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Managing uncertainty in orthopaedic trauma theatres

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Abstract

The management of acute healthcare involves coping with a large uncertainty in demand. This uncertainty is a prevailing feature of orthopaedic care and many scarce resources are devoted to providing the contingent theatre time for orthopaedic trauma patients. However, given the variability and uncertainty in the demand much of the theatre time is not used. Simulation was used to explore the balance between maximising the utilisation of the theatre sessions, avoiding too many overruns and ensuring a reasonable quality of care in a typical hospital in the United Kingdom. The simulation was developed to examine a policy of including planned, elective patients within the trauma session: it appears that if patients are willing to accept a possibility of their treatment being cancelled, substantially greater throughputs can be achieved. A number of approximations were examined as an alternative to the full simulation: the simpler model offers reasonable accuracy and easier implementation.

Keywords: Health services; Simulation; Risk management

1. Introduction

There are two elements to the demand for health services: the planned, elective patients who typically spend time on a waiting list before being allocated an appointment for their treatment and the non-elective patients who have to be treated urgently. The management of the non-elective patients is particularly difficult: their arrival is inherently stochastic and the treatment requirements of individual patients can vary considerably. Strategic approaches to managing the uncertainty in orthopaedic demand have been explored including the option of concentrating health services such that one larger hospital serves a greater population [3]. Other proposals focus on the management of the non-elective treatment within a hospital. Some aspects of the interaction of the treatment of the planned and the emergency patients, such as the management of Accident and Emergency Departments, have been explored in previous studies [11]. The requirement for operating theatre time is especially difficult to satisfy in an efficient manner. Operating theatres must be available for the non-elective patients but theatre time has been identified [16] as a major constraint in many hospitals limiting the number of elective patients that may be treated. The problem is

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especially severe in the orthopaedic specialty that has to treat a large proportion of non-elective patients. Following the recommendations of the National Confidential Enquiry into Perioperative Deaths [4], one approach which is now generally adopted in acute hospitals in the United Kingdom is the use of the trauma session [20]. Typically [12] only 15% of non-elective patients require an operation within 6 hours of admission: the remainder can be treated within 24 hours, or an even longer period for some injuries. Many patients are sufficiently stable that their treatment can be delayed for a few hours until a scheduled, trauma session in which a number of patients may be treated. Indeed it can be beneficial for theatre treatment to be delayed until the shock of an accident has dissipated. The trauma session was encouraged as a means of improving the quality of care of patients by ensuring that all were treated within a reasonable time but it also eases the problems of managing the stochastic demand. Often the orthopaedic trauma care is based on a dedicated theatre session each weekday. Given the highly uncertain demand this session is often under-utilised though sometimes the trauma demand is high and the session will overrun. While staff accept the need for working beyond the scheduled times occasionally, their flexibility has limits: the design of the trauma session has to achieve a balance between maximising the utilisation of a scarce resource and avoiding too many overruns.

In an attempt to improve the utilisation of theatre time it is the practice in some hospitals to treat a few selected elective patients in trauma sessions [18]. These elective patients are offered a shorter waiting time in exchange for a accepting a certain risk of cancellation. While some hospitals regard this as a useful practice, it is not widely acknowledged in the acute sector. Indeed, the current government policy offering rights of redress to patients whose operations are cancelled on the day of surgery would seek to penalise hospitals for adopting this practice [7].

Simulation is well established [5,9] as a technique for analysing health care systems. In particular, simulation has been employed in many studies supporting capacity planning in an uncertain environment, such as the provision of beds and intensive care facilities [1,10,17]. Relatively few simulations of operating theatre activities are documented; possibly this is due to the reported difficulties of gaining access to staff [14]. The current study involved a series of simulation experiments to assess proposals for improving the utilisation of orthopaedic trauma theatre sessions in a typical United Kingdom district general hospital. This hospital serves a population of 400,000 and admits 3000 non-elective orthopaedic patients per year. While the detailed results are particular to this hospital, the experiences provide some insight into the general questions about managing uncertainty in non-elective theatre sessions. Although specific simulations have proved valuable in the design of many health care systems, the cost of such studies can be prohibitive and in some circumstances a simpler methodology is desirable [13]. In an attempt to disseminate the guidelines suggested by the simulations of the current study, an alternative analytic approach was developed. If it can be demonstrated that the approximations of the alternative models do not reduce the accuracy of the results significantly, the comparative ease of implementation can make the analytic approach a more attractive option.

