleep medicine as his clinical subspecialty area, and was keen to reduce wait times at the Calgary sleep center (at the time, they were over a year). As he sought a methodology to address this problem, he was introduced to simulation modeling by Tom, Diane and Paul Rogers. He eventually pursued an MS degree in Health Services Research and (with Diane as one of his co-supervisors), developed a DES model of the sleep center and used it to test a number of scenarios proposed by the administration.

He presented this work at WSC (Pendharkar et al. 2012) and the Canadian OR Society conference, and also published it in the medical literature (Pendharkar et al. 2015).

Sachin thinks the acceptance of simulation by healthcare practitioners and administrators continues to increase, perhaps driven by increasing demands on constrained resources and the push for operational efficiency. Although "back of the napkin" calculations are still often used to make funding or resource allocation decisions, there is growing appreciation that complex problems often require advanced methods such as simulation. However, in his view the academic medical community does not seem to think that simulation modeling warrants publication in major medical journals (or maybe the simulation modelers don't!). He suspects that this is due to the lack of reporting on the results of implementation. Without these implementation results, simulation may be seen as identifying a series of "what ifs" that have not been validated in the real world, and he feels this is a major criticism of simulation.

For Sachin, the biggest challenge can be stated in one word: data. Most health systems and clinical research studies do not collect the right data for operational analysis. Furthermore, variation is difficult to capture when these data are not collected regularly. The unfortunate consequence is that approximations and assumptions are required, which may compromise the validity of the model and reduce the likelihood that results will be trusted by stakeholders. However, he believes that in future, the evolution of data collection and monitoring will revolutionize simulation modeling. More health systems are moving to real time collection of electronic data with linkage of large datasets to answer important clinical and research questions. The "Big Data" movement, coupled with the growth in computing power, will allow more sophisticated models to be built and will permit all stakeholders (including clinicians, health system administrators and patients) to be better engaged in the model results, perhaps through near real-time modeling. Furthermore, such large-scale health analytics will be the key to a precision medicine approach to modeling and health system improvement.

Sachin (in our view rightly) feels proud to have been able to educate his colleagues and health administrators on the value of simulation modeling. As a frontline clinician with experience in simulation, he thinks it carries weight with non-experts when someone who appreciates both the clinical and operational perspective can speak to the power of simulation. Furthermore, clinicians tend to respond positively to logical arguments arising from scientific methodology; Sachin's understanding of simulation and its application to complex health service delivery problems has allowed him to stimulate more interest in this technique among his clinical colleagues.

7.4 Vikram Tiwari

Vikram is the only one of our younger interviewees who is an industrial engineer by academic background, although he now has a faculty position in a medical school and is also Director of Surgical Analytics at the Vanderbilt University Medical Center. In his PhD dissertation he used Arena to simulate patient flows in a hospital to test the impact and interaction of variability and flexibility of resources on throughput. He later collaborated with physicians from the VA Houston on many research projects where both DES and Monte Carlo simulation modeling were deployed – surgery duration prediction, impact of adding hospitalist on emergency department flow, surgical block scheduling, among others. In his current job role, he frequently relies on simulation for addressing capacity planning and management questions. He was especially pleased when the senior leadership of the Vanderbilt University Hospital found the simulation results of a patient-flow project to be so useful that one senior manager commented – "*you might have just saved us from making a large capital investment in additional bed capacity*". This research is described in Tiwari and Sandberg (2016).

Vikram believes the availability of simulation add-ins for Excel, and healthcare specific simulation software, have made it possible to build simple simulation models quickly and perform analysis. This 'rough cut' analysis is often sufficient for helping make many practical real-world operational decisions. Another benefit that has emerged over the past decade is the amount of data being captured at all healthcare organizations – both process and clinical. Although he believes that decision makers in most healthcare organizations continue to remain oblivious of the potential of simulation modeling, he thinks this is not their fault. Academics in OR have not fully demonstrated and effectively disseminated the potential of simulation via publications that practitioners read. He said (and we wholeheartedly agree!) that it is incumbent upon OR researchers to publish simulation work in healthcare journals (Tiwari et al. 2014).

Vikram said the biggest challenge is extracting the true nature of the decision makers' problem to minimize model specification creep. It is essential to understand the incremental value of additional model detail so as to convince the project sponsor of the diminishing returns by adding more complexity in the models. We agree this seems to be a particular issue in healthcare, and support Vikram's view that simulation modelers must be fully conversant with the business needs of the hospital.

Looking forward, Vikram believes that healthcare practitioners and administrators familiar with OR methods, and simulation modeling in particular, will always be in demand in healthcare organizations. A further promising trend is the teaching of optimization and simulation methods to medical school students in schools where there is a dual MD-MBA program, such as the Owen Graduate School of Management at Vanderbilt University, where Vikram teaches. He believes the field of simulation will benefit immensely from "OR trained" medical practitioners (like Sachin) embedded within healthcare delivery systems.

8 CONCLUSION

8.1 Nothing new under the sun?

Looking back over the past 50 years, it is tempting to think that we have not really made much progress. Many of the same issues recur as in the 1970s: e.g. long wait times for surgery, rising costs of nursing home care and crowding in ERs. Why haven't we solved these problems yet? It is also striking that even as far back as the 1970s, employee healthcare insurance formed a major budget item in the automobile industry! Specific diseases, disasters or policies have stimulated much modeling work over the years, such as the AIDS epidemic, Ebola, pandemic influenza, homeland security, and the consequences of "Obamacare". Simulation has contributed to many of these areas, but often this work has only been possible because of the availability of government funding, largely driven by political motivations. Other less fashionable areas, such as mental health or social care, have attracted much less attention and grant funding, despite constituting a far greater cost burden nationally.

Other things have changed remarkably little over the years. It is striking that in the Kennedy et al. paper from WSC'77, the project team included a remarkably broad range of people: in our experience, active stakeholder engagement in the modeling process is a critical success factor for a healthcare simulation model to be useful in practice, and all the interviews with pioneers testify that this was the same back in the 1970s. Sadly, despite all this evidence and despite major advances in both software and hardware, there is still a general lack of implementation of simulation in healthcare, compared with other sectors such as manufacturing industry or defense.

Although we now live in the era of "big data", sophisticated information systems and electronic health records, it seems that getting hold of decent data for modeling is still just as difficult as it was 50 years ago. Information governance, patient confidentiality regulations and ethical constraints designed for medical research conspire to put barriers in the way of today's healthcare modeler, even though we normally only need anonymized data to fit activity durations in our simulations. In fact, reading some of the interviews with pioneers, it seems that it was actually easier to get data back in the 1970s than it is today.

8.2 Some things definitely have changed

Simulation software (and hardware) have changed beyond all recognition. Both will always influence what simulation modelers can do. The rise of healthcare specific simulation tools like MedModel has helped to increase the popularity of simulation, and the global success of SIMUL8 is very much an outcome of Mark Elder's vision back in the 1990s. No doubt students the world over welcomed the move away from writing bespoke code to using COTS packages, but this has come at a price. It can be very difficult to make a COTS package do something it was not designed for, and there are many times when the researcher gets frustrated by supposedly "user-friendly" features that actually make life more difficult when you are trying to do anything non-standard. Moreover, as Ray Paul points out, sometimes these features actually prevent people from thinking: like a GPS, they need to be used with caution and always combined with a strong pinch of common sense. The same is true of animation, which is no substitute for proper validation although it is very useful indeed for winning over "hearts and minds".

Hardware developments, such as mobile devices and cloud computing, have led to major changes and have meant that cash-strapped healthcare organizations now have access to a range of tools that would have previously been far beyond their budgets. However, only time will tell whether these advances will translate into increased implementation of simulation modeling.

8.3 Looking forward: the next 50 years

One area of future applications of simulation modeling and analysis is in medicine. Monte Carlo methods have gained interests in a variety of domains. Medical research is an area where simulation can be a valuable tool for understanding a variety of scenarios, performing sensitivity analysis, and training future physicians. Many medical schools have simulation laboratories where residents and medical students are trained using dummy patients. Like flight simulators, many of these simulation experiences can be transitioned into a computer environment, providing new uses for computer simulation in medical training. Indeed, identifying ways to exploit simulation modeling into medical simulation centers is a rich area of potential value in enhancing the delivery of healthcare services, by providing a broader swath of environments in which medical residents and students can be trained.

The future of simulation in healthcare remains bright. As the breadth of problems grows, so will the modeling and methodologies available to address them. Our younger interviewees all commented on the enormous potential of "big data", for example the automated collection of routine patient flow data through the use of new technology like RFID, and through linked datasets. The only limitations are the imagination of the simulation researchers and healthcare practitioners in setting a vision for what they can achieve.

REFERENCES

Bailey, N.T.J. 1952. "Operational Research in Medicine". *Operational Research Quarterly* 3:24-29.

Brailsford, S.C. 2007. "Advanced Tutorial: Advances and Challenges in Healthcare Simulation Modeling". In *Proceedings of the 2007 Winter Simulation Conference*, edited by S. G. Henderson, B. Biller, M.-H. Hsieh, J. Shortle, J. D. Tew, and R. R. Barton, 1436-1448. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S.C. 2008. "System Dynamics: What's in it for Healthcare Simulation Modelers?" In *Proceedings of the 2008 Winter Simulation Conference*, edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, and J. W. Fowler. 1478-1483. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S.C., P.R. Harper, B. Patel, and M. Pitt. 2009. "An Analysis of the Academic Literature on Simulation and Modelling in Health Care". *Journal of Simulation* 3:130-140.

Brailsford, S.C. 2015. "Hybrid simulation in healthcare: new concepts and new tools". In: *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 1645-1653. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Crookes, J.G., D.W. Balmer, S.T. Chew and R.J. Paul. 1986. "A Three-Phase Simulation System Written in Pascal". *Journal of the Operational Research Society* 37:603-618.

Davies, R. 1978. "A Study of a Renal Unit". *Journal of the Operational Research Society* 30:873-884.

Davies, R. and H.T.O. Davies. 1994. “Modelling Patient Flows and Resource Provision in Health Systems”. *Omega* 22:123–131.

Dumkrieger, G., T.R. Huschka, and J.R. Stubbs. 2014. “Modeling the Effect of Shorter Shelf Life of Red Blood Cells on Blood Supplies.” In: *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1293-1304. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Farrow, S.C., D.J.H. Fisher, and D.B. Johnson. 1971. “A Statistical Approach to Planning an Integrated Haemodialysis/Transplantation Program. *British Medical Journal* 2:671-676.

Fetter, R.B. and J.D. Thompson. 1965. “The Simulation of Hospital Systems”. *Operations Research* 13:689-711.

Fone, D., S. Hollinghurst, M. Temple, A. Round, N. Lester, A. Weightman, K. Roberts, E. Coyle, G. Bevan, and S. Palmer. 2003. “Systematic Review of the Use and Value of Computer Simulation Modelling in Population Health and Healthcare Delivery”. *Journal of Public Health Medicine* 25:325–335.

Fries, B.E. 1976. “A Bibliography of Operations Research in Health-Care Systems. *Operations Research* 24:801-814.

Hollocks, B. W. 2008. "Intelligence, Innovation and Integrity – KD Tocher and the Dawn of Simulation". *Journal of Simulation* 2: 128-137.

Hundert, M. and J. Feldman. 1977. "Determining Nursing Policies by the Use of the Nursing Home Simulation Model". *Journal of Nursing Administration* 7:35-41.

Huschka, T.R., B.T. Denton, B.J. Narr, and A.C. Thompson. 2008. “Using Simulation in the Implementation of an Outpatient Procedure Center”. In *Proceedings of the 2008 Winter Simulation Conference*, edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, and J. W. Fowler, 1547-1552. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Huschka, T.R., T.R. Rohleder, and B.T. Denton. 2012. "Using Simulation to Design and Improve an Outpatient Procedure Center." Management Engineering for Effective Healthcare Delivery: Principles and Applications. IGI Global, pp 216-228.

Jacobson, S.H. and E.C. Sewell. 2002. “Using Monte Carlo Simulation to Determine Combination Vaccine Price Distributions for Childhood Diseases”. *Health Care Management Science* 5:135-145.

Jun, J.B., S.H. Jacobson, and J.R. Swisher, J.R. 1999. “Application of Discrete-Event Simulation in Health Care Clinics: A Survey”. *Journal of the Operational Research Society* 50:109–123.

Kennedy, F.D., J.C. Wright, M.J. Anderson, and P.C. Cooley. 1970. “Simulation in Mental Health Planning”. In *Proceedings of the 1970 Winter Simulation Conference,* 52-28. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Kernighan, B.W. and P.J. Plauger. 1976. *Software Tools*. Addison-Wesley: New York.

Lane, D.C., C. Monefeldt, and J.V. Rosenhead. 2000. “Looking in the Wrong Place for Healthcare Improvements: A System Dynamics Study of an Accident and Emergency Department”. *Journal of the Operational Research Society* 51:518-531.

Pendharkar, S.R., D.P. Bischak, and P. Rogers. 2012. “Evaluating Healthcare Systems with Insufficient Capacity to Meet Demand.” In: *Proceedings of the 2012 Winter Simulation Conference,* edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher, 859-871. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Pendharkar, S.R., D.P. Bischak, P. Rogers, W. Flemons, and T.W. Noseworthy. 2015. “Using Patient Flow Simulation to Improve Access at a Multidisciplinary Sleep Centre.” *Journal of Sleep Research* 24:320-327.

People.com, 28 March 1983. http://people.com/archive/attorney-david-marks-charges-that-a-texas-nursing-home-was-a-house-of-horrors-vol-19-no-12/ , accessed 29.04.17

Standridge, C., C. Macal, A.B. Pritsker, H. Delcher, and R. Murray. 1977. “A Simulation Model of the Primary Health Care System in Indiana”. In *Proceedings of the 1977 Winter Simulation Conference*, 349-358. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Swisher, J.R., S.H. Jacobson, J. Jun, and O. Balci. 2001. "Modeling and Analyzing a Physician Clinic Environment Using Discrete-Event (Visual) Simulation." *Computers and Operations Research* 28:105-125.

Swisher, J.R. and S.H. Jacobson. 2002. "Evaluating the Design Of a Family Practice Healthcare Clinic Using Discrete-Event Simulation". *Health Care Management Science* 5:75-88.

Tiwari, V., D.C. Krupka, and W.S. Sandberg. 2014. "Calculating the True Cost of Robotic Hysterectomy." *Healthcare Financial Management* 68: 80-86.

Tiwari, V. and W.S. Sandberg. 2016. "Perioperative Bed Capacity Planning Guided by Theory of Constraints." In *Proceedings of the 2016 Winter Simulation Conference,* edited by T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 1894-1903. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers,Inc.

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

Welch, J.D. and N.T.J. Bailey. 1954. "Appointment Systems in Hospital Outpatients Departments". *The Lancet* 1:1105-1108.

Wilson, J.C.T. 1981. "Implementation of Computer Simulation Projects in Health Care". *Journal of the Operational Research Society* 32: 825–832.

AUTHOR BIOGRAPHIES

SALLY BRAILSFORD is Professor of Management Science at the University of Southampton, UK. She received a BSc in Mathematics from the University of London, and MSc and PhD in Operational Research from the University of Southampton. Her research interests include simulation modeling methodologies, system dynamics, health service research and disease modeling, and the modeling of human behaviour in healthcare systems. She was awarded the title of Companion in Operational Research by the UK OR Society in 2016, and is the only person ever to have won the Society's Goodeve Medal three times: in 2004 for modeling emergency healthcare services in Nottingham, in 2006 for modeling chlamydia infection, and in 2015 for modeling the supply and demand for dental care in Sri Lanka. She is chair of the European Working Group on OR Applied to Health Services (ORAHS) and is Editor-in-Chief of the journal *Health Systems*. She is on the editorial boards of *Health Care Management Science*, the *Journal of Simulation*, and *Operations Research for Health Care*. Her email address is s.c.brailsford@soton.ac.uk.

MICHAEL CARTER is a Professor in the Department of Mechanical and Industrial Engineering at the University of Toronto, and former Director of the earlier Centre for Research in Healthcare Engineering. He received his doctorate in Mathematics from the University of Waterloo in 1980. Since 1989, his research focus has been in the area of health care resource modeling with a variety of projects in hospitals, home care, rehab, long term care, medical labs and mental health institutions. He has supervised more than 160 engineering students in over 100 projects with healthcare institutions. He currently has 18 students (7 doctoral, 5 masters and 6 undergrad) working in the area. He was the winner of the Annual Practice Prize from the Canadian Operational Research Society (CORS) four times (1988, 1992, 1996 and 2009). In 2000, he received the CORS Award of Merit for lifetime contributions to Canadian Operational Research. He is on the editorial board for the *Journal of Scheduling* and the journal *Health Care Management Science*. His email address is mike.carter@utoronto.ca.

SHELDON JACOBSON is Professor of Computer Science, and the Director of the Simulation and Optimization Laboratory and the Founding Director of the Bed Time Research Institute, at the University of Illinois at Urbana-Champaign. He holds a B.Sc. and M.Sc. in Mathematics from McGill University and a Ph.D. in Operations Research from Cornell University. He has served on the faculties at Case Western Reserve University (1988-1993), Virginia Tech (1993-1999), and the University of Illinois (1999-present).

He served as Program Director for the Operations Research program at the National Science Foundation from 2012-2014. He serves as the focused issue editor for *IISE Transactions, Operations Engineering and Analytics*. He is a Fellow of both IISE and INFORMS. His research activities in health care, which most recently center around public health, are greatly enhanced by his brilliant wife, Janet A. Jokela, MD, MPH, FACP, FIDSA. His email address is shj@illinois.edu.