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HYBRID SIMULATION IN HEALTHCARE: NEW CONCEPTS AND NEW TOOLS

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ABSTRACT

Until relatively recently, developing hybrid simulation models using more than one simulation paradigm was a challenging task which required a degree of ingenuity on behalf of the modeler. Generally speaking, such hybrid models either had to be coded from scratch in a programming language, or developed using two (or more) different off-the-shelf software tools which had to communicate with each other through a user-written interface. Nowadays a number of simulation tools are available which aim to make this task easier. This paper does not set out to be a formal review of such software, but it discusses the increasing popularity of hybrid simulation and the rapidly developing market in hybrid modeling tools, focusing specifically on applications in health and social care and using experience from the Care Life Cycle project and elsewhere.

1 INTRODUCTION

The concept of hybrid modeling is not new, and many researchers have proposed frameworks for combining different methods: not just simulation methods, but many other operations research (OR) modeling approaches. Some of these are described in the following paragraph. Discrete-event simulation (DES) is commonly combined with optimization and most modern DES software tools contain an optimization engine as an add-in, for example OptQuest for Arena or Simul8. The research philosophy literature distinguishes between methodologies, methods, approaches, paradigms, tools and techniques. This paper focuses more narrowly on models which combine two or more different simulation modeling paradigms: DES, system dynamics (SD) and agent-based modeling (ABM).

There is a substantial literature on multimethodology and mixed methods research which extends far beyond the disciplines of OR and management science. As far back as the 1980's, Jackson and Keys (1984) argue that since all OR methods have different strengths, weaknesses, benefits and limitations, mixing or combining methods offers the potential to overcome some of the drawbacks of using a single approach. Peter Bennett (1985) discusses three levels at which different OR methodologies could be applied. The lowest level, *Comparison*, involved using two methods entirely separately, for the purpose of solving different aspects of a problem which either method used on its own could not tackle. The next level, *Enrichment*, aims to enhance one method (the main method) by using elements of the other. The highest level, *Integration*, treats the methods on an equal footing and uses elements of each to generate something totally new. In the specific context of DES and SD in healthcare, Chahal and Eldabi (2008) propose another three-layer framework of "formats". The *Hierarchical* format consists of two separate models, one strategic (usually SD) and one operational (usually DES), run sequentially, so that the outputs of one model become the inputs of the other. Typically the DES model is used to explore the practical implementation of strategies emerging from the SD model. The *Process - Environment* format also consists of two models, a DES embedded inside an SD model, but run (partly) in parallel, so that data are exchanged between models at runtime in a cyclic manner. Here the two models inform each other in a more dynamic and interactive manner. Finally, in the *Integrated* format, the "Holy Grail" described by Brailsford, Desai and Viana (2010) (and also Bennett's highest level), there is one single unified model with no distinction or demarcation between the DES part and the SD part. Brailsford, Desai and Viana argue that the "holy grail" of genuinely combining the philosophy of both approaches has not yet been attained in OR/MS, and say "*Despite a long history of modeling tools in other disciplines such as engineering or computer science, which combine continuous and discrete parameters, there is as yet no genuinely integrated simulation methodology which reflects the differing world-views of DES and SD modelers*."

In a survey paper on mixed methods as used by practitioners, Munro and Mingers (2002) observed that OR methods were often combined because different methods were required to tackle different aspects of the problem at hand, and that in practice, methods were often mixed in an ad-hoc or emergent manner. This finding has been echoed by many researchers who have argued the need for combining DES and SD in the context of healthcare systems, which are characterized by complexity, inter-connectedness and variability. For example, Brailsford, Churilov, and Liew (2003) argue that "ailing emergency departments" suffer from a variety of different problems which require therapeutic treatment with a combination of DES and SD. Many of the hybrid models in the healthcare modeling literature fall into Chahal and Eldabi's *Profess-Environment* category, recognizing that while a "whole systems" approach is essential for capturing the feedback dynamics in large, complex systems, the key role played by individual patient variability and unpredictability cannot be overlooked.