2. The demand for theatre time

Data describing the procedure times of non-elective orthopaedic patients were obtained from the hospital's theatre system. The times include an allowance for the necessary cleaning and preparation between patients. The characteristics of the patients' demand for theatre time are summarised by the distribution of procedure times of Fig. 1;

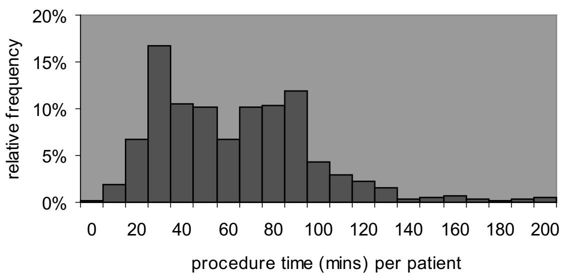

Fig. 1. Theatre procedure time for non-elective patients.

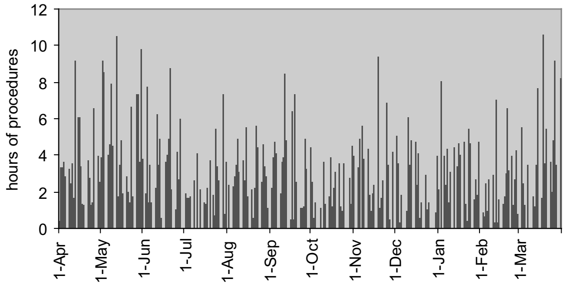

Fig. 2. An example of a year in a trauma theatre.

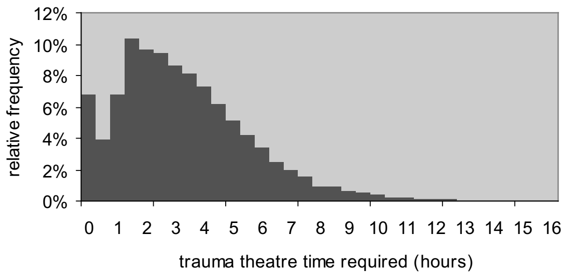

Fig. 3. Trauma theatre time required per day.

the mean procedure time is 64.6 minutes and the standard deviation is 37.8 minutes. The distribution is bimodal and there is no simple analytic function that provides an adequate fit. In addition to the uncertainty about the procedure times the arrivals are also stochastic: a Poisson model was adopted with mean interarrival times varying with the hour, day and season. A simulation was constructed in Microsoft Excel to explore the total daily trauma theatre demand. The patients' interarrival times were generated assuming the Poisson model and their requirements were sampled from a seasonally classified set of observations from the theatre data employing a bootstrap, resampling methodology [6]. This approach ensured that the seasonal characteristics of the demand were preserved: both the mean admissions rate and the nature of the patients' diagnoses vary over the year. While the mean annual number of non-elective orthopaedic admissions was 3000, many of the patients did not require theatre treatment and others were treated in emergency sessions. A typical annual demand for trauma theatre time is illustrated in Fig. 2. The model was used to generate 100 years of activity in the trauma theatre; the daily demand was recorded and used to produce the relative frequency distribution of Fig. 3. On 7% of days no patients require any trauma theatre treatment.

3. Determining the appropriate length of the trauma session

Theatre time is a scarce resource and scheduling too much trauma theatre time may divert resources away from elective patients contributing to a growth in waiting lists. Given the trauma demand, as summarised in Fig. 3, management need to determine the appropriate length of the trauma theatre session. If the scheduled trauma session is too short patients would not be turned away but staff would frequently have to continue working long beyond their scheduled finish time. While if the trauma session is too long staff and scarce resources would be idle for much of the time. Inevitably a service such as a trauma theatre cannot expect to have a very high utilisation but some balance is necessary between the possibility, and length, of overrun and the efficient use of resources.

