Application and comparison of two modelling techniques for hospital bed management

MARK MACKAY AND PETER H MILLARD

Mark Mackay is Chief Consultant with the Economics and Finance Business Improvement Unit of the South Australian Department of Human Services.
Peter H Millard is the Eleanor Peel Professor of Geriatric Medicine at St George's Hospital Medical School, London.

Abstract

The use of the bed occupancy management and planning system (BOMPS) and the Sorensen multi-phased bed model were used to assess the implications of a hospital expanding its emergency facility. BOMPS flow modelling generates resource utilisation data dependent on the best visual and statistical fit between mixed exponential equations and time of bed occupancy; the Sorensen model creates models based on probabilities and length of stay distributions. Both models identified the presence of two streams of flow. However, there were differences in the number of beds identified as being short and longer stay. The advantage of flow modelling is that it enables decision-makers to pre-test their decisions.

Introduction

Health care providers are experiencing continued pressure to achieve increased activity levels while reducing expenditures (Clerkin, Fos & Petry 1995; Duckett 1995; McClean & Millard 1995; Duckett 1998). Quantitative modelling methods have been developed by Harrison and Millard (1991); Harrison (1994); McClean and Millard (1995a, 1995b), and Sorensen (1996) to assist health care managers, clinicians and planners manage hospital beds. While such methods are designed to appeal to hospital managers or health planners, it has been suggested that health workers will resist the use of such methods and continue to use rule of thumb models when planning for bed changes in health care settings (Xiao-Ming 1995).

Quantitative modelling provides hospital managers and policy makers with the possibility of analysing the effects of changes prior to actual implementation. In recent times quantitative modelling has been applied to bed management (Clerkin, Fos &

Petry 1995; Gove, Hewett & Shahani 1995; McClean & Millard 1995a, 1995b; Xiao-Ming 1995; Sorensen 1996). Simulation and queuing or flow rate modelling techniques can be applied to bed management problems (Xiao-Ming 1995; El-Darzi et al. 1998).

The management and planning of inpatient hospital bed use continues to be subject to a lack of rigorous determination, despite the widespread use of quantitative modelling techniques in industry. The implications of opening or closing beds, or changing the type of services provided, are consequently not fully investigated prior to implementation. The ramifications for inpatient activity and financial costs are therefore unlikely to be appreciated fully at the time of change.

This article compares the use of the bed occupancy management and planning system (BOMPS) developed at St George's Hospital in England to the multi-phased bed modelling model proposed by Sorensen (1996) applied to a bed management scenario involving an Australian emergency patient data set. The models were used to assess the implications of a hospital expanding its emergency facility. The proposed facility was to provide additional emergency capabilities to support a larger nearby hospital and be limited to four beds. The demand for non-complicated emergency cardiac services was seen as warranting the establishment of emergency services to treat a limited number of patients suffering symptoms that included chest pain. In order to avoid a duplication of services within the geographical area, this facility was not intended to provide a fully equipped cardiac emergency service.

The authors detail why modelling of beds should occur and describe two techniques that were used to model bed numbers for the proposed expansion of emergency services. The results of the analysis are presented, followed by a discussion of the advantages and disadvantages of each modelling technique. Areas of future research are also identified.

Why model?

Inpatient activity has traditionally been described using measures such as the simple average length of stay and the turnover per bed (Harrison & Millard 1991). Average length of stay is calculated in two ways. The lengths of stay of discharged patients are summed and divided by the number of discharges. Alternatively, the number of discharges or admissions can be multiplied by 365 and divided by the bed allocation or the percentage bed occupancy. The flaw with these simple measures is that patient length of stay is skewed. A possible explanation for this skew is the existence of one or more patient sub-groups having a longer length of stay than the other patients. For example, a patient population may be made up of acute, medium and long length of stay patients. Furthermore, both methods ignore the fact that a proportion of the beds may be unavailable for throughput, because they are occupied by long stay patients. Consequently, managers and clinicians cannot make fully informed decisions based upon these simple formulae.

Quantitative modelling is used by a range of health professionals. The function of such modelling should provide clarification to decision-makers (Williams 1995). Such modelling should also provide managers and clinicians with tools that result in improved decision-making in relation to the prediction of inpatient bed numbers.

Quantitative modelling

Multi-phased bed modelling

Sorensen (1996) has developed a technique called multi-phased bed modelling that aims to provide health care professionals with simple models that can be used to determine inpatient bed requirements. The model proposed by Sorensen relies on simple mathematical formulae and defining the stages or phases of admission through which a patient passes after admission to a hospital. These phases are based upon the length of stay. Sorensen's model is an extension of the model applied to a bed planning problem for an acute and psychiatric hospital by Pendergast and Vogel (1988).

Sorensen identifies four phases through which a patient may pass: same-day patients, short stay inpatients, extended stay inpatients and long stay inpatients. The flow of patients through the various stages of the model is dependent upon their length of stay. Patients only flow out of the model if one of three conditions is satisfied, namely: discharge home, discharge to another institution or death. The model is illustrated in Figure 1.