This paper presents some insights into the development of hybrid models in healthcare, based on many years' experience with trying to implement such models in a variety of software environments. Section 2 sets the context for the discussion, and Section 3 describes the author's experience with developing insights into hybrid modeling. Section 4 contains a couple of example models and the paper concludes with a reflective discussion in Section 5. In particular, we consider whether the quotation above from the "Holy Grail" paper still remains true. Again, I emphasize that this paper does not set out to be a systematic software review but represents the personal, and undoubtedly idiosyncratic, views of the author.

2 BACKGROUND AND CONTEXT

In the UK, almost all health care is funded by taxation and provided free at the point of delivery by the National Health Service (NHS). At a local level, in England health care services – surgical operations, medicines, treatments etc - are purchased from NHS hospitals and primary care providers on behalf of their local population by a group of clinicians (a Clinical Commissioning Group, CCG). Each CCG has the challenging task of deciding how best to use their allocated budget. In contrast, social care (ranging from help with "activities of daily living" such as shopping, cooking, using the bathroom and so on, through to residential care) is mostly paid for by the individual themselves. Only the very poorest people with critical social care needs receive financial support from the state, and this is means-tested. The majority of people either purchase care directly from private providers, or receive "informal" care, i.e. from family, neighbors, or the charitable sector. State-funded care is not provided nationally but at local level by the Local Authority (county council) where the person resides. Health and social care are therefore paid for by different organizations from different budgets, and this can lead to complex relationships between the health and social care systems, especially in the elderly who are the greatest consumers of both.

The Care Life Cycle project (CLC 2015) was a five year multidisciplinary research program at the University of Southampton, funded by the UK Engineering and Physical Sciences Research Council (EPSRC). The project, which ran from 2010-15, was one of four major EPSRC-funded projects whose overarching aim was to apply "complexity science" methods to real-world problems. The Care Life Cycle (CLC) focused on issues of supply and demand for health and social care in a changing and ageing society. It was led by a demographer, Jane Falkingham, and used both complexity science and traditional simulation modeling methods.

Three of the CLC models were presented at the 2012 Winter Simulation Conference (Noble et al. 2012; Brailsford et al. 2012; Viana et al. 2012). The third of these was a hybrid simulation model, developed in the software AnyLogic, for the eye disease age-related macular degeneration (AMD). The model combines discrete-event and agent-based simulation, and also, embedded in each agent, a pair of individual compartmental models (one for each eye) for disease progression. The overall aim of the hybrid model was to use the specific example of AMD to explore the wider links between the health and social care systems in the UK.

3 HYBRID SIMULATION SOFTWARE: FROM BLISSFUL IGNORANCE TO CONSCIOUS AWARENESS

My first experience with any kind of simulation was in the late 1980's, when I developed a small DES model for HIV infection as part of my Masters degree. The model was coded from scratch in Pascal, a popular programming language at the time. Although it was a standard three-phase DES (Tocher 1963) it did include some SD-like feedback aspects whereby infected people transmitted the infection to susceptible people: the probability of infection depended on the numbers of susceptible and infected people and also on the disease stage of the infected person. This was a classical SI model of infectious disease, and as such (I have since learned) would commonly be modeled using SD. This model then became the basis for my PhD model, which again was coded in Pascal (Borland Turbo, which I believe is now obsolete). I thus developed a taste for coding my own models, enjoying total control over the model logic and the freedom and flexibility this entailed. I was even able to include "SD-like" features without even realizing I was doing it! In fact it was not until the mid to late 1990's that I became aware of system dynamics as a modeling approach. SD was not taught on many UK OR Masters degrees and was not widely regarded as one of the mainstream OR techniques in the 1980's.

At the time I was doing my Masters, very few UK universities used commercial off-the-shelf (COTS) DES software for teaching. The COTS software at the time was very expensive and most universities expected students either to be able to write code or to use bespoke teaching software with limited functionality. In my view, it was only when Simul8 appeared during the 1990's that students were widely exposed to software tools that they might use in their later careers. Nevertheless, the early versions of Simul8 were too restrictive to use for research, at least for people like myself who were accustomed to the flexibility of "code it yourself" (CIY). I continued to write my own code in Turbo Pascal, using a simulation approach developed by Ruth Davies called POST (Patient Oriented Simulation Technique: Davies and Davies 1994), in which entities could be in several places at once. The POST approach enabled me to develop models with "ABM-like" features, for example linking entities in models for mother-to-child transmission of HIV in sub-Saharan Africa (Rauner et al. 2005). Again, this model was developed before I knew anything about ABM.

Looking back, it feels that while I was still coding models myself I was living in a state of naive and blissful ignorance. When I included infection dynamics in my MSc model, or linked entities in the African HIV model, it did not even occur to me that I was developing hybrid models. The behavioral models I developed with Bernd Schmidt (Brailsford and Schmidt 2003) included agent-like aspects to capture patient behavior: yet at the time, I had not heard of ABM and did not worry about what modeling paradigm I was using or why it might be difficult. The freedom of CIY meant that if some aspect of a problem situation required a particular logical rule or behavior, then you just encoded that rule or behavior. In my "DES is Alive and Kicking" paper for the Journal of Simulation (Brailsford 2014) I argue, with illustrative examples, that many characteristics of agent-based models can just as easily be captured in DES and that many of us had been doing ABM all through the 1990's without even realizing it.

This halcyon period came to an end when COTS packages became the norm. Of course, there are massive benefits in being able to use a COTS tool, in terms of speed of model development, use of graphics and reporting tools, not to mention all the "housekeeping" aspects such as distribution fitting, sampling, random number generation and output analysis. I am certainly not arguing for a return to CIY, especially for teaching students. However any package will require the user to think, and conceptualize a model, in a particular way. For example, most DES software tools contain some facility to model continuous, as well as discrete event phenomena, and can therefore be adapted (although not always easily) to depict the underlying structures of SD models. Similarly, most SD software tools contain the facility to model queuing processes or stochastic variables. Nevertheless, these packages are essentially either a DES environment with some continuous features, or an SD environment with some discrete or stochastic features. The challenge of modeling queues or activities in an SD tool, or including feedback dynamics in a DES tool, makes me long for the days when I could just write my own code.

The software AnyLogic (www.xjtek.com/AnyLogic) still remains the only package which can genuinely represent DES, ABM and SD models on an equal basis. It allows users to build hybrid models which flow seamlessly from one paradigm to the other, without worrying about model boundaries, hierarchies or frameworks, but just depicts the problem features in the most appropriate paradigm for that feature and then joins them up in an intuitive way. It offers nearly all the main features available in paradigm-specific software tools such as Vensim, Powersim and iThink/Stella (SD tools) and Arena, Witness, Simul8 and ProModel (DES tools). However, this flexibility comes at a price. Even in the latest release, the user needs to be reasonably familiar with Java code, and there is a "jack-of-all-trades" effect: an expert user of any of the above paradigm-specific tools may at times yearn to use their preferred software.

AnyLogic has its origins in computer science and fundamentally, has an ABM "worldview". Another interesting new development, but starting from an SD worldview, is Ventity, an object-oriented tool which at the time of writing is still awaiting release (Yeager et al. 2014). Ventity has its roots in Vensim, but appears to be closely aligned with ABM. Ventity claims to support:

- *Entity type definitions, providing objects or modules*
- *Attributes used to identify and categorize individual entities*
- *Collections of entities automatically generated and tracked by attribute*
- *Aggregation and allocation functions that make one-to-many or many-to-many mappings among collections and individual entities*
- *References, or special attributes used to connect entities of the same or different types*
- *Actions, providing for discrete events like the dynamic creation and deletion of entities*

(Yeager et al. 2014).

From a healthcare modeling perspective, it is both a strength and a weakness of using SD that "material" flows, i.e. patient flows, have to be aggregated. It is a strength because frequently data are simply not available at a highly aggregated level and this tends to force the modeler to keep models simple – almost always a good thing. However, there are times when it is necessary to disaggregate: to quote Einstein, a model should be as simple as possible, but no simpler. For example, there may be times when it is essential to distinguish between genders, or by age group, or by smoking status, and so on. One of the difficulties with using SD for systems where stocks need to be arrayed many times is that not only are such models difficult to represent on-screen, but the internal logic is very difficult to manage. Every time an extra dimension is added to an array, the number of states increases multiplicatively (the *curse of dimensionlity)* and therefore Ventity offers a way to avoid the need for very large, sparse matrices.

4 EXAMPLE MODELS

4.1 The chlamydia model

Viana et al. (2014) describe a hybrid DES-SD model for the sexually transmitted infection (STI) chlamydia. This has several aspects in common with the Care Life Cycle AMD model presented in Viana et al. (2012), although it does not reflect social care. Chlamydia is very common in young people aged 18-25 and is largely asymptomatic. If detected, it is easily treated by antibiotics, but treated people can be infected again and if they have a sufficient number of repeated infections they are at risk of developing serious and even life-threatening complications, known as sequelae. The model was developed in collaboration with St Mary's Hospital in Portsmouth. The National Chlamydia Screening Programme (NSCP) was established in 2003 to screen young people at greatest risk. The estimated annual cost of chlamydia and its sequelae in the UK in 2003 was estimated to be more than £100 million (NCSP 2015). The NSCP had generated greatly increased demand for the hospital STI clinic, which was struggling to cope and wanted to use its resources more effectively.

A DES model of the hospital STI outpatient clinic was embedded within an SD model of the infection process within the wider community. This model uses two separate specialist packages, the DES tool Simul8 and the SD tool Vensim, which communicate via an Excel interface. Both Simul8 and Vensim can write to and read from Excel. People cannot book appointments for the STI clinic, but just show up, are tested, and if necessary treated with a simple course of antibiotics. If the clinic is crowded, the queues get long and people are unwilling to wait. Therefore they do not get tested (or treated). This then increases the proportion of infected people in the community, leading to an increase in new infections and further increases the demand for the clinic. The SD part of the model captures this feedback effect.

The combined model runs in monthly time steps, as follows. The SD model first runs for one month and generates the demand for that month, in terms of the number of people in the population who are identified as having chlamydia through screening, contact tracing, self-presentation and reporting to the STI clinic for treatment. This monthly demand is then exported from Vensim into Excel, which disaggregates the demand into inter-arrival rates based on historical data analysis, which can vary over time, to be used as arrival distributions in Simul8. The DES clinic model then runs for 20 iterations and the average number of people treated is exported from Simul8 through Excel to the SD model. The SD model advances a time step and the whole process starts again. For a more detailed explanation of the model including model validation, data requirements, results and reflections see Viana et al. (2014).

In his 2014 Wintersim paper, Viana describes the challenges of developing this model and compares it with the Care Life Cycle AMD model, which was developed in Anylogic. The chlamydia model is what Chahal and Eldabi would term a *process-environment* model, i.e. two separate models (a DES embedded within an SD model) that run in parallel and communicate. The DES represents part of the whole system, the part where individual variability is important and queueing occurs at bottlenecks. Viana was an experienced modeler in both software tools and was able to develop the two individual models very rapidly. As always in this kind of modeling exercise, data collection at the hospital was the most time-consuming aspect, since most of the necessary data for the SD model (chlamydia transmission rates) were available from the literature. The most technically challenging aspect of the modeling was developing the Excel interface and trying to optimize run speed, since reading from and writing to considerably Excel slowed up the model execution.

4.2 The Care Life Cycle AMD model

The general model structure is described in Viana et al. (2012). Essentially, it combines an agent-based model representing individuals with AMD with a DES model of the outpatient clinic. The patient agents contain two simple embedded state transition models which represents the progression of AMD in each eye. This is affected by treatment, which slows down the disease process. Each patient has a social care need status, and this, in conjunction with the level of social care provision, affects their probability of clinic attendance. Social care provision is represented by a state chart which consists of three states: not required, partly met and fully met. The agents interact with the DES model when the scheduled time of their clinic appointment arrives. The patient may (or may not) attend the clinic, and may (or may not) receive treatment, depending on the congestion in the clinic and the overall performance of the clinic. In the terminology of Chahal and Eldabi (2008), this is a truly *integrated* hybrid model. The different components of the model are intertwined within the same software implementation and (in theory at least) there is seamless transition between the different sections and paradigms within the model.