A simple Monte Carlo simulation was undertaken using the patient demand model, incorporating the seasonal Poisson arrivals and the resampled seasonally classified patients. The simulation was used to generate 100 years of demand data for a hospital with an annual mean admission rate of 3000 non-elective orthopaedic patients. Assuming a typical distinction between emergency and trauma patients this mean admission rate implied a mean annual trauma demand of 735, with the other patients either requiring no theatre treatment or being treated as emergencies. The effect of adopting a range of scheduled trauma hours was explored and the implications summarised as three measures: the mean daily overrun (in Fig. 4), the mean number of overruns per day (Fig. 5) and the utilisation (Fig. 6) of the theatre sessions. All of the results presented as graphs include 95% confidence intervals about the estimates of the means but the intervals are typically very small. Identifying the most appropriate allocation of trauma time depends on the relative weights

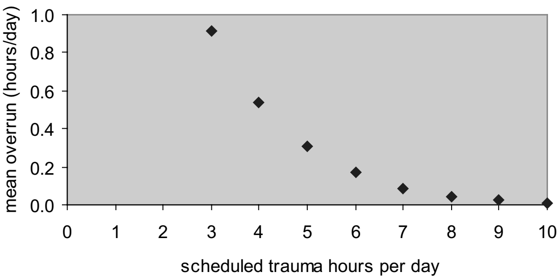

Fig. 4. Theatre overrun.

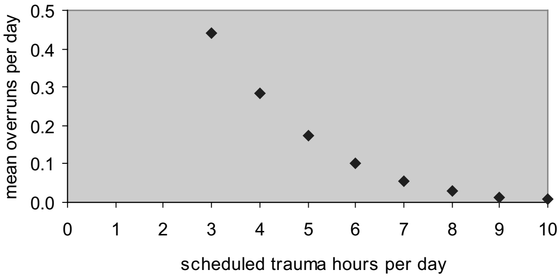

Fig. 5. Number of overruns.

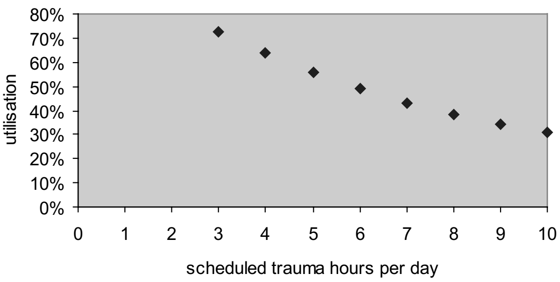

Fig. 6. Theatre utilisation.

attributed to three measures; as in many simulation studies the output is not a simple optimum but guidance to help management make a better decision [2]. The simulation experiments suggested that a theatre schedule that allows for 5 hours of trauma procedures per day would achieve a mean utilisation of 55% and typically result in an overrun once per week, with a mean total overrun of 1.6 hours per week. This may be acceptable to the staff who accept a degree of uncertainty when working in a trauma session. Any significant reduction in the degree of overrun of the trauma sessions could only be achieved by accepting a major decline in the utilisation of the theatre.

4. Elective patients in trauma sessions

In practice the scheduled sessions are usually planned as part of a 7 hours theatre day: a requirement for a trauma session of 5 hours implies that the remaining 2 hours could be used for other patients. Even a short additional list of 2 hours per day could enable the treatment of a large number of elective patients over the year reducing orthopaedic waiting lists substantially. Typically it might be possible to incorporate elective patients in 255 of the planned trauma sessions per year, suggesting an extra 510 hours of elective theatre time. However, there will be occasions when trauma demand is high and there will be a need for more than 5 hours for trauma procedures: the effective additional availability of elective theatre time will be reduced and elective patients will be sent home, their treatment deferred. There are similarities to the dynamic stochastic knapsack problem [15] though in this case the uncertainty is associated with the capacity of knapsack, or the available theatre time, rather than the arrival and nature of the objects to be selected and packed. A more sophisticated discrete event simulation was constructed using Simul8 [19] to explore the effects of including scheduled elective procedures in the trauma session and the trade-off between maximising the utilisation of the theatre sessions and minimising the probability of disappointing patients. An overview of the logic of simulation is provided in Fig. 7.

The simulation involved two main activities: selecting elective patients for the scheduled session and treating the patients in theatre. Processes and customs can vary but a standard set of assumptions reflecting typical practice were incorporated in the simulation:

1. Elective theatre lists are compiled weekly, considering all the potential elective patients that might be treated in the five sessions.

