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Discrete event simulation for performance modelling in health care: a review of the literature

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Discrete Event Simulation (DES) has been widely used in modelling health-care systems for many years and a simple citation analysis shows that the number of papers published has increased markedly since 2004. Over the last 30 years several significant reviews of DES papers have been published and we build on these to focus on the most recent era, with an interest in performance modelling within hospitals. As there are few papers that propose or illustrate general approaches, we classify papers according to the areas of application evident in the literature, discussing the apparent lack of genericity. There is considerable diversity in the objectives of reported studies and in the consequent level of detail: We discuss why specificity dominates and why more generic approaches are rare.

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1. Introduction

Discrete Event Simulation (DES) is one of many different tools and methods used in the analysis and improvement of health-care systems. There are many applications of non-simulation techniques, such as heuristic optimization, but their review is outside the scope of this paper. Likewise, there are simulations other than discrete event approaches, such as system dynamics (SD) and agent-based modelling. Occasional references to these other approaches are made in this paper, but the main focus is DES modelling of patient flows through hospital facilities.

This review stems from the DGHPSim project (www.hospitalsimulation.info), in which a generic DES model of whole hospital performance was developed, and also as part of the first author's PhD research. The last 10 years have seen the publication of two extensive reviews: Jun *et al* (1999) and Fone *et al* (2003) but since then the literature has expanded. To illustrate this, Figure 1 shows the result of a simple reference count to evaluate the scale of this expansion. The search uses Publish or Perish (2009), with the search term 'Discrete Event Simulation' accompanied by the 'Patient', 'Healthcare', and 'Hospital'. Though this could hardly be described as a comprehensive analysis, it does show that the number of papers, which mentioned DES and health care, has increased considerably in recent years.

Health care is an enormous field and there are many different ways of analysing it. Here, we take a simple division between primary, secondary, and tertiary care. In the UK, primary care is provided by general practitioners and their associated staff. Secondary care, again in the UK, is provided by hospitals that usually include outpatient, inpatient and day-care facilities; some also provide emergency care. Finally, tertiary care is usually provided in highly specialized units for conditions such as cancer and cardiac surgery. The boundaries between these domains have become blurred in recent years and this trend seems set to continue. Here, our focus is on patient flow in secondary care provided by hospitals, with demand for those resources treated as exogenous.

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2. Existing surveys of simulation in health care

As health-care simulation is an active area of research and practice, it is not surprising that literature reviews exist. Such reviews first appeared about 30 years ago and there is no sign that the flow will cease. Hence, this review stands on the shoulders of others, adding extra comment and analysis as appropriate. It is probably true, also, that others will be writing reviews now, in addition to the one provided here.

Early reviews include England and Roberts (1978), which examines reports of 92 simulation models, and gives some idea of the long history of simulation. This paper also reviews the other modelling approaches in health care and of the efforts to implement simulation models, despite limited computing power. However, it seems that in the 1960s and 1970s, few studies reported any successful use of models. The authors argue that barriers to implementation include a lack of economic incentives, no vested authority, non-quantifiable data, dehumanizing formulations, and no commitment to follow up. Perhaps the only difference today is that we have very large electronic data sets available.

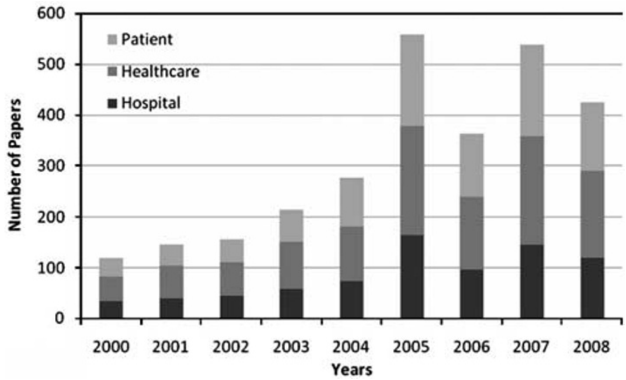

Figure 1 Number of papers in health-care simulation.