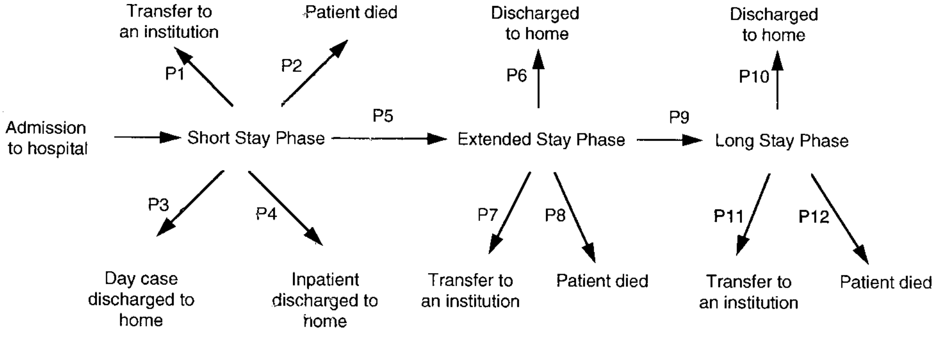

Figure 1: Patient flows in the multi-phased bed model (Sorensen 1996).

Given historic event data, the probability of events or pathways and the outcome of the patient admission can be determined. The identification and representation of the pathways enable hospital managers to consider the ramifications of:

- being able to discharge patients earlier (for example by transferring the patient to another institution), and
- patients being unable to be discharged as a consequence of changes at external organisations (for example, other institutions no longer being willing to accept patients due to budgetary constraints).

The model proposed by Sorensen has been modified for this study to overcome potential pitfalls that may arise due to the differences between the European and Australian health care systems. The Sorensen model mixes same-day patients with separation pathways. It is suggested that the mixing of patient inflows and outflows is not appropriate in this instance, because the admissions are unplanned. Consequently, the need to identify beds for planned same-day admissions does not exist. To overcome this, three strategies could be adopted, namely:

1. exclude same-day patients from the model, as same-day beds are specifically set aside from other inpatient beds and are not staffed for patients requiring overnight admission
2. create a dichotomous model based upon the types of admission, with one branch of the model for same-day patients and the other branch of the model for patients admitted overnight, or
3. include same-day patients with short-stay patients as in-flows to the model.

We adopted the third approach, because the patient group consisted of emergency patients. Unlike elective patient admissions, emergency patient admissions are not planned, thus while some patients may be admitted and discharged on the same day, the provision of separate same-day beds will not occur. Had this analysis been related to elective activity, the option chosen would have depended on whether same-day patient beds were separate from other inpatient beds.

One of the benefits of the Sorensen model is that it identifies the ramifications of bed blockages. However, confining the model to three potential destinations upon discharge (death, other institution or home) prevents analysis of the effects of changes, such as changes in the provision of external institutional care, on the number of hospital beds required. Consequently, we expanded the pathways proposed by Sorensen to identify all the actual patient destinations following separation.

BOMPS modelling

BOMPS modelling is based on an observation that the pattern of current occupancy data can be well fitted by curves generated using mixed exponential equations. Mixed exponential modelling forms the basis of BOMPS (Harrison & Millard 1991). BOMPS is an MS-DOS decision support system (a new Windows version is currently being written) that is the culmination of over 20 years of work by Millard at a London teaching hospital in collaborative research with Harrison and McClean (Millard & Harrison 1991; Harrison 1994; McClean & Millard 1995a, 1995b).

The mixed exponential equations are used to create performance measures concerning the compartments through which inpatients may flow. The equations reflect actual bed occupancy patterns for a single day if based on data collected for a single day (census approach) or the average occupancy if the data is for an extended period such as a year (average census approach). The compartments do not represent physical locations within the hospital, but represent periods of time for which patients are admitted.

There are three possible compartments, namely: the first compartment, the second compartment and the third compartment. The number of compartments used in a model is determined on the basis of the number of exponents required to obtain the best mathematical fit of the underlying actual data. BOMPS provides three models of patient flow:

- a single-compartment model (where all patients have the same length of stay)
- a two-compartment model (where there are short and long stay patient populations), and
- a three-compartment model (where there are short, medium and long stay patient populations).

All patients enter the model at the same point, that is, the first compartment. Assuming the model has more than one compartment, patients either flow on to the second compartment, die or are discharged. Similarly, if a third compartment exists, patients will flow on to the third compartment, die or be discharged. Following admission into the third compartment patients either die or are discharged. The flow of patients through the model is illustrated in Figure 2.

Performance measures that are generated by the software include the overall estimated (exponential) average length of stay and the size, rates of flow and conversion rates between short stay, medium stay and long stay compartments. The benefit of exponential analysis of occupancy data is that it identifies the components of the current inpatient workload and facilitates the development of dynamic models (Harrison 1994).

The software enables what-if scenarios to be modelled to enable bed planning to occur prior to making changes to actual bed arrangements. We used the software to model the possible impact on patient flows through a four-bed emergency service unit designed for patients having the same profile as those in the original data.