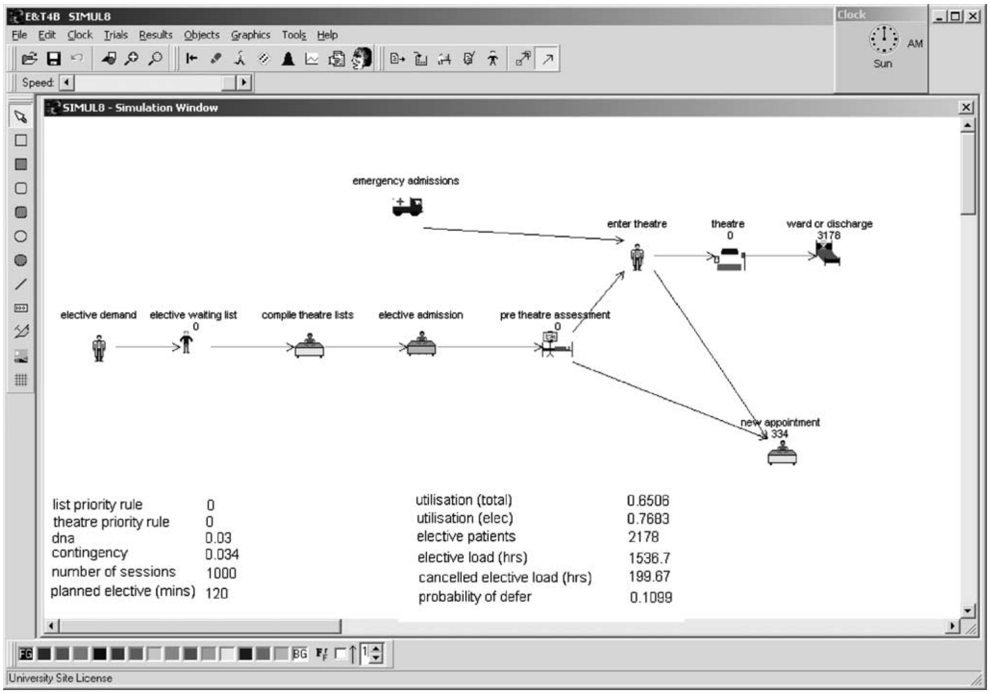

Fig. 7. Overview of the simulation logic.

2. The elective lists are compiled by first identifying the session with the most unallocated time remaining. The potential patients are ordered by a priority rule (e.g. longest first or random) and the first is scheduled in the chosen session: the patient's appointment is noted and the remaining availability adjusted. If the procedure duration is greater than the available theatre time the patient is rejected for scheduling within a trauma session; the patient will have to be treated in a conventional elective session.
3. Some patients fail to attend their allotted treatment session while others may have the treatment postponed if the pre-theatre assessment indicates that surgery would not be safe given their condition. Despite efforts to minimise the number of such patients a proportion are classified as "did not attend"; in the present example this proportion is relatively low at 3.0%.
4. The procedure times employed are actual times, including the time for preparation between patients. In practice the theatre lists have to be compiled using staff's experience and estimates of procedure times. The theoretical theatre utilisations that are possible assuming perfect information are not achievable in practice so the model incorporated a planning contingency associated with each procedure. The value of this contingency was determined by iterative experiments: a figure of 3.4% was found to be sufficient to explain the inevitable discrepancy between the theoretically achievable utilisations of theatre sessions, assuming prior knowledge of the actual procedure times, and the actual mean utilisations.
5. Treatment in the theatre is organised such that trauma patients have priority. If necessary the theatre session will overrun the scheduled time and continue until the trauma patients' treatments are complete.
6. The elective patients are treated in an order specified by a priority rule (e.g. longest first or random).
7. The theatre session will not overrun in order to complete the treatment of an elective patient. If there is insufficient time for an elective patient's

procedure the treatment will not begin and the patient will be deferred.
8. If a patient's treatment is deferred, the patient will receive an appointment in a conventional elective session with minimal chance of any further postponement of the treatment.

5. Varying the length of the elective session

The complete session was assumed to be 7 hours and a range of allocations for the elective list was considered from 0 to 4 hours. In the initial simulation experiments the patients were selected from the elective waiting list using a "longest first" priority rule which approximates to typical practice. The number of elective patients requiring theatre treatment was 2600 p.a.; the elective procedure time requirement of an individual patient is described by the distribution of Fig. 8, the mean being 70.8 minutes. As the length of the scheduled elective list increases the mean utilisation of the complete 7 hours session rises considerably, as in the "controlled selection" results of Fig. 9. Though the mean utilisation levels of pure elective sessions, which can often reach 86%, may not be achievable, much elective treatment could be undertaken within the trauma sessions. Including a very short elective list with a limit of 30 minutes has some

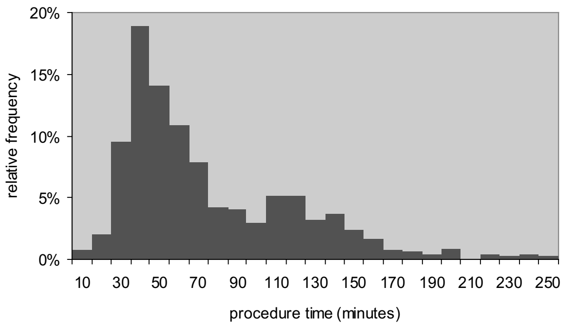

Fig. 8. Elective procedure times.

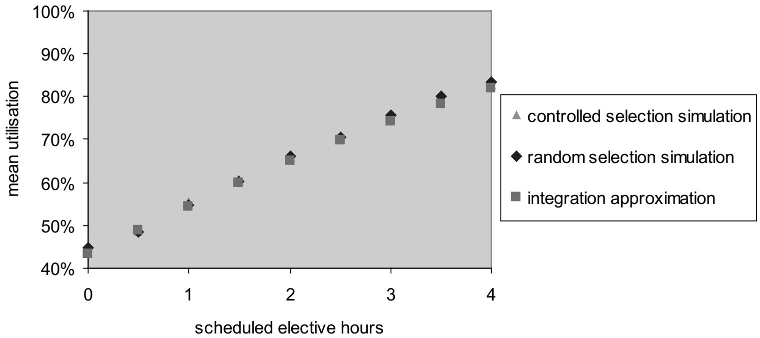

Fig. 9. Theatre utilisation.

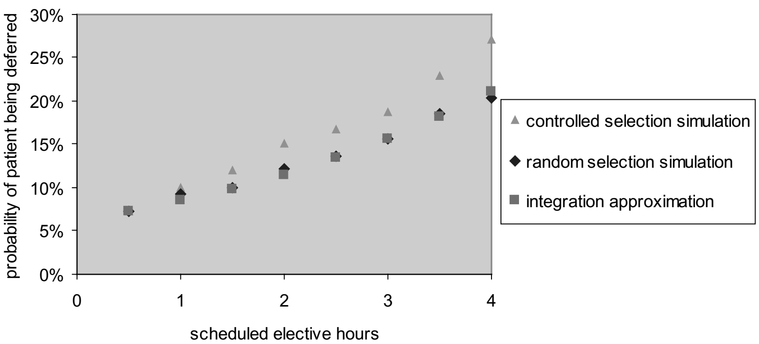

Fig. 10. Probability of treatment being deferred.

value but it can be difficult to find many patients requiring such short procedures. The longer the scheduled elective list, the easier it is to pack the allotted time more efficiently; this relationship is a manifestation of the universal characteristic of packing problems [8] that wastage is reduced as the bin size increases. The simulation suggests that a significant volume of elective work could be undertaken: a planned sub-session of 2 hours could permit an extra 390 hours of procedures, or 13% of the total elective theatre procedure time requirement. However, even with a short list of just 30 minutes there is a significant probability of the procedure being deferred since the trauma requirement can readily exceed 6.5 hours (see Fig. 3). As the length of the elective sub-session increases so the probability of being deferred increases, as in Fig. 10, and a 2 hours elective list implies a probability of the patient being deferred of 15%.

6. Exploring the patient selection criteria

The results of the experiments reflect local conditions and practice as summarised in the simulation's assumptions. In particular different doctors and hospitals may well adopt alternative selection criteria when selecting patients. The sensitivity of the results to the assumptions about the selection criteria was explored by comparing the consequences of adopting two selection schemes: controlled (employing a longest first priority rule) and random. A random selection of patients introduces a bias towards those requiring shorter procedures, as illustrated by the mean procedure times of Table 1. Selecting a large proportion of shorter procedures could distort the distribution of the procedure times of the remaining elective patients being treated in the conventional elective sessions making it more difficult to schedule these sessions efficiently.

Table 1
Mean procedure time (minutes) of selected elective patients

	Scheduled elective hours = 2	Scheduled elective hours = 4
All elective patients	70.8	70.8
Controlled selection	79.1	106.6
Random selection	41.3	51.7

Figs. 9 and 10 include the results of varying the length of the scheduled elective list using the random selection rule. The effect on the mean utilisation, and the additional elective hours, is small: the principle of mixing elective patients in trauma sessions does not appear to be dependent on the local practice and the method of selecting patients. However, the probability of being deferred is affected by the method of selection. Assuming a two hour elective list, the probability of being deferred can be reduced from 15% to 12% by adopting a random selection scheme rather than the controlled selection; if a four hour list is employed, the probability of deferral can be reduced from 27% to 20% by adopting different selection criteria. This is a consequence of the very different characteristics of the elective patients treated under the two selection regimes: the random selection results in the treatment of more patients but with shorter procedures. If the trauma demand is high and encroaches upon the elective list this can have a dramatic effect with a high proportion of the scheduled activity having to be cancelled if the list consists of one or two patients with long procedures, as in the case of the controlled selection. However, a theatre list based on a random selection typically contains more, shorter procedures and the consequences of a high trauma demand are less dramatic with a lower proportion of the scheduled procedures having to be deferred.

7. An alternative to simulation

While simulation is well established [5,9] as a methodology for analysing the organisation of health care, suitably skilled staff may not be readily available and a simpler approach is sometimes desirable [13]. An alternative approach to modelling the effect of mixing trauma and elective patients was explored by adopting approximations enabling the use of a simple numerical spreadsheet to analyse options for the design of trauma sessions. The approximate model depends on two critical assumptions:

(i) The probability distribution of the non-elective theatre time requirement can be estimated by the empirical frequency distribution.
(ii) The utilisation of a short elective theatre list will be the same as that of a longer 3.5 hours theatre list.

The assumptions were validated in a comparison of results with the more accurate simulation model, as reported later.

The alternative model considered:

L length of the complete theatre session (7 hours in the present example)
X_0 theatre time allocated for elective patients
X actual theatre time available for elective patients, once trauma patients have been treated
T theatre time requirement for trauma procedures

Then

$$X = \begin{cases} X_0 & \text{for } T \leqslant L - X_0, \\ L - T & \text{for } L - X_0 \leqslant T \leqslant L, \\ 0 & \text{for } L \leqslant T, \end{cases} \tag{1}$$

$$\begin{aligned} \therefore \quad E[X] &= \int_{T=0}^{L-X_0} X_0 f(T)\,\mathrm{d}T \\ &\quad + \int_{T=L-X_0}^{L} (L-T) f(T)\,\mathrm{d}T \\ &= X_0 P(T \leqslant L - X_0) \\ &\quad + \int_{T=L-X_0}^{L} (L-T) f(T)\,\mathrm{d}T. \end{aligned} \tag{2}$$

The relative frequency distribution of Fig. 3 was employed as an approximation to $f(T)$. Assuming 255 trauma sessions per year, $L = 7$ hours, the expected extra elective hours p.a. were estimated for different values of X_0. For example, if 2 hours of elective treatment are scheduled the approximate model suggests that the expected number of actual elective hours available is 451 p.a. rather than the $2 \times 255 = 510$ hours suggested by ignoring the possibility of the trauma requirement exceeding 5 hours per day. Scheduling 4 hours of elective treatment per day in the trauma sessions would provide 730 expected elective hours, rather than $4 \times 255 = 1020$ hours which might be estimated if the excessive trauma demands were ignored.

In practice it will not be possible to achieve 100% utilisation of the additional elective hours; the utilisation depends on both local practice, e.g. the attitude of the staff, and the inherent difficulty of scheduling activities with a significant degree of uncertainty about their duration. A detailed study of elective orthopaedic procedures at a typical hospital with 3.5 hours orthopaedic elective theatre sessions indicated a mean utilisation (U_e) of 86%. Discussions at other hospitals suggests that this figure is reasonable though theatre utilisations vary considerably and are dependent on many factors including the specialty, the surgeon and the anaesthetist. Scheduling a short 2 hours list could be more problematic than a 3.5 hours list and lower utilisations may be experienced. Lacking any more empirical data, the utilisation of the elective time was assumed independent of its length. This assumption could be the source of discrepancies when comparing the utilisations with those obtained by simulation.