Ten years later, Smith-Daniels *et al* (1988) takes a broader look at Operational Research (OR) applications in health care, including simulation. It argues that, prior to the 1980s, research efforts often failed during the implementation phase because it became impossible to balance the conflicting objectives of physicians, nurses, hospital administrators, boards of directors, and other health-care professionals. However, the authors argue that the growth and establishment of large health-care organizations in the US, such as Health Maintenance Organizations, means that the decisions regarding capacity and resources are better defined due to the clearer objectives of these large organizations. Although this is a step towards successful implementation of models, it is clearly not enough on its own.

Lehaney and Hlupic (1995) come closer to the current era of simple-to-use simulation software tools, though it covers the era immediately prior to their introduction. Computing power was limited in that era, but the review points out the prospective potential of simulation in health care by examining existing literature. Although it is not a review specific to simulation, Flagle (2002) reviews some origins of OR in health care, including simulation.

Two recent reviews are more comprehensive and systematic than their predecessors: Fone *et al* (2003) and Jun *et al* (1999), which, despite their different publication dates, cover more or less the same time period, though they take very different approaches. In addition, although not focused on DES, Brennan *et al* (2006), suggests a taxonomy of model structures for economic evaluation of health technologies and, in so doing, identifies the role of DES in health economics.

Fone *et al* (2003) is a report of a systematic review of the literature on health-care simulation between 1980 and 1999 and follows a route familiar to readers of systematic reviews in health care. This review aimed to assess the quality of published studies and to consider their influence on policy, rather than on operations. Publications are divided into five categories: hospital scheduling and organization, infection and communicable disease, costs of illness and economic evaluation, screening, and finally, miscellaneous. The analysis of the papers included reveals that most of the modelling effort had been at a micro level. That is, there was extensive OR work in detailed modelling of specific aspects of the hospital, such as emergency departments, operating theatres, outpatient departments, inpatient wards, and intensive care units. Fone *et al* (2003) also reports that the quality of the papers seems to have improved over the survey period. However, such a judgement must be tentative, as very few papers provide enough detail of model implementation, which is important given the views of Proudlove *et al* (2007).

However, it is clear from Fone *et al* (2003) that attempts to model whole hospitals are rare, an issue to which we shall return later. Why should this be? One possible reason (Günal, 2008) is the difficulty of representing the complexity of hospital activity within a simulation model that must, like all models, be a simplification. Appropriate simplification can be a surprisingly complex process and it may be easier to carve off one part of hospital activity, for example an Accident & Emergency (A&E) department or outpatient clinic, rather than attempting a model with much broader scope.

Jun *et al* (1999) surveys approximately a 30 years period, including most of the 20 years covered in Fone *et al* (2003), and classifies models according to the objectives of the studies of which they are part. The review is in three parts:

1. Scheduling and patient flow,
2. Sizing and planning of beds, rooms, and staff,
3. A discussion on future-research areas.

The main focus of the review is advances in simulation software, including optimization linked to simulation. As with Fone *et al* (2003), the survey reveals that most of the models reported are of discrete parts of hospitals, such as emergency rooms, clinics, and operating theatres. Jun *et al* (1999) specifically searched for simulations of complex, integrated and multi-facility systems but concluded that there seems to be a lack of such models in the literature. Jun *et al* (1999) suggests that the major reasons for this gap are first, the level of complexity in these models and consequently the data needs and, secondly, the resource requirements including the time and money needed to conduct such research. They suggest that the key to success is to decide on the appropriate level of detail. Increased detail leads to more realistic representation, which should increase the confidence of stakeholders—a view that assumes how a model will be used. However, increased detail requires extensive, validated data and this may be expensive and time consuming to collect, if indeed it can be collected at all.

Building on these earlier reviews, the next section analyses the literature, mainly the more recent, according to the application area on which the paper is focused.

3. Literature on specific health-care applications

3.1. A&Es

A&E units seem the most popular area for simulation modelling in health care, which may not be surprising, as they are relatively self-contained and have easily observable processes that cover relatively short time periods of a few hours. It may also be true that improvements in performance are easier to demonstrate and link to specific actions, which may not be true elsewhere in health care. Hence, reports of A&E simulations easily outnumber models of other hospital units. Almost every year the Winter Simulation Conference proceedings include one or more papers on A&E simulations. Examples include: Ferrin *et al* (2007), Ruohonen *et al* (2006), Sinreich and Marmor (2004), Miller *et al* (2004), Wiinamaki and Dronzek (2003), and Alvarez and Centeno (1999).