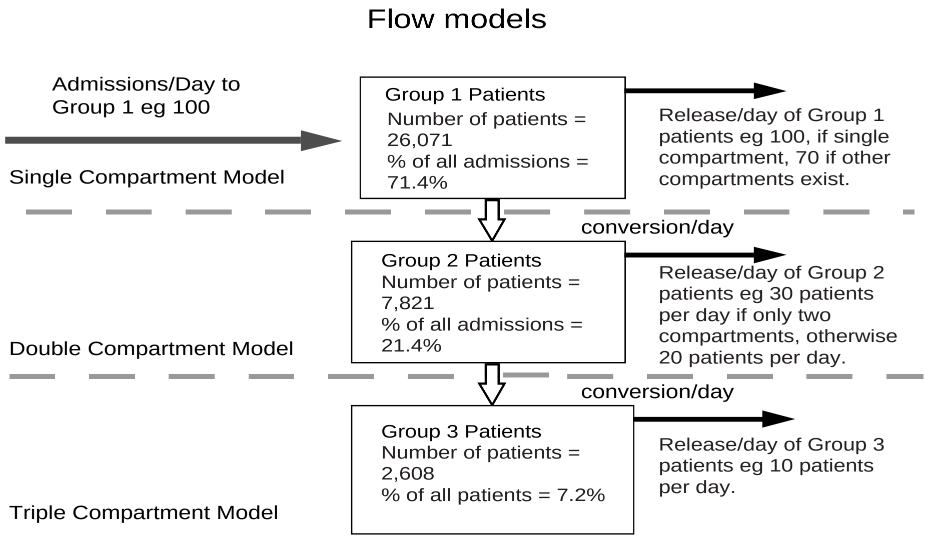

Figure 2: Patient flows in the bed occupancy management and planning system. The dashed lines separate the compartments through which patients may flow.

Methodology

Patient information for the 1997–98 financial year was obtained from the Integrated South Australian Activity Collection database pertaining to emergency patients that may have presented with chest pain at a large public hospital. Patients with chest pain may belong to various clinical groups. Data extraction on the basis of wards or clinical specialities was not appropriate as this would have captured patients who did not relate to the study, that is, those who did not present with chest pain symptoms.

Patients with respiratory, cardiac or gastric problems may present with chest pain. The Australian national diagnosis-related groups (AN-DRGs) enable benchmarking of resources used in the provision of services for homogeneous groups of patients. While the AN-DRGs are not designed to provide hospital managers or clinicians with bed planning information they are designed to categorise patients using clinical information that results in groups of patients with homogenous resource usage. This data is widely used and consequently, data was extracted on the basis of AN-DRGs that included chest pain as a likely symptom. The bed modelling approaches do not rely upon the need for homogenous resource usage as they are not concerned with resource usage, but with determining bed numbers.

Patients discharged following admission for chest pain should be assigned to the AN-DRG version 3.0 (V3) 261. The AN-DRG classification was based upon the

International Classification of Diseases, 9th Revision, Clinical Modification (ICD-9-CM). While patients assigned to AN-DRG 261 present with chest pain, patients assigned to other DRGs may also present with symptoms that include chest pain. Consequently, it was also necessary to extract data relating to other DRGs where emergency patients may have presented with chest pain. Clinical opinion was sought to obtain a list of AN-DRGs that included chest pain as a likely symptom and that would result in patients being sent to the proposed emergency facility for examination.

The data analysis and modelling was based upon all the patient information extracted and not just that relating to AN-DRG 261.

The patient information extracted included the following details:

- date of admission
- date of discharge
- day of admission
- DRG category
- admission category (elective or emergency)
- source of admission (for example, transfer from another hospital, referral by the patient's general practitioner)
- destination upon discharge (for example, discharged home, self-discharged, died, transferred to another hospital, transferred to a nursing home)
- patient age, and
- patient gender.

Statistical information pertaining to the emergency patient sample was obtained using SPSS for Windows V8.0.0, a statistical package. The data was then converted into a Paradox V3 format and loaded into the BOMPS E-fit (exponential fitting) and what-if modules for further analysis. The E-fit module was used to derive the exponential equation based upon the dates of admission contained in the database. The time in days that have elapsed since admission is calculated and the best-fit curve is determined. The model that obtained the highest R-squared value and lowest sum of squares value was chosen. The parameters of the best-fit equation were then used to generate resource usage statistics for each compartment and the overall model.

A Microsoft Excel V5.0c spreadsheet was used to construct the multi-phased bed model articulated by Sorensen (1996) using the same data. The various phases of the model are based upon an arbitrary grouping of patients on the basis of length of stay. The decision as to how patient groups should be established was therefore based upon the cumulative frequency distribution and the average length of patient stay in the first compartment (3.56 days) of the BOMPS model. Based on the distribution of length of stay at discharge in Figure 2, a decision was made to group the patients into one of two groups:

- those staying four days or less (phase 1), and
- those staying more than four days (phase 2).

Also, the use of two patient groups rather than three patient groups facilitated comparison of the two modelling methods.

Results

Profile of Sample

The statistical profile of patients contained in the sample is detailed in Table 1 and is based on historical data from the 1997–98 financial year analysed using SPSS for Windows.

Table 1: Profile of emergency patients that may have presented with chest pain

Statistical profile of the emergency patient sample	Number	Percentage of Total
Historical data		
Number of same-day patients	103	8%
Number of patients admitted for overnight (one day)	282	23%
Number of patients admitted two or more days	830	68%
Total number of patients	1 215	100%
Average length of stay (including same-day)	3.45	
Standard deviation of length of stay	3.91	
Maximum length of stay	46	
Average length of stay (excluding same-day)	3.77	
Standard deviation of length of stay	3.94	
Total admissions by day of week		
Sunday	161	13%
Monday	196	16%
Tuesday	181	15%
Wednesday	163	13%
Thursday	186	15%
Friday	150	12%
Saturday	178	15%
Repeat admissions		
Number of patients admitted two or more times	600	49%

Note: based upon all admitted patients (same-day included)

While the average length of stay for this group of patients is not long (regardless of whether same-day patients are included or excluded), it is skewed as indicated by the standard deviation being greater than the average, as shown by the frequency distribution in Figure 3.

Based upon the cumulative frequency distribution (refer to Figure 4), approximately 80% of patients have an average length of stay of four days.

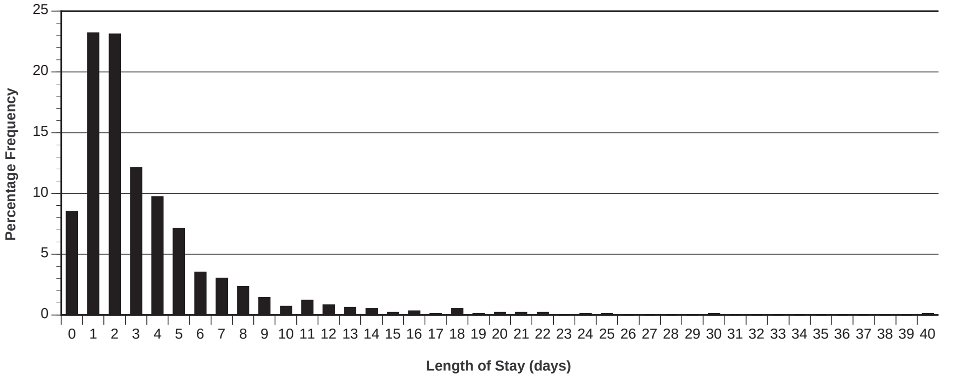

Figure 3: Frequency distribution of the length of stay for the sampled patients

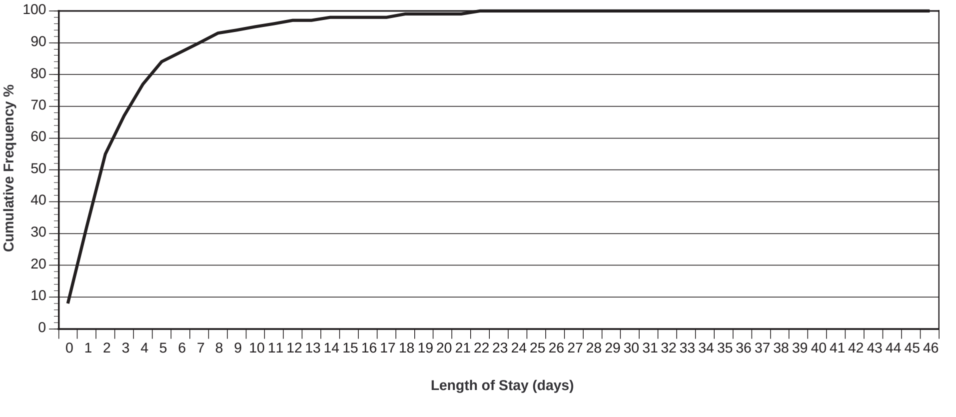

Figure 4: Cumulative frequency distribution of inpatient length of stay

Almost half the patients were admitted more than once during this financial year. The additional admissions may or may not relate to the original reason for the patient's presentation to the hospital.

Admissions for this group of patients were found to be reasonably even on all days. Based on the available data it would be necessary to provide a seven-day emergency facility for this group of patients.

The number of occupied beds is detailed in Figure 5. The seven-day moving average is also shown and this highlights the trend in occupied bed number changes. The number of occupied beds varies throughout the year. At no time of the year, however, were there any unoccupied beds.

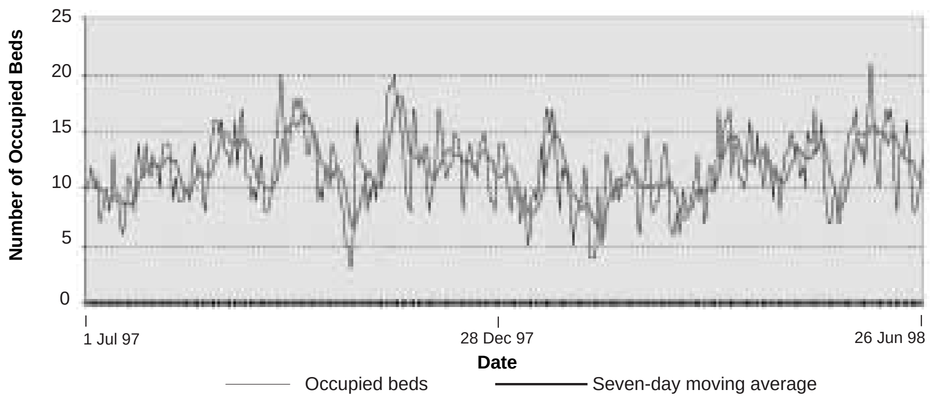

Figure 5: Number of occupied beds and the seven-day moving average

BOMPS model

A two-compartment model was found to best describe the profile of the patients contained in the sample. The equation for the model is given by a double exponential equation in the form of:

$y = Ae^{-Bx} + Ce^{-Dx}$

where x is the patient's length of stay in days, up to the present, and y is the number of patients who have been admitted for at least x days. A, B, C and D are empirical parameters that are computed to provide the equation with the least-squares best-fit to the observed values (Harrison & Millard 1991). For the data, it was found that:

A = 12.8893	standard error = 0.467523
B = 0.3302	standard error = 0.010004
C = 2.0295	standard error = 0.481466
D = 0.1072	standard error = 0.012901

Least squares = 0.2258

Coefficient of multiple determination (R^2) = 0.9994

The BOMPS program provides two statistics to enable the user to determine how well the model predicts the observed data. The least square value was minimised during the modelling process and was reported as 0.2258, indicating that the model predicts the observed data well.

The coefficient of multiple determination (R^2) indicates the proportion of the bed number variance explained by the model. The range of R^2 is 0 to 1. The model explained 99.9% of the variance in bed numbers. Thus, the model should predict the requirement for beds for the sampled patients very well.

Based upon the BOMPS model it would appear that 14.9 beds are required for this patient group. To overcome the stochastic nature of admissions and the fact that patients are not admitted as mathematical fractions, a 16-bed emergency facility or unit would actually be required (that is, for compartment one, 13.6 beds would become 14 beds and for compartment two, 1.3 beds would become 2 beds). The patient flow rates and bed requirements obtained from the BOMPS model are detailed in Tables 2 and 3, and illustrated in Figure 6.

Table 2: Summary statistics for the BOMPS model

		General information			
Health agency or region	**Labels**	**Admissions (day)**	**Admissions (year)**	**Average stay (days)**	**Average daily occupied beds**
Chest pain 1997–98 model	A	3.8	1,398	3.9	14.9
Actual data	A1	3.3	1,215	3.5	11.7
Difference (A-A1)	A2	0.5	183.3	0.4	3.3
Percentage difference (A2/A1 x100)		15%	15%	13%	28%

Note: based upon all admitted emergency patients (same-day emergency patients are included).

Table 3: BOMPS compartment statistics

Health agency or region	Chest pain 1997–98 model	Percentages	Actual data	Percentages
Labels	A		A1	
First compartment				
Number of patients discharged (%)	1350	(97)	1191	(98)
ALOS for patients discharged	3.1		3.1	
Average stay (days) for all patients	3.6		3.3	
Number of beds used (%)	14	(91)		
Second compartment				
Number of patients discharged (%)	48	(3)	24	(2)
ALOS for patients discharged	9.8		6.7	
Number of beds used (%)	1	(9)		
Reliability statistics				
Sum of squares	0.2258			
R-square	0.999464			

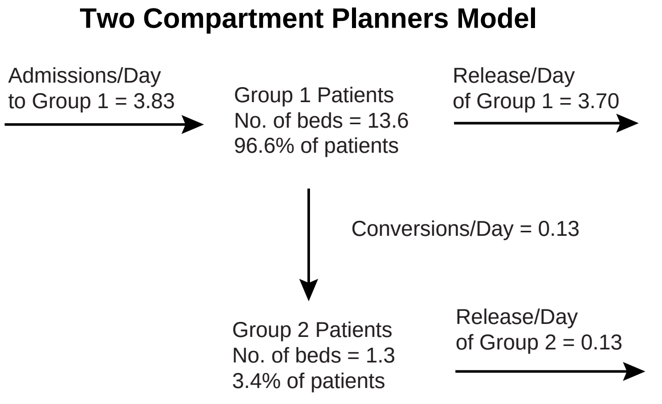

Figure 6: BOMPS model describing the flow of the sampled patients

Multi-phased Sorensen bed model

Table 4 details the various patient separation pathways identified for the study patient population, together with the probability of separation, the average length of stay and calculated bed numbers. The multi-phased bed model is illustrated in Figure 7.

Table 4: Probability of patient pathways and required bed numbers

Group	Pathway	Nature of patient separation	Number of patients	Probability of separation	Average length of stay	Calculated number of beds required
1	P1	home	877	0.722	1.9	6.36
1	P2	other hospital – up transfer	7	0.006	1.9	0.05
1	P3	nursing home or hostel	19	0.016	2.3	0.17
1	P4	died	8	0.006	1.1	0.03
1	P5	other hospital – down transfer	5	0.004	2.2	0.04
1	P6	self discharge	15	0.012	0.9	0.05
2	P8	home	263	0.216	8.3	8.32
2	P9	other hospital – up transfer	2	0.002	7.5	0.06
2	P10	nursing home or hostel	6	0.005	13.2	0.3
2	P11	other hospital – down transfer	7	0.006	12.6	0.34
2	P12	other health care accommodation	2	0.002	7	0.05
2	P13	self discharge	1	0.001	12	0.05
2	P14	died	3	0.002	15.3	0.18
Total			1 215	1	3.5	16

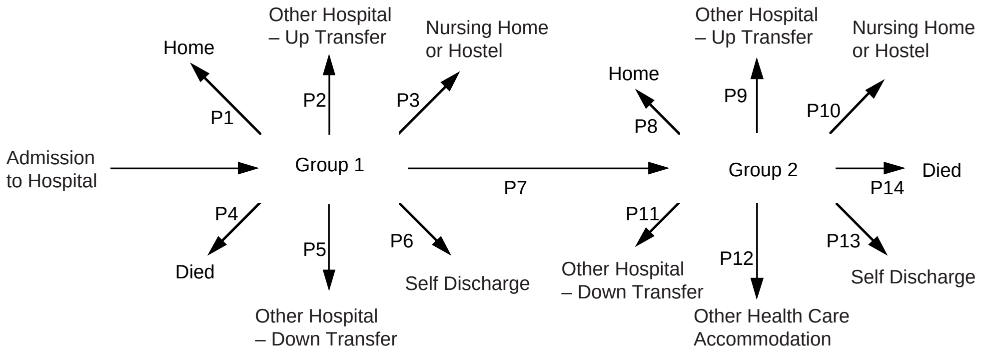

Figure 7: Pathway model describing patient flow

Approximately 23% of patients were discharged (or died) from phase 2 (pathway P7) of the model. The summary statistics for the model are presented in Table 5.

Table 5: Sorensen phase statistics

Health agency or region	Chest pain 1997–98 model	Percentages	Actual data	Percentages
First phase				
Number of patients discharged (%)	931	(77)	931	(77)
ALOS for patients discharged	1.9		1.9	
Number of beds used (%)	6.7	(42)	4.8	(42)
Second phase				
Number of patients discharged (%)	284	(23)	284	(23)
ALOS for patients discharged	8.6		8.6	
Number of beds used (%)	9.5	(58)	6.7	(58)

What-if scenario

In order to test the usefulness of the models, the models were used to assess the implications of a different hospital establishing an emergency facility to treat a limited number of patients suffering symptoms that included chest pain. The number of beds available at the alternative facility was limited to four inpatient beds.

Using the BOMPS what-if module, the number of available beds required was reduced to four to determine a model to describe the proposed scenario. This model is detailed in Table 6 and Figure 8.

Table 6: BOMPS profile of patient flows based on the what-if scenario modelling

Modelled data	
Group 1 – short stay patients	
Total beds required per day	3.7
Proportion of all patients	97%
Expected length of stay	3.56
Patient release rate per day	0.99
Conversion rate from group 1 to group 2 (patients per day)	0.04
Group 2 – medium stay patients	
Total beds required per day	0.4
Proportion of all patients	3%
Expected length of stay	9.84
Patient release rate per day	0.04
Overall	
Patients admitted and discharged per day	1.03
Total beds required	4
Admissions per year	375

Note: based upon all admitted patients (same-day included)

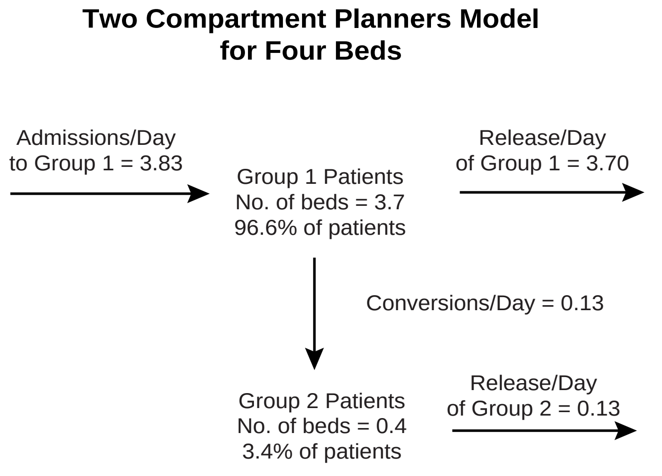

Figure 8: BOMPS model of patient flows for a four-bed scenario

The BOMPS model was based upon a four-bed unit, however, at a practical level, such a unit would require five beds, because on some occasions there would be an overlap of medium and short stay patients. Alternatives to establishing a five-bed unit include using existing beds in other wards at the hospital, or transferring the fifth patient to another hospital.

Using the Sorensen multi-phased bed model, it was determined that 1.7 beds would be required for the Phase 1 or short stay patients and 2.3 beds would be required for the Phase 2 or medium stay patients.

Differences between the models

The two models provide different information in relation to a number of parameters. The proportion of patients allocated to each group varies as detailed in Table 7.

Table 7: Proportion of patients allocated to each group

	Sorensen model	BOMPS model	Difference
Phase 1/Group 1	72%	97%	–25%
Phase 2/Group 2	28%	3%	25%

Note: figures are based upon ALOS = 3.56 days

The figures in Table 7 are based upon an average length of stay of 3.56 days for patients assigned to group 1 of the BOMPS model, thus the proportions for the multi-phased bed model phases have been interpolated. The difference between the actual patient numbers assigned to the groups or phases for each model was tested for significance using a chi-squared test. The difference was found to be significant (calculated $\chi^2 = 270.8$, $\chi^2_{(\chi=0.05,1)} = 3.84$).

Given the difference in the number of patients distributed between the two equivalent sections of the two models, it was not unexpected that differences between the models were found with respect to the average length of stay and the number of beds required by each group (refer to Tables 8 and 9).

Table 8: Average length of stay of patients assigned to each group

	Sorensen model	BOMPS model	Difference
Phase 1/Group 1	1.89	3.56	–1.67
Phase 2/Group 2	8.57	9.84	–1.27

Table 9: Number of beds assigned to each group

	Sorensen model	BOMPS model	Difference
Phase 1/Group 1	1.67	3.70	–2.03
Phase 2/Group 2	2.34	0.40	1.94

While the overall number of beds required under the what-if scenario was the same for both models (it was a given condition), the different proportions of patients assigned to each group have differing resource implications.

Table 10 details the length of stay when 50% and 75% of patients from the first group or phase from each model were discharged and the actual cumulative data.

Table 10: Comparison of predicted discharge length of stays

Proportion of patients discharged from group or phase 1	Sorensen model	BOMPS model	Actual data
50% of patients discharged	2	2.0989	2
75% or patients discharged	3	4.1978	4

The Sorensen model accurately predicts the length of stay when 50% of patients are discharged, but is considerably less accurate when 75% of patients are discharged. The BOMPS model, however, closely predicts the actual length of stay when 50% and 75% of patients are discharged. The inaccuracies associated with the Sorensen model may be expected, given the subjective nature of determining the groupings. Furthermore, the BOMPS model is based upon an exponential function, which mirrors the way that the number of patients remaining in hospital decreases as length of stay after admission increases, and thus should be expected to predict the length of stay for specified clearances of patients from the hospital system.

Discussion

The use of modelling in relation to bed planning

As in industry, the modelling of inpatient activity to determine bed numbers could provide useful information for health agency managers and health service planners, particularly in relation to strategic planning or change planning exercises. While simple formulae based on average length of stay may be of use as a general guide when determining the number of beds required, a simple average length of stay oversimplifies the complexity associated with different types of patients, skewed length of stay and separate patient flows. So it may result in poor decision-making, especially in light of the available information collected by most health agencies.

Modelling, as undertaken by the authors, not only identifies patient flows and bed numbers, but highlights sources of bed blockages resulting from either long staying patients or factors external to the hospital. The identification of different patient flows will also provide clinicians with a new opportunity to explain why some patients require a longer stay in the health unit compared to other patients. Also, discussion can be focused on what actions, if any, could be offered to reduce the number of longer stay patients. The existence of different patient groups may also serve to reinforce that humans are not machines. Natural healing processes cannot be constantly reduced in order to meet the financial constraints of health systems (Millard 1998).

The most important aspect of modelling is that it provides hospital managers and clinicians with the opportunity to test planned changes prior to implementation. For example, the expansion or reduction in bed numbers will alter the number of patients admitted at any one time, but how long after the change to bed numbers has occurred will it take for admissions to stabilise, *ceteris paribus*? What happens if the expected length of patient stay declines? What are the ramifications of reducing the number of longer staying patients as a consequence of better or different treatment? The use of modelling enables such questions to be answered before changes are actually implemented and to determine the expected changes to admission numbers and bed requirements. Such information can allow managers and clinicians to more properly plan for change.

The development of the models described in this article can enable both central agency staff and health unit staff to gain a better understanding of the likely patient admissions, patient flows and potential sources of bed blockage resulting from the planned addition of emergency beds. Such information may facilitate more meaningful discussions between health agency staff and central staff when planning changes to health service delivery.

Differences between the models

BOMPS modelling has been used to model patient behaviour in a geriatric department for the period from 1969 to 1984 and was found to predict patient turnover reasonably well (McClean & Millard 1993). A strength of exponential fitting of occupancy data is that it focuses attention on the use being made of beds by longer-term patients. However, a weakness is that it generates admission data based on the estimation of flow rates occurring on one day. In this study we used an average daily census over the year and the relationship between observed admissions of 1215 in Table 1 and the modelled predictions of 1398 in Table 2 is close. Based upon the results obtained thus far, together with the application of statistical tests, flow modelling would appear to be reasonably robust.

The three main differences between the two models are:

- the use that they make of length of stay
- how patients move through the model, and
- the way that the results are generated, for the Sorensen model uses discharge data while the BOMPS model uses prevalence data.

In the BOMPS model, bed occupancy and use is predicated on length of stay after admission being exponentially distributed. In the Sorensen model, length of stay is considered to be normally distributed. This fundamental difference in the approach to measuring length of stay explains the differences between the bed utilisation forecasts in the two models.

The BOMPS model is a flow model, which means that all patients enter at one point and then proceed through the various compartments. The Sorensen model, however, is not a true flow model. Although patients appear to flow through the Sorensen model, the actual method of calculation prescribed by Sorensen (1996) is based upon patients being allocated to a phase upon the basis of length of stay and discharge destination. This is evidenced by the fact that the probabilities for the entire model sum to one, rather than the probabilities for phase 1 plus the probability of moving to phase 2 summing to one, and the probabilities of phase 2 summing to one. The absence of true patient flow through the Sorensen model places limitations upon the ability of modellers to conduct extensive what-if analysis compared to BOMPS modelling.

Advantages of using BOMPS in relation to bed planning

The limitation of resources in a public service sector that is experiencing increasing demand due to the ageing of the population, combined with the increasing expectations of the consumers and the emotive nature of health care, places managers in circumstances where increased scrutiny of decisions is likely. Consequently, decisions affecting the allocation of beds must be defensible. The benefit of using theoretical models of patient flow, such as BOMPS, to underpin decision-making is that hospital managers will have an explanatory tool, underpinned by theory, that they can use to pre-test the impact of their decisions. Such a tool should provide hospital managers with an improved information base on which to base discussions with clinicians prior to introducing changes to services.

The equations that underpin the BOMPS package not only provide managers with the number of beds required to service a given patient population, but enable them to gain an understanding of the various options available through the what-if modelling option. The interactions between the various patient streams and the duration that will be required to effect any changes to the service are also calculated, thus providing clinicians as well as managers with additional information.

The information required to analyse patient flows relies upon the existing patient management data which is readily available and does not require the collection of additional information. The information obtained by analysing occupancy can also be used in conjunction with other approaches to bed management (such as that proposed by Sorensen) or software packages (such as simulation software) to gain further insight into the patient flow (Sorensen 1996; El-Darzi et al. 1998).

The BOMPS package is currently available as shareware software and can be downloaded from the Internet. The cost of the software and the investment in time required to learn how to use the package is minimal and should not prevent the introduction of the software at any Australian or United Kingdom hospital.

Disadvantages with BOMPS modelling in relation to bed planning

Patient flow modelling may appear to be mathematically complex to those not used to basing decisions (especially those related to bed numbers) on exponential functions and half-lives. Also, introducing new methods of data analysis modelling does require expertise in the use of patient databases and statistics, which may deter some clinicians and health managers from investigating how the new methods of data analysis may be of benefit to them (Watt 1995). The data processing required to achieve output from BOMPS, however, can be performed by people without an elementary understanding of logarithmic functions and statistics, provided that sufficient training is made available by personnel with appropriate expertise. Many of the professionals employed in the health sector will have the necessary skills to interpret the resulting output.

While BOMPS was originally written as a research tool in 1991 for the MS-DOS environment and not the Windows environment, it can nevertheless be operated on systems using MS Windows or MS Windows 95. Consequently, it may appear to be user-unfriendly, especially to those used to working in a Windows environment. The package, however, is simple to operate and this should not deter managers and clinicians from using such a package. BOMPS is currently being upgraded to operate in a Windows or Windows NT environment, which should resolve any qualms users may have in relation to the operating environment.

Advantages with multi-phased bed modelling

The multi-phased bed modelling proposed by Sorensen (1996) enables the user to gain a good understanding of the potential bottlenecks that prevent patient discharge and result in bed pressures. The resulting model is mathematically quite simple in comparison to flow modelling and can be created in the Windows environment by anyone skilled in spreadsheet design.

Disadvantages with multi-phased bed modelling

The need for the manager to build a specific model in relation to each scenario to be examined is time-consuming. Not only does the data have to be collected, but probabilities of discharge must be determined and the model manually constructed. Additionally, the determination of the number of phases used in a model and the length of patient stay associated with each phase is subjectively determined, and this may reduce its validity.

While knowledge of exponential mathematics is not required, the construction of the model nevertheless requires an understanding of statistics and spreadsheets. The design of the model and the nature of the output are clearly affected by the skill of the modeller. Thus, staff skilled in advanced spreadsheet design are needed to undertake the modelling. Additionally, it is considered likely that clinicians and managers will be reluctant to invest time in developing such models, unless they already have an appreciation of the nature of patient discharge and wish to demonstrate it in a defensible manner.

A combined approach

Both models draw attention to the use being made of allocated beds by longer-term patients. Table 4 shows that an important determinant of bed availability and length of stay (even in patients presenting to a public hospital with acute chest pain) is the availability of alternative discharge accommodation.

In order to obtain the best long-term planning solution, the best compromise between the two approaches would be to combine the identification of patient discharge destination as in the Sorensen model and use the BOMPS model to model the flow of patients according to discharge destination. Given that the bed number and patient number output from the BOMPS modelling is additive, this would enable a comprehensive picture of hospital activity to be established. For small patient populations, however, it may not be possible to construct meaningful flow models for all discharge destinations. Reducing the number of discharge destinations by grouping similar destinations, or grouping on the basis of the number of patients discharged, may overcome this limitation.

The combination of approaches, that is, creating BOMPS models for patient groups selected on the basis of discharge destination, would enable clinicians and hospital administrators to consider the ramifications of attempting to reduce patient length of stay with the possible consequential problems associated with particular discharge destinations.

Limitations of modelling

The successful use of modelling is dependent upon a number of factors, including the accurate identification of patients when modelling a specific service and the robustness of the modelling technique. Although modelling can be used to provide a scenario of what may occur when a new service is offered at a health facility, it will only be useful if the patient profiles used to establish the models are relevant, that is, the model is based upon the correct patient group as identified on the basis of AN-DRGs, age, gender or other appropriate categories. Additionally, it is assumed that the length of stay and mix of the patients used to determine the model is not likely to change, for whatever reason, in the immediate future.

Seasonality

Figure 5 illustrated the daily variations in the number of beds occupied by patients included in the analysis. A similar finding of variation in bed numbers was reported by Wyllie, Kidson and Wyllie (1988) in relation to a study that examined occupied bed fluctuations in a surgical practice.

The use of models for determining patient flow and bed numbers based upon annual data is of use for general planning purposes. In order to reflect the changes in bed occupancy that occur throughout the year it is more useful to construct models that represent more limited periods of time. Such modelling ensures that planning for variations in bed requirements due to seasonal factors or other factors can occur. For example, models can be constructed for each week or month.

While it is possible to construct multiple models, the actual number of models constructed will ultimately depend upon the time available to build the models, particularly in the case of the Sorensen model, which must be constructed from scratch each time. Additionally, there must be sufficient data to enable the construction of meaningful models.

Internal and external factors

The provision of inpatient services is also constrained by numerous internal and external factors which impinge upon the meaningfulness of any model developed. Internal factors that affect the provision of services include staffing levels, operating theatres, diagnostic support services and the physical capacity of the health unit (Sorensen 1996). External constraints include the ability of step-down facilities to admit additional patients.

Meaning of the statistics

Both the BOMