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Modelling radiology department operation using discrete event simulation

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Abstract: Recent policy announcements by Australian government departments suggest a need to explore the use of process management principles, normally applied to manufacturing industry, to healthcare services management. The research presented in this paper is part of a broader project that uses discrete event simulation coupled with visual display of results to reduce patient flow in hospital emergency departments (EDs). It is conjectured that such visual approaches will enable clinicians to better understand the simulation models and plan for work process improvements.

Given its relationship to the ED, this paper focuses on patient flow in a radiology department. The paper summarises current scheduling practices in one Australian public hospital and provides a basis for future investigation of strategies to improve resource utilisation and average patient wait-times. Key parameters of current scheduling practices such as equipment and human resource availability, booking timeslot duration and patient mix are also identified for the purpose of visually simulating patient flow within the imaging department and optimising patient scheduling.

To ensure the models accurately reflected hospital process, primary and secondary data were collected. Primary data were sourced from observations of work flow, patient flow, and departmental practices; these observations were then validated through interviews with hospital staff. Secondary data were sourced from hospital records and included information on the sonography department – more specifically, its patient case-mix, its activity level, patient bookings and schedules, staff rosters, and award constraints. These data spanned a period of three months.

Using the collected data, a simulation model was built to illustrate current departmental processes to hospital staff, and identify areas for improvement. This was achieved using Tecnomatix Plant Simulation® software. The visual nature of the program helped staff to readily understand the complex relationship between hospital departments, and examine feasible strategies such as increasing staff resources and/or altering booking timeslot duration to enhance patient flow.

Simulation has been used as a method of providing hospitals with an objective and a justifiable basis for proposing and making change. This was duly indicated by hospital staff who proceeded to use the models to inform decisions about ways to improve the operation of the radiology and emergency departments. Future research is needed to evaluate the implementation of simulated solutions, as this would help to validate the use of discrete event simulation in health services management research.

Keywords: *Radiology department, health services management, access block, discrete event simulation*

1. INTRODUCTION

Although pivotal to enhancing population health, patient access to hospital services is often stymied (Paoloni and Fowler, 2008). This is partly due to a mismatch between capacity and demand, particularly within emergency departments (EDs) (CFECUSHS, 2007). In Australia for instance, there were approximately 6.7 million presentations to EDs in a recent 12-month period (AIHW, 2008) – an increase of 400,000 patients from the previous year (AIHW, 2007); however, Australian public hospitals have a limited capacity to meet this demand (Booz Allen Hamilton, 2007).

One symptom associated with the limited capacity of EDs is access block (Cameron and Campbell, 2003). This occurs when patient stay in an ED exceeds eight hours, consequent to the limited availability of an inpatient bed (Paoloni and Fowler, 2008). Although international and national statistics are limited, an examination of data from one Australian state suggests that thirty to forty percent of emergency patients exceed this eight-hour limit (ACEM, 2004). Given that the functionality of an ED degrades once access block exceeds ten percent, this statistic constitutes a serious concern.

Access block represents a costly problem. In addition to increasing risk to patient health (Erikson et al., 2001), it affects the allocation of limited public resources and the management of healthcare services. In particular, it is associated with decreased efficiency in the ED (Derlet, 2002) and increased inpatient stays (Richardson, 2002). Given the interconnected nature of hospital departments, access block is likely to hinder patient flow throughout a hospital (Fitzgerald et al., 2008). It can thus reduce the efficiency of the surgical, intensive care, radiology, and pharmaceutical departments, among others.

Access block is caused by a multitude of factors. In addition to insufficient inpatient beds, access block is attributed to limited workforce capacity; an ageing population; the increasing number of young patients (under 25 years) who access EDs as a substitute for primary care (Booz Allen Hamilton, 2007); the increasing number of patients requiring intense and/or continued hospital treatment (Duckett, 2007), thus overcrowding hospital departments (Fatovich and Hirsch, 2003); a decline in community services including nursing homes and mental health services, which in turn adds further strain on the hospital system (Duckett et al., 2007); changing patient expectations, largely consequent to improved access to health information; changing referral patterns, with 86 percent of patients self-referring to EDs; increased use of ambulance services, which has risen by ten percent annually in the last two years; the limited access of day clinics and private practitioners (RACS, 2004); the decline in bulk billing among general practitioners (Hopkins and Speed, 2005); and funding arrangements that focus on elective surgery and outpatient care (ACEM, 2004).

The systemic nature of these problems is likely to require long-term solutions. However, this does little to remedy the immediate challenges of access block within EDs. Given that a significant percentage of hospital admissions are via EDs (Yin Meng and Spedding, 2008); given that EDs attend to the most urgent clinical cases; and given the costs associated with access block, it is essential to identify ways to improve patient flow in the ED, and thus, the interconnected departments.

One approach that holds promise for healthcare services is lean thinking. Typically applied to the manufacturing industry (Reinertsen and Shaeffer, 2005), lean thinking aims to provide products or services ‘in the most efficient manner by improving flow and eliminating waste from processes (NA, 2008). This is achieved by understanding current processes, identifying areas for improvement, and implementing necessary change. The application of lean thinking to private industry has helped to improve productivity, reduce waste, and lower costs – and it is these strengths that hold promise for healthcare services.

Extending international research (Medeiros et al., 2008, Yin Meng and Spedding, 2008), this paper demonstrates the potential benefit of discrete event simulation for Australian healthcare services. Using an Australian hospital department as a case study, the paper describes the way a simulation software program was used to understand complex departmental processes within a virtual environment, and identify strategies that would potentially improve patient flow. Although this project forms part of a larger study (Fitzgerald et al., 2008), the focus of this paper is the use of simulation to understand (and potentially improve) current departmental processes.

2. DISCRETE EVENT SIMULATION

Discrete event simulation allows scenarios involving different resources or procedures to be modelled quickly with little cost and no risk. This is made possible by representing the operation of a system as a chronological sequence of events. Each event occurs at an instant in time and marks a change in the system

(Robinson, 2004). Discrete event simulations have been used widely in the manufacturing industry (Semini et al., 2006). Typically, the system maintains a clock that controls the instants of time during which events occur and are monitored. Other common features are sources of components, queues or buffers where components accumulate awaiting processing, processes that perform an operation, as well as drains or sinks that allow parts to exit the system. To capture varying distributions of components, random number generators are generally used. Typically when modelling a real system, data is collected on the frequencies of parameters, arrival rates and/or process times of operations. This information is then analysed statistically to determine a distribution that can be mimicked with the random number generator. The simulation typically maintains a set of statistics on the number of items produced, resource use, waiting times, and so forth.

Most discrete event simulation software incorporates an extensive visual interface which facilitates model construction and display of results. Using such graphical computer software, macro and micro processes can be portrayed and tinkered with, and the expected effects of such tinkering can be surmised. Such simulations thus provide predictive value, allowing users to experiment with innovative change without the need to pilot such change *in vivo*. Substantial work has been carried out in the Netherlands (Hans et al., 2008) in the realm of operating theatre scheduling simulation and various studies have emerged from the U.K. (Komashie and Mousavi, 2005), Canada (Duguay and Chetouane, 2007) and Finland (Ruohonen et al., 2006) concerning emergency departments.

3. METHODOLOGY

3.1 Hospital Setting

The hospital department to which discrete event simulation was applied is situated in a NSW public hospital that serves a highly populated and ethnically diverse community (SSWAHS, 2007a). The region is also characterised by high levels of unemployment and encompasses nine of the ten lowest socio-economic communities within metropolitan Sydney. Serving a highly populated community, the ED has experienced significant increases in demand (SSWAHS, 2007b). From 2005-06 to 2006-07, the area health service witnessed an increase of ED presentations by over 30,000; an increase of ED admissions by 9.5 percent; the highest ambulance presentations in the state; and a rise in the number of primary care patients from 22 to 28 percent. Despite improved performance within the area health service to which it belongs, such improvement was not always demonstrated within the hospital's ED. For instance, from 2005-06 to 2006-07, the area's Emergency Admission Performance (EAP) improved from 67 to 76 percent; however, figures from the hospital reveal a decline from 66 to 61 percent – the lowest of all hospitals within the area. With increased demand, the ED experienced recurrent access blocks. This was indicated by hospital personnel and observed by the researchers. To reduce access block, hospital personnel perceived the radiology department as a key problem area where patient delays often occurred. The radiology department performed a number of diagnostic procedures including ultrasounds (sonography), CT scans and x-rays; this paper focuses on the sonography department. Ultrasounds were offered over seven sixty-minute timeslots each day.

3.2 Data Collection

The researchers observed scheduling practices, request processing, patient preparation processes, as well as results processing. These were observed from three access points into the sonography department – namely, when the patient arrived as an inpatient, an outpatient, or an emergency patient. The researchers also identified key activities, materials and resources, as well as input and output parameters. To ensure accuracy, observations were conducted at different times (namely, mornings, afternoons, and over an entire workday); observations were verified through staff interviews; and observations were compared with the ward-book, which is used to record patient arrival and departure times, as well as patient case-mix. Patient wait-time was calculated from the time a patient was scheduled to receive a procedure to the time the patient was collected by a sonographer – this is because the data indicated that inpatients who had arrived in the department prior to their scheduled time, entered the sonography room on the scheduled time. To prepare the data for analysis, official records about sonography procedures and the wards that initiated the procedures were coded. Following this, the collected data were cleaned by excluding illegible, unclear or illogical records (for instance, improbable procedure times, as confirmed by the sonographers), and completing missing data by comparing the ward-book and the booking records. Data were integrated under several assumptions; namely: appointments were scheduled hourly from 9.00 am to 4.00 pm; a break was scheduled from midday to 1.00 pm each day; six emergency slots were available each day, which were divided over available rooms and used only by the ED; the time patients require to undress and dress was incorporated into the procedure time; and patients arrived on time.