Ferrin *et al* (2007) demonstrates a DES model (EDSim) that is used to develop processes for increasing throughput in an emergency department (ED) in the USA as part of a system that permitted the diversion of ambulances in peak demand periods, which had financial implications for the client ED. Their investigations included the introduction of discharge lounges, shortening the length of stay (LoS), and bypassing triage. EDSim is intended as reusable software for use by their company that specializes in the analysis and improvement of A&Es. Miller *et al* (2004) and Miller *et al* (2003) are earlier papers that present other versions of what is effectively the same model. Various authors address the differences between EDs and conclude that working with a new ED does not require 'reinventing the wheel'. They suggest that a generic A&E model, like their own EDSim, can be used to help EDs to solve many common problems.

Miller *et al* (2006) also discusses the use of EDSim, but with a special focus on data collection using Radio Frequency Identification (RFID) tags. These tags are electronic devices, which can be attached to entities such as patients and doctors to periodically report their locations to a server computer, thus enabling automated data collection. Interestingly, they report that using RFID tags in this way, though seemingly attractive, offers no significant cost:benefits over data collected using expert opinion. Difficulties faced by the project team included patients removing tags and the cost of lost tags.

Also aiming at reusability, Sinreich and Marmor (2004) reports a 'generic process ED model' built using Arena simulation software. In their discussion, they analyse ED models based on their level of abstraction, leading to a spectrum from fixed to generic. Perhaps not surprisingly, they conclude that their own model is better suited to the other task than other, more detailed models. Their work investigated similarities in processes across five EDs and suggests a metric that is labelled as the 'similarity measure'. They conclude that a simple, intuitive, and easy-to-use model is best suited to meet users' needs. Within this, they suggest that the processes characterized by the type of patients or specialty allow models to be used relatively generically, which suggests great similarity across the EDs studied.

Fletcher *et al* (2007), reports the use of a generic A&E model in the UK. This model was originally developed to inform national policy but also found use locally in individual A&Es for improving performance. The term generic implies a reusable DES model, in this case one that is delivered to A&Es in 10 National Health Service (NHS) Trusts in the UK. The Trusts varied in their degree of adoption of the model and only three trusts actually claim to have implemented improvement strategies suggested by the modelling team. The model is a very good example of a 'transferrable, reused, generic model'. One important conclusion of this study is that a model is more successful if it has limited dependency on special data collection. It seems that presenting the user with sensible default values eases users in developing their understanding and appreciation of the model.

Using SD rather than DES, Lane *et al* (2003) presents insights from a case study of an A&E in London. Though this work reports a SD model, it deserves a mention in this review. This is mainly because the life cycle of the project resembles a typical A&E DES project's phases, such as understanding client's needs, analysing the system, and model building. The paper gives a short diary of the project, how the meetings were organized, what was discussed, and problems faced with the client. Even though the client objected to the project members' use of average rates for admission and service times, she is eventually convinced. In an earlier paper, Lane *et al* (2000) demonstrates the use of SD in modelling A&Es to show that reduction in dedicated emergency bed capacities for patients admitted from A&E does not increase waiting times but may instead increase cancellation rates for elective treatments. Their holistic approach demonstrated that looking at one performance measure in the system can be misleading. For example, in the case of A&E, pushing the hospital to the limit of reducing A&E waiting time may cause more elective cancellations: an important insight for policymakers.

There are many other examples of A&E models that are built for specific hospitals and in great detail such as Duguay and Chetouane (2007) and Takakuwa and Shiozaki (2004). In these two studies, physical layouts of the emergency departments, very detailed care processes, staff shifts, diagnosis and expertise-based service times, bed ready times, and test results transfer times are all included in the models. Though these models incorporate much detail, the use of these models is very limited for example, solving waiting time issues in a specific treatment room or a specific type of patient.

3.2. Inpatient facilities

Modelling inpatient care has been also an active research area for many years. DES is used for many purposes in this field, though mainly for testing mathematical models developed. Patient flows to hospital beds, bed occupancy, and LoS are common foci. For example, Millard (1994) uses compartmental modelling approaches to model bed occupancy. The methodology does not include the explicit use of DES, however in some papers Millard and others use DES to demonstrate how their mathematical models might be used in real life.