Viana's experience, as reported in his 2014 Wintersim paper, is that there was a very steep learning curve with the previous version of Anylogic and his lack of Java programming skills was a serious drawback initially. The initial modeling was actually shared between two people, Viana (an OR modeler) and Rossiter (a computer scientist) which led to a number of technical challenges, highlighted in Brailsford et al. (2013b) which discussed the question whether hybrid modeling was actually more trouble than it was worth. However, in order to address the requirements of one of the key model stakeholders, the consultant ophthalmologist (Andrew Lotery) who originally approached the university team to develop a model that could help manage congestion in the clinic, we really only needed a more detailed version of the DES sub-model of the original hybrid. Since Viana found the new version of Anylogic (v7) much more intuitive, he actually opted to develop this new model in Anylogic.

This model is hugely complex and detailed, encompassing 15 AMD clinic sessions, 8 special injection sessions and 90 other sessions for all other eye conditions over the course of a week. These clinic sessions run in parallel over ten half-day sessions, share some staff, both nurses and imaging technicians, and compete for other resources (treatment rooms and equipment). Table 1 presents some highly aggregated results for a range of experiments, starting with the baseline actual data (collected in June 2013) and then scenarios in which patient demand and/or resources were also increased as follows:

- Increased Resources: over the week, nurses were increased from the baseline 164 to 202 and imaging staff were increased from 54 to 72 (the units are half-days worked); the available rooms and equipment for six different procedures including visual field checks, Fundus Fluorescein Angiography and Optical Coherence Tomography were each increased 3 to 4, and the available rooms and equipment dedicated for AMD injection treatments were increased from 6 to 8.
- Increased Demand: the clinic session times remained the same (4-hour morning and afternoon sessions) but procedure times were reduced by roughly 25%, so that the total number of appointment slots per week increased from 1871 in the baseline scenario to 2410 in the Increased Demand scenario. In particular, the number of available slots per week in AMD clinics increased from 228 to 285, the number of AMD injection slots increased from 165 to 209, and the number of non-AMD ("other clinic") slots increased from 1538 to 1992 per week.

Each scenario was run for 20 iterations: Table 1 presents the averages from these 20 runs.

Table 1: Results from a series of experiments with the AMD clinic model.

	Weekly Total Appointments Completed	**Weekly Total Appointments Missed**	**Weekly Total Appointments Left Early**	**Weekly Total Missed Injections**	**Weekly Total Overrun Time (minutes)**
Baseline: patient numbers and all resources as at June 2013					
AMD clinics	158.5	39.75	29.75	-	4,104
Injection clinics	124.45	29.75	10.8	39.4	1,996
Other clinics	1,183.15	265.05	29.8	-	13,570
As baseline but with increased resources					
AMD clinics	181.45	41.85	4.7	-	2,324
Injection clinics	126.45	29.35	9.2	38.3	1,681
Other clinics	1,201.6	262.6	13.8	-	6,998
Increased demand with baseline resources					
AMD clinics	131.15	52.35	101.5	-	4,855
Injection clinics	129.75	38.15	41.1	72.6	2,373
Other clinics	1,308.35	343.65	264	-	19,347
Increased demand and increased resources					
AMD clinics	180.1	51.55	53.35	-	4,061
Injection clinics	151.95	35.55	21.5	53.05	1,997
Other clinics	1,434.75	339	142.25	-	16,620

It can be seen that the clinic treats over 70,000 patients annually and that even in the increased resource scenario, nearly 40 patients a week miss their injections either because they do not attend for their appointment, or because the clinic is so congested they have to leave early without being treated. Although clinics are allowed to overrun, a patient waiting time tolerance is built into the model to reflect the reliance of some older patients on hospital transport to take them home. These behavioral parameters were derived from the data collected in June 2013. It is clear that even with extra resources, the hospital would still have to rely on clinic overtime in order to be able to meet demand. Moreover, referring back to the hybrid model, if the social care aspects were improved so that fewer patients failed to attend and were able to wait longer, clinic overrun time would increase still further.

5 REFLECTIONS

At the 2015 annual conference of the UK Chapter of the International System Dynamics Society, the software Ventity was demonstrated and there was much talk about agent-based modeling. It seems the various simulation modeling communities, which were totally separate 20 years ago, are finally converging. The number of SD papers at WSC continues to grow; Hybrid Modeling has been promoted from a mini-track in 2014 to a full track in 2015; the AnyLogic user community is increasing and one frequently comes across applications these days, several very nice examples of which can be found in this track.

An expert programmer will almost certainly find commercial software packages frustrating. They force the user to think in a particular way and often conceal and obfuscate things that an expert user would like to be able to modify. Conversely, a novice user will find even the most user-friendly tool challenging. In 2010 the UK's Network for Modelling & Simulation in Health (MASHnet) was commissioned to study the take-up in the UK NHS of a simulation and modelling tool called Scenario Generator. This is a Simul8 product designed specifically for strategic planning in healthcare, also designed to be as user-friendly as possible, and was offered free of charge to all healthcare organizations for one year. Among many interesting findings (Brailsford et al 2013a), we found that among those organizations that had tried to use Scenario Generator but had given up, there were two polar opposites of user. Firstly, of course, some people really struggled even with the basics, but at the other extreme, there were a few experienced Simul8 users who found Scenario Generator too restrictive. In its efforts to be user-friendly, it had hidden a lot of functionality "under the bonnet" which people with some knowledge of simulation found intensely frustrating. These findings were replicated to some extent in the Care Life Cycle project team's experience with using AnyLogic.

Returning finally to the hypothesis that "*there is as yet no genuinely integrated simulation methodology which reflects the differing world-views of DES and SD modelers*", I admit I have shifted my stance on this over the past five years. I still think it remains true that people of a certain age who have grown up calling themselves "system dynamicists" do see the world in a different way to people (also of a certain age) who have grown up thinking that "simulation" is synonymous with DES. However, in my view such people are a dying breed. Increasingly, a generation of OR/MS students are learning both approaches (and also, to some extent, ABM) and are recognizing that both these paradigms are just part of the management scientist's toolbox. We are still some way from the Holy Grail, but the increasing popularity of AnyLogic, the launching of Ventity, and the developments in many other COTS software tools which have recognized the demand for multi-paradigm modeling, are all evidence that slowly, things are changing and some sort of convergence is taking place.

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REFERENCES

AnyLogic, http://www.xjtek.com/AnyLogic, Accessed April 04, 2015.

Bennett, P. G. 1985. "On Linking Approaches to Decision Aiding: Issues and Prospects". *Journal of the Operational Research Society,* 36 (7). 659-669.

Brailsford, S. C., L. Churilov, and S. Liew. 2003. "Treating Ailing Emergency Departments With Simulation: An Integrated Perspective. In: *Proceedings of Western Multiconference on Health Sciences Simulation. Florida,* edited by J. Anderson, Society for Modelling & Simulation International (SCS), San Diego, CA.

Brailsford, S. C., and B. Schmidt. 2003. "Towards Incorporating Human Behaviour In Models Of Healthcare Systems: An Approach Using Discrete Event Simulation". *European Journal of Operational Research* 150(1): 19–31.

Brailsford, S. C., M. S., Desai, and J. Viana. 2010. "Towards The Holy Grail: Combining System Dynamics And Discrete-Event Simulation In Healthcare". In *Proceedings of the 2010 Winter Simulation Conference,* edited by B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, 2293-2303. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S. C., M. Evandrou, R. Luff, R. Shaw, J. Viana, A. Vlachantoni, and R. M. Willis. 2012. "Using System Dynamics to Model the Social Care System: Simulation Modeling as the Catalyst in Linking Demography to Care Delivery". In *Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany,* edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A. M. Uhrmacher, 1058-1069. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Brailsford, S. C., T. Bolt, G. Bucci, T. M. Chaussalet, N. A. Connell, P. R. Harper, J. H. Klein, M. Pitt and M. Taylor, 2013a. "Overcoming the Barriers: A Qualitative Study of Simulation Adoption in Primary Care Trusts in the NHS". *Journal of the Operational Research Society,* 64, 157-168.

Brailsford, S. C., J. Viana, S. P. Rossiter, and A. R. Channon. 2013b. "Hybrid Simulation for Health and Social Care: The Way Forward, or More Trouble Than it's Worth?" In *Proceedings of the 2013 Winter Simulation Conference, Washington, DC,* edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 258-269. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc

Brailsford, S. C. 2014. Discrete-Event Simulation Is Alive And Kicking! *Journal of Simulation* 8(1): 1–8.

Care Life Cycle. 2015. "The Care Life Cycle [Project]." Accessed 29 March, 2015, from http://www.southampton.ac.uk/clc.

Chahal, K., and T. Eldabi. 2008. "Applicability of Hybrid Simulation to Different Modes of Governance in UK Healthcare". In *Proceedings of the 2008 Winter Simulation Conference, Miami, Florida,* edited by S. J. Mason, R. R. Hill, L. Mönch, O. Rose, T. Jefferson, and J. W. Fowler, 1469-1477. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc

Davies, R., and H. T. O. Davies. 1994. "Modelling Patient Flows and Resource Provision in Health Systems". *Omega* 22(2): 123–131.

Jackson, M. C., and P. Keys. 1984 "Towards a System of Systems Methodologies". *Journal of the Operational Research Society,* 35 (6). 473-486.

Munro, I., and J. Mingers. 2002. "The Use of Multimethodology in Practice—Results of a Survey of Practitioners". *Journal of the Operational Research Society,* 53(4): 369-378.

National Chlamydia Screening Programme (NCSP). 2015. NCSP website. Accessed April 04, 2015 from www.Chlamydiascreening.nhs.uk/ps/Chlamydia.asp.

Noble, J., E. Silverman, J. Bijak, S. Rossiter, M. Evandrou, S. Bullock, A. Vlachantoni, and J. Falkingham. 2012. "Linked Lives: The Utility of an Agent-Based Approach to Modelling Partnership and Household Formation in the Context of Social Care". *Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose and A. M. Uhrmacher, 1046-1057. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc

Rauner, M. S., S. C. Brailsford, and S. Flessa. 2005. "The Use of Discrete-Event Simulation to Evaluate Strategies for the Prevention of Mother-To-Child Transmission of HIV in Developing Countries". *Journal of the Operational Research Society* 56(2): 222–233.

Simul8 website, http://www.simul8.com, Accessed April 04, 2015.

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

Vensim website, vensim.com. Accessed April 04, 2015.

Ventity, http://vensim.com/vensims-new-partner-ventity/, Accessed April 04, 2015

Viana, J., S. Rossiter, A. R. Channon, S. C. Brailsford, and A. J. Lotery. 2012. "A Multi-Paradigm, Whole System View of Health and Social Care for Age-Related Macular Degeneration". *Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A. M. Uhrmacher, 1070-1081. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc

Viana, J., S. C. Brailsford, V. Harindra, and P. R. Harper. 2014. "Combining Discrete-Event Simulation and System Dynamics in a Healthcare Setting: A Composite Model for Chlamydia Infection." *European Journal of Operational Research,* 237, 196-206.

Viana, J. 2014. "Reflections on Two Approaches to Hybrid Simulation in Healthcare". *Proceedings of the 2014 Winter Simulation Conference, Savannah, GA*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1585-1596. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Yeager, L., T. Fiddaman, and D. Peterson. 2014. Entity-Based System Dynamics. Available from http://vensim.com/wp-content/uploads/2014/08/Entity-Based-System-Dynamics-v2.pdf, Accessed April 04, 2015.

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