To facilitate the modelling, a process view of sonography in the imaging department was developed (Figure 1). This is based on Event-driven Process Chain (EPC) methodology and represents basic process components: process paths, events, functions and logical operators as the basis for process modelling and simulation in this study. Furthermore, each process path (functions and events) and individual functions are associated with several different data elements, such as activities, documents and resources.

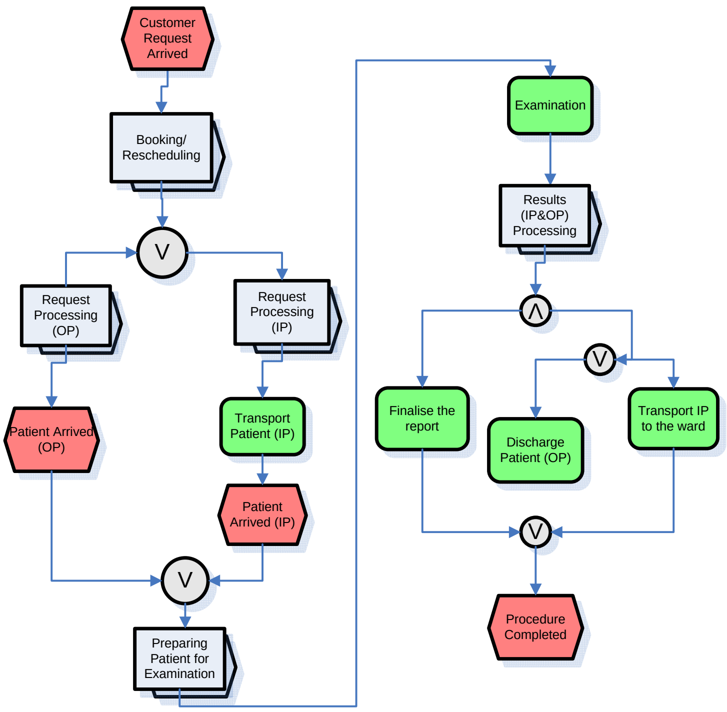

Figure 1. Process View of Sonography in the Imaging Department

3.2.1 Procedure Types and Scheduling

There were 38 ultrasound procedures performed in the radiology department. The six most common were explicitly modelled, and the remaining types were collapsed into one group (Table 1).

Table 1: Procedure Types and Frequencies

Procedure	Frequencies	Percentage
Abdominal ultrasound	88	28
Carotid artery Doppler	53	17
Lower leg ultrasound	32	10
Obstetric ultrasound	18	6
Pelvic (female) ultrasound	48	15
Renal ultrasound	30	10
Others	45	14
TOTAL	**314**	**100**

The scheduling of these procedures was largely constrained by room availability; staff availability; timeslot duration; cancellations; as well as meetings (Table 2).

Table 2: Room Availability and Utilisation

Day	Nº of Rooms	Timeslots Used	Cancellations	Meetings
1	3	19		2
2	3	17	2	2
3	2	14		
4	3	18		3
5	2	14		
TOTAL		**82**	**2**	**7**

From these data, it was conjectured that room use from 9.00 am to 5.00 pm over a five-day period was approximately 80%. Simulation would reveal a truer measure of room use.

3.3 Data Mining

To simulate departmental processes, it was necessary to determine a statistical distribution for the different procedure times. A commonly used distribution function for the time to complete a task is the gamma distribution shown in equation 1 (Law and Kelton, 2000).

$$f(x;\alpha,\beta) = \frac{x^{\alpha-1} \quad e^{-\frac{x}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \quad (1)$$

An important characteristic of this distribution function is that the parameters α and β are related to the mean and the variance as follows: Mean = αβ, Variance = $\alpha\beta^2$. To test the hypothesis that the procedure times have a gamma distribution function, a chi-squared (equation 2) goodness of fit test was performed. This test divides the entire data range into k (depending on the number of available data) adjacent intervals $[a_0, a_1)$, $[a_1, a_2)$,…$[a_{k-1}, a_k)$. The researchers then compared the actual proportion of procedure times that fit into the interval j (=N_j) to the expected proportion of procedures times that would fall in the interval if sampling from the gamma distribution (=X_j). The chi-squared value (χ^2) can be calculated as follows:

$$\chi^2 = \sum_{j=1}^{k} \frac{(N_j - X_j)^2}{X_j} \quad (2)$$

If there is good-fit between the generated distribution and the observed data, the χ^2 is expected to be less than the specified value for say 95% confidence (Table 3). Based on the data collected, gamma distributions were found to be suitable for all procedures in this study.

Table 3: Distribution of Procedure Times with Descriptive Statistics

Procedure	Mean (min.)	SD (min.)	χ^2 (95%)
Abdominal	54	19	11.09 (14.0)
Carotid artery	58	16	8.13 (14.0)
Lower leg	39	12	4.56 (9.48)
Obstetric ultrasound	49	11	1.11 (7.81)
Pelvic (female)	48	15	6.83 (12.59)
Renal	39	14	7.6 (11.07)
Others	42	19	1.2 (11.07)
TOTAL	**49**	**18**	

Compared to the current timeslot of sixty minutes, the overall mean of each procedure is 49 minutes. This suggests that resource utilisation might be improved by reducing each timeslot to fifty minutes. This is expected to be verified by simulating current practices with the simulation software. Although the investigations are continuing, preliminary simulation results suggest a 14% increase in capacity as a result of such a reduction.

4. RESULTS

In the sonography department, three equipped sonography rooms were serviced by 2.6 (fulltime equivalent) staff members. Each room was modelled as a process component, with patients included in the model as moveable units; staff members as workers with a 12-month roster, including sick leave, annual leave, training days and rostered days off; and procedures allocated a sixty-minute timeslot. Appointments were thus scheduled on an hourly basis from 9.00 am until 4.00 pm. A staff break was scheduled at midday. An average of five minutes was allocated for sonographers to complete a report for each patient.

Informed by the data collected, inpatients, outpatients and emergency patients were generated according to the observed distributions and procedure times (Tables 1 and 3). Results of the simulation are presented in Table 4. Due to the visual nature of the simulation package, hospital staff viewed the simulation and confirmed its accuracy.

These results highlighted the relatively low use of the room and hospital resources. Investigations are currently in progress to examine the following alternative strategies: (1) increasing the number of sonographers so that each of the three rooms is fully staffed; (2) reducing the booking timeslot duration from 60 minutes to 50; (3) allocating one of the three sonography rooms solely to ED patients; and (4) a combination of options (2) and (3).

Table 4: Simulation of Current Departmental Practices

Outcome Measure	Current Situation
Waiting Time (min:sec)	4:39
Total patients	3,927
Inpatients	1,784
Outpatients	994
Emergency patients	1,149
Staff overtime (min:sec)	8:43
Room utilisation	54%
Room use including weekends	13%
Utilisation of sonographers	85%

5. DISCUSSION AND CONCLUSIONS

This paper has described the way a simulation software program was used to understand complex departmental processes within a virtual environment, and identify strategies to potentially improve patient flow in an ED. Plant Simulation software was useful for several reasons – first, it provided a way to clearly demonstrate to staff the relationship between process change and improved efficiency; and secondly, it provided a platform for discussion and a better understanding of the inter-connectivity of processes across different departments More specifically it allowed for the modelling of patient frequencies, the varying times of hospital procedures, staffing constraints and patient movements. Simulated processes could be observed for long periods to draw conclusions about hospital capacity and patient-wait times. Simulation with a visual interface encouraged the involvement of practitioners in observing and validating the model. The results confirmed initial impressions that resource utilisation was low; it also provided a quantitative basis for varying critical parameters to improve patient throughput, and thus reduce access block. Parameters suggested for variation include the timeslot duration, number of available staff and the allocation of emergency patients.

Despite the potential value of simulation four limitations must be acknowledged. First, it does not include a consideration of less tangible factors that affect the overall model – these include human error, lack of preparation, and interruptions. Second, although the hospital provided extensive data, significant amounts were incomplete or erroneously transcribed and required cleaning; this reduced the sample size. Third, it is probable that the models did not include all key parameters that influence departmental processes – including, demand and request times – in the absence of these data, assumptions were made for the purpose of modelling. Finally, manufacturing simulation software often tends to be primarily unit-driven – that is, it relies on the arrival of manufacturing units which then causes functions or processes to be activated. Although this paradigm might be appropriate for some medical environments, like a medical practice, it may not be readily applicable to a sonography department where patients are only scheduled if staff members are available. In cases such as these, substantial additional programming in the package is necessary.

Simulation such as this can provide hospitals with an objective and a justifiable basis for proposing and making change. Its catalytic validation was indicated when it was used by hospital staff to inform decisions about ways to improve the operation of the radiology and emergency departments. Future research is needed to evaluate the implementation of simulated solutions, as this would help to validate the use of such approaches in health services management research.

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