Figure 2 is a summary of compartmental modelling, which is an analytic method based on discrete time that fragments patient stays into defined periods (compartments). These compartments can have clinical or logical meaning. For example for stroke patients, a three-compartment approach (short stay, medium stay, long stay) is used in Vasilakis and Marshall (2005) to estimate the number of patients in any state and their LoS. Another example is Harrison *et al* (2005), which presents a simulation model, which is a stochastic version of Millard–Harrison deterministic bed occupancy model. This is a Monte Carlo model rather than a DES model but it takes seasonality and day-of-week variations into account. Compartmental models use mixed exponential or phase-type distributions for cohort of patients. For example, Millard *et al* (2001) modelled bed occupancy using mixed exponential equations. This methodology is especially useful for modelling LoS distributions with heavy tails such as those occurring in the treatment of elderly and stroke patients. Taking note of this, it can be used to model patient movements between hospital wards.

There are several examples, on the applied simulation side, of how DES is used in modelling inpatient. El-Darzi *et al* (1998) presents a simulation model for evaluating LoS, occupancy, emptiness, and bed blocking in a hospital's geriatric department. Although for a single specialty, this model shows that a compartmental approach is suitable for representing long-stay patient's clinical activities in a hospital. There are also examples of multi-specialty models

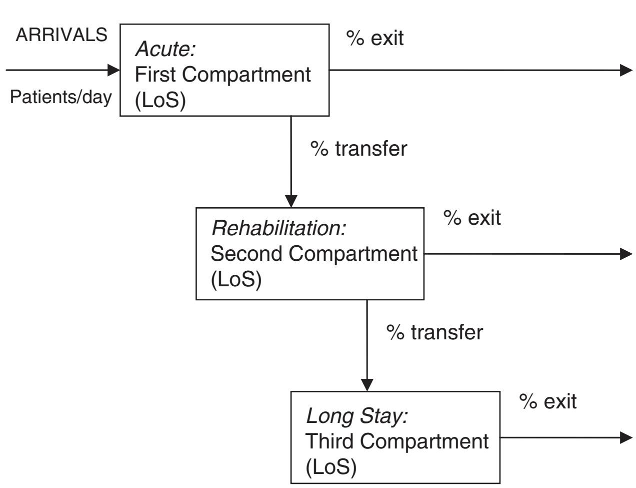

Figure 2 Compartmental model example.

such as Harper and Shahani (2002), which presents a flexible but very detailed simulation model that is used for investigating operational level inpatient-related questions; such as, what if a new respiratory unit is added? This model uses the TOCHSIM simulation executive and is written in the Delphi programming language. It is used in a number of hospitals and, being detailed, requires substantial user inputs.

On a related issue, Proudlove *et al* (2007) suggests that, in health-care modelling, a combination of simplicity and supportive presentation is more important than aiming at a complex and detailed representation when trying to support people to develop their thinking. They illustrate the argument with two examples in which simple Excel-based bed simulation models were built for clients and conclude that providing simple tools can help local system owners make sense of their systems. This is not only true for operational-level models but also true for policy-level models. For example, Bagust *et al* (1999) is an influential paper that reports a simulation of inpatient beds for emergency admissions using Excel spreadsheets, concluding that the risk of a hospital bed shortage is low when mean bed occupancy remains under 85%. This simple yet effective model demonstrates that bed crises occur not necessarily because of poor management but because of the nature of stochastic arrivals.

3.3. Outpatient clinics

It is not surprising that outpatient clinics are also commonly modelled using DES as they have some common characteristics with A&Es. However, outpatients do have some important differences from A&E departments and the focus tends to be on scheduling and capacity planning, as in Levy *et al* (1989), Hashimoto and Bell (1996), Guo *et al* (2004). However most of the studies in the literature mainly focus on 'micro' waiting in outpatient clinics; that is the waiting time when patients arrive in the clinic and wait till doctors call them for treatment. The delay is generally in a matter of minutes. What is more significant for patients is that the delay between patients' need for specialist treatment (referral date) and actual date of treatment (outpatient clinic date). This type of delay is 'macro' level compared to in-clinic waiting.

There are many different types of clinics offered across specialties, such as audiology, ophthalmology, and orthopaedics. The simulation literature tends to also follow specialty distinctions and gives full attention to the chosen specialty. For example Harper and Gamlin (2003) presents a detailed simulation model of an ENT clinic, built in Simul8 with the front end in Excel. A number of different appointment schedules were tested and the study showed that, at this particular clinic, patients' in-clinic waiting times could be reduced significantly through improved appointment schedules and better management of the schedule. Other examples include Eldabi *et al* (1999), which presents a simple simulation model (Adjuvant Breast Cancer-ABCSim) for trials of two alternative treatments to breast cancer, and Giachetti *et al* (2005) which presents a dermatology clinic simulation for designing an appointment system for the clinic. The clinic in question runs a block appointments policy in which groups of patients arrive at the same time in a day. This policy is essential for reducing doctors' idle time and also useful when the clinic cannot predict no-shows. The authors propose an 'open access' appointment policy ('today's work today') in which patients call for an appointment in the morning and are seen the same day—which assumes there is sufficient capacity available.

There are many other examples of outpatient clinic models that are built for specific hospitals and for specific specialties including Wijewickrama and Takakuwa (2005) and Takakuwa and Katagiri (2007). These two specific models are very detailed simulations of outpatient clinics in a large hospital and incorporate layouts of four floors of the hospital and include all possible patient pathways, service times, and all human resources.

Not all outpatient clinic models are designed for specific clinics and Kuljis *et al* (2001) is a good example. This describes a generic outpatient clinics model, CLINSIM, which was built for the OR Division of the UK Department of Health to observe how operating policy can influence patient waiting times. The model was used in 20 clinics, apparently with some success. Paul (1995) presents CLINSIM in more detail, which, like many other models, focuses on in-clinic waiting times. Though technically sound and offering a way to analyse and improve such clinics, it seems that the actual use of CLINSIM has been limited. The same may be true of other general models of hospital functions. It may be because of a lack of incentives or because the actual organizational structure and power relations between different professional groups mitigates against such approaches, however this does not seem to have been researched.

Genericity in outpatient simulations is approached from a slightly different angle by Swisher *et al* (2001), which reports how a single clinic model was first built as a template and used, suitably parameterized, for other clinics in a network of family clinics in the US. This work is one of the examples of modelling of independent health-care facilities relying on a common scheduling and information centre. Similarly, in an earlier study (Hancock and Walter (1984)), the same approach, that is building a template model and populating it by suitable parameterization, is used to solve a scheduling problem of 19 hospital departments. The individual model, or the template model, is used to build a network of clinics and in this regard the approach resembles object-oriented concepts.

As mentioned earlier, the majority of these papers report models built to solve scheduling problems in outpatient clinics. An extensive review of literature in this specific area is given by Cayirli and Veral (2003). The same authors used simulation to evaluate the performance of different appointment systems (Cayirli *et al* (2006)). Their generic simulation is designed to test a fictional outpatient clinic with alternative appointment systems. Two types of patients considered, new (N) and return (R). They tested different sequences of slots in the system, such as NNNRRR, or NRNRNR, or no sequencing and based on first-call-first-appointment basis. They conclude that patient sequencing is an important factor that affects the system's performance.

3.4. Other hospital units

The literature has also many examples of DES models of other hospital units not mentioned above, including simulation models of intensive care units, laboratories, operating theatres, surgical suites, pharmacies, and screening units. Rather than giving the details of these studies, a list is given in Table 1 for convenience. It is noteworthy that all of these papers cover a specific unit of a hospital and focus on solving specific problems in this unit. Especially popular units studied are operating rooms and critical care units.

Among the many other examples of unit-specific simulation models is Blake *et al* (1995), which began as an attempt at a generic whole hospital model, started by building a surgical unit, intending to extend its use to other units. They rejected the concept of building a completely general model of a surgical unit. Instead, they chose building a base model (Operating Room Scheduling Simulation) as part of the decision support tool they built and tailor it for other sites. However, even building the base model took 6 months and 3–4 months to customize it for each site. It is also noteworthy regarding this particular study that the model is actually a 'trace driven' model that is patient arrivals and service events are generated directly from historical data of the hospital.

3.5. Whole hospital simulations

It is impossible and impractical to have a whole hospital DES model that includes everything in a hospital: all models are simplifications (Pidd, 2003). An appropriate level of abstraction and scope must be chosen when attempting whole hospital simulation. The literature has very few examples of such studies. Surprisingly, though, Fetter and Thompson (1965) is a very early example of DES that reports a whole hospital simulation, with a special interest in maternity processes. The aim of this work was to give a decision support tool to hospital administrations to predict the consequences of design changes and alternative policies. They created three models of hospital subsystems: (1) maternity suite, (2) a surgical pavilion, and (3) an outpatient clinic. The maternity model was used to analyse patient load and bed occupancy. The surgical pavilion model is, apparently, simple to support experiments with surgical schedules. Unscheduled surgeries have priorities and are

Table 1 Other hospital units' DES models

Hospital unit	*Reference*
Operating room	• Ferrin *et al* (2004): operating room simulation for scheduling. • Lowery and Davies (1999): a model to evaluate operating room requirements.
Critical Care Unit (ICU, ITU, paediatric ICU)	• Griffiths *et al* (2005): Simulating an ICU with a queuing model. • Cahill and Render (1999): ICU bed requirement. • Kim *et al* (1999): A model for ICU's capacity problems. • Romanin-Jacur and Facchin (1987): optimal planning for a peadiatric intensive care.
Laboratory	• Couchman *et al* (2002): A model for a biochemistry laboratory to predict the future performance. • Ramis *et al* (2002): A generic simulation model built for a company, which operates a network of clinic laboratories.
Pharmacy	• Wong *et al* (2003): the use of simulation for a hospital's pharmacy for redesigning the medication ordering, dispensing and administration process.
Diabetic retinopathy unit	• Davies *et al* (2000): A model for evaluating screening services for diabetic retinopathy.
NHS walk-in centre	• Ashton *et al* (2005): A model of an NHS Walk-in Centre.
Maternity unit	• Johnson (1998): A model for evaluating maternity process in a hospital.

generated according to a probability distribution. The last model is an outpatient clinic model. It starts from the schedule of the doctors and can generate detailed reports showing waiting times of patients, idle times of doctors, etc. The models were independent of each other.

Cochran and Bharti (2006) reports a study in which the objective was to balance bed unit utilizations in a 400-bed hospital. After starting with a queuing network approach, they decided to use DES to cope with the complexity of hospital operations. However this model does not extend its use to the pre-admission phases, and is limited to bed-related operations. Van der Meer *et al* (2005), on the other hand, covers the phases an elective patient passes through, though only for a single specialty, orthopaedics. The objective in this study was to reduce elective patients' waiting times. Although their model is very detailed and specific to the hospital studied, the use of DES is suggested as a good communication tool between the stakeholders and modellers, as also suggested by Eldabi and Paul (2001), and Baldwin *et al* (2004).

Moreno *et al* (2000)'s approach was different in the sense that special emphasis is given to model building rather than its use. A simulation library was built from scratch. Although the authors claim that this simulation code library is specific to hospital operations, it is believed that it is a general purpose simulation library. The authors illustrate its use in a Spanish hospital to predict the hospital's future performance such as waiting times and queue lengths. The idea is to help hospital managers to consider the deployment of resources and the model is, to some degree, linked to the hospital's information system. There are three sub-systems in the overall model; human resources, hospital management, and the dynamic model of the hospital. Patient flow resides at the core of the model, which includes a diagrammatic representation of five major types of patient flow: medical, surgical consulting, medical hospitalization, surgical hospitalization, and emergency.

Although not directly related to the DES literature, Brailsford *et al* (2004) reports a study of the use of SD to model emergency and on-demand health care in Nottingham, UK. The paper includes a representation of patient flows through different departments in a hospital. The model covers the whole health system from NHS Direct to outpatient clinics and A&E departments. A supplementary DES model was also built for an A&E department.

4. Literature on other relevant issues

There are other issues not mentioned so far, but relevant to this review, such as simulation project life cycles, client involvement in simulation projects, reasons for using DES, and barriers to implementation, all in a health care context.

Discussing the simulation project life cycle, Harper and Pitt (2004) propose a framework for successful implementation. Two points come into prominence: the importance of selecting the right level of detail in models, and client involvement in DES projects. Choosing the right level of detail is especially important for saving time in the model development phase, and also for convincing stakeholders on the use of model. Lehaney *et al* (1998) also emphasize the use of animation in gaining users' confidence, although animation often increases the level of detail in simulation models and may not be appropriate for all applications.

The importance of client involvement in health-care simulation projects is pointed out by many scholars, including Lehaney *et al* (1998), Lane *et al* (2003), Brailsford *et al* (2004), Harper and Pitt (2004). It should, though, be noted that these papers are concerned with projects carried out for specific clients, with specific objectives, and hence with the models built for specific purposes. However, simulation projects that are carried out using generic models are different in terms of client involvement, since clients cannot engage in model development, or the model is already developed. However these clients should be involved in other phases of the project, such as in experimentation.

There is continuing discussion on which type of simulation is best suited to health-care modelling, especially between DES and SD. Brailsford and Hilton (2001) compare the use of DES and SD in health care. They note that SD models are not well suited to detailed modelling and cope rather badly with stochastic variation, which is an important issue in the demand for emergency health care. Commenting on the need for detailed modelling, Davies and Davies (1995) is unusual in pointing out generic problems in modelling health systems. These are that: patients may: renege from queues, take part in multiple activities, terminate activities prematurely, and switch to another activity while their current one is in progress. These issues differentiate health care from other domains. Davies and Davies (1994) comments on why DES is more useful than other OR/MS techniques: the need for an individual patient focus, the importance of resource constraints, the primacy of clinical decision process, the power of animation and visualization to communicate with the users, and more realistic representation without restrictive mathematical assumptions.

Models are built to help decision-makers solve their problems but have these models been implemented? Wilson (1981) reviewed over 200 papers in health-care simulation but found that only 16 of these report the outcomes of successful implementation. He argues that this rate is low due to a number of reasons. First, a simulation project is often initiated by decision-makers who seek urgent solutions to their particular problems having already carried out a thorough analysis of the situation. As the timing is crucial for the decision-makers, simulation analysts are expected to generate quick solutions, which they failed to do so due to the time spent in collecting and analysing data. Second, the simulation process is expensive (this may have changed due to better software). And third, when quick solutions are expected, modellers tend to oversimplify the models, which can cause decision-makers lack of confidence. Even after 25 years of this review, all these barriers to the successful implementation of simulation still exist to some degree in all domains, including health care.

5. Conclusions

From the literature reviewed here, a number of important conclusions can be drawn about simulation modelling in health care.

5.1. Most reported studies are unit specific

First the applied studies reported in most papers are unit specific. That is, their focus is the solution of specific problems in individual units of health-care systems, such as staff-demand mismatch in A&E departments, reducing waiting times in outpatient clinics, and better-utilizing hospital beds. Though the publication of such case studies serves to illustrate the breadth of work going, this does lead to two problems. The first is that there is no general sense of the literature moving forwards, because many papers tend to be reports of rather similar work on rather similar problems. This is not to argue that case studies should not be published but is a recognition that individual case studies rarely lead to generalizable insights or to general theory, unless the authors work very hard to do so. That is, case studies often stay as examples of what can be done, or in some cases of what might be done, rather than as illustrations from which practitioners and researchers might learn and develop further ideas. After so many years using simulation methods in health care it seems important to encourage authors to focus on generalizable issues when writing case studies, unless the case is in a new area of application. These issues include the generalizable approaches to tackle particular problems (eg representation of task switching by clinicians) and also the problems faced by the researchers for which they feel better approaches are needed—unsolved research problems and challenges, if you wish.

A further problem with unit-specific models and case studies is that they usually assume rather tight boundaries around the system elements being modelled. That is, most existing work is directed at the simpler problem of modelling part of the hospital system instead of tackling the complexity of comprehensive modelling of the hospital as a whole system. Of course, all models are simplifications, but appropriate simplification is what matters. There is a danger, when modelling a single unit, of ignoring what happens over the other side of the wall. That is, useful though they are, unit-specific models and simulations may miss the big picture. Conventional, piecemeal modelling of hospital departments must in general take the rest of the hospital as a ‘given’. That is, an intensive care unit (say) can be successfully modelled on its own only by making very simple assumptions about how its activities influence and are influenced by what is going on in the rest of the hospital. In practice, however, the links between hospital departments can be quite subtle, and may require careful modelling. Carving a piece of the hospital off in this way can, obviously produce useful results, and is likely to be much better than basing decisions and plans on hunches. There seems to be very few examples of simulations that attempt a more holistic view so as to allow side effects and unintended consequences to become more apparent.

5.2. Most reported studies are facility specific

Many, if not most, of the DES models described in the literature were built for specific hospitals and are never, in any way, reused. It seems that health-care modellers do not reuse models produced by others, but instead build their own each time. Opinions vary about the value and feasibility of reuse (Robinson *et al*, 2004), but it seems hard to imagine that 1000 outpatient clinics require 1000 different simulation models. The relative paucity of reuse in health-care simulation could, of course, be because the literature may lag some way behind the practice and this, and limited budgets, may mean that there are also limited opportunities to find out what other workers are doing.

There may, though, be good reason for so little reuse. Robinson (2002) suggests that there are many different reasons for using simulation and gathers these into three stereotypes of simulation practice: software engineering, process of organizational change and facilitation. Software engineering approaches favour large models, often developed by sizeable teams and at considerable expense—hence planning for reuse makes much sense. However, under the other two stereotypes, models are essentially thrown away at the end of a project and, in the case of facilitation, may not be properly 'used' at all, as the process of model creation may illuminate enough about the pinch points of a system for appropriate action to be taken as the light dawns. This point, valid though it is, raises a further question about the papers in the literature: were they properly 'used' and, what does this mean?

There is also the economics to consider and there are two aspects to this. First, the question of who pays for the work, which may link to other commercial considerations that may prevent or inhibit reuse (people may simply not wish to share their work, or not at a price others are willing to pay). Secondly, modern simulation software is easy to use and the model creation phase of any project may be relatively short compared to other work that has to be done. Linked to this, it may not be possibly to wholly reuse a model, but some adaptation may be needed. Hence it may simply be cheaper or easier to start again with a new model rather than attempt to modify an existing model produced by others.

Repeating the same point made earlier about case studies, it would, though, be a step forward if papers that describe facility- and unit-specific applications showed that they had learned from the insights proposed by others. It would also be a step forward if the papers provided general and conceptual descriptions of their approach with enough detail to permit others to use their approaches, if not their models.

5.3. How are DES models used in health care?

Given the above two points it should be no surprise that a major finding of Fone *et al* (2003) is that most health-care simulation applications in the literature attempt to provide support for better operational decision-making and planning. Examples include the redesign of staff schedules, adding or removing beds, increasing the number of nurses, and other clinicians. By contrast, very few report higher-level use such as policy-level analysis. That is, there has been extensive OR work in detailed modelling of specific aspects of the hospital, such as A&E, operating theatres, outpatients, inpatient wards, and intensive care units, which links to the above two points about unit- and facility-specific applications.

In general, the intention in most papers seems to have been to model the detailed processes of care in order to deploy human resources, capital and equipment in an optimal fashion. However, there has been remarkable little work done on modelling a hospital as a whole system. This is disappointing given the clear linkages between different entities within the hospital, such as the flows of patients between emergency departments, operating theatres, and inpatient wards. This could, of course, be because DES methods are not well suited to addressing these problems. The DGHPSim project (Günal and Pidd, 2006, 2007, 2008) demonstrates, however, that DES methods can be used in this way if appropriate thought is given to the level of detail and data sources needed in the model, even when individual patient flows are modelled.

A further issue that is rarely discussed openly is the extent to which DES models are actually used for real decision-making in health care, which may be particularly acute in models of health-care delivery rather than disease and screening models. If a model is to be used, the various stakeholders need to be convinced of its benefits and also need to appreciate its limitations. Needless to say, this is not straightforward and may not be something that greatly interests the mainly academic authors of the papers reviewed. Though the modelling team may be convinced that a model is valid, this is no guarantee that the model will be used at all or in the way anticipated. As DES approaches have been used in health care for over 30 years, it may be time to take a serious look at this issue of model implementation and use.

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