The total utilisation (U) of the trauma session was estimated as

$$U = \begin{cases} \frac{T + U_e X}{L} & \text{for } T \leqslant L, \\ 1 & \text{for } T \geqslant L, \end{cases}$$

i.e. if the session overruns due to a very high trauma demand the utilisation is recorded as 100%. (The excess time $T - L$ could then be noted as an overrun and the expected overrun estimated to support an investigation of the appropriate value of L.)

$$\therefore \quad E[U] = \int_{T=0}^{L} \frac{T + U_e X}{L} f(T)\,\mathrm{d}T + \int_{T=L}^{\infty} f(T)\,\mathrm{d}T.$$

Given the value of X for the different ranges of T as noted in (1):

$$\begin{aligned} E[U] &= \int_{T=0}^{L-X_0} \frac{T + U_e X_0}{L} f(T)\,\mathrm{d}T \\ &\quad + \int_{T=L-X_0}^{L} \frac{T + U_e(L-T)}{L} f(T)\,\mathrm{d}T \\ &\quad + \int_{T=L}^{\infty} f(T)\,\mathrm{d}T. \end{aligned} \tag{3}$$

Employing the empirical relative frequency distribution of Fig. 3 as an approximation to $f(T)$ again and assuming $L = 7$ hours and $U_e = 86\%$ for all X, the total expected theatre utilisations were estimated for various X_0 and recorded in Fig. 9 as "integration approximation". The results are very similar to those obtained in the simulation experiments also noted in Fig. 9. Inevitably the results are dependent on local practice: the estimates of the overall theatre utilisation are sensitive to the value of the mean elective utilisation. Assuming $X_0 = 4$, $U_e = 80\%$ implies an estimate of the overall theatre utilisation of 72%, compared to 82% when $U_e = 86\%$ and 84% if $U_e = 90\%$.

A simple estimate of the probability of an elective patient being postponed was also obtained by making the further simplifying assumption that the mean number of elective patients scheduled for treatment as part of the trauma session N_0 is proportional to the time allocated for elective patients X_0, and that the mean number of patients completing their treatment $E[N]$ is similarly proportional to the mean time actually available $E[X]$. Hence the proportion of patients having their treatment deferred is:

$$\begin{aligned} \mathrm{P}(\text{patient deferred}) &= 1 - \frac{E[N]}{N_0} \approx 1 - \frac{E[X]}{X_0} \\ &\approx 1 - \Bigg(\mathrm{P}(T \leqslant L - X_0) \\ &\qquad + \int_{T=L-X_0}^{L} \frac{(L-T)}{X_0} f(T)\,\mathrm{d}T\Bigg). \end{aligned} \tag{4}$$

Again using the relative frequency distribution of Fig. 3 as an approximation to $f(T)$, the probability of an elective patient being treated was estimated for a range of values of X_0. Fig. 10 depicts the increasing probability of postponement as the scheduled elective time in the trauma session is increased: the results using the "integration approximation" are very similar to those of the simulation experiments assuming a "random selection" of patients suggesting that the approximations are reasonable.

In practice the distribution of Fig. 3 may not be readily available, in which case the method can be simplified further by adopting a single year's trauma activity as an approximation of $f(T)$ without introducing any major error. For example, the calculation of the extra elective hours per year given a scheduled 2 hours list per session was undertaken using a single year's trauma demand. The calculation was repeated using 100 years of generated trauma demand and the extra elective hours noted at each iteration. The mean extra elective hours obtained from using individual years' data was 390 p.a., with a standard deviation of 6.3 hours p.a., compared with the expected extra elective hours of 388 p.a. derived when using the distribution of Fig. 3.

8. Conclusions

Simulation provides a method for examining the design of orthopaedic trauma theatre sessions and the trade-off between utilisation and overrunning. The utilisation of trauma sessions can be increased by scheduling orthopaedic elective patients within the sessions. Patients being treated in this manner will have to accept a probability of being postponed but given the possibility of earlier treatment this should be an attractive option for many. In the example of a typical District General hospital in the United Kingdom, if a probability of postponement of 15% is acceptable a 2 hours elective list can be scheduled as part of the weekday 7 hours trauma session. The elective capacity generated by adopting this policy could satisfy 13% of the annual demand for orthopaedic elective theatre treatment in the typical hospital. While the precise results depend on assumptions about the patient selection criteria, the sensitivity is not great and principle of mixing elective and trauma patients appears to be robust. Simulation is needed when exploring the detailed effects of local practice but an alternative, simpler model offers very similar results despite various approximations. The simpler model is more readily implemented and appropriate for many practical planning purposes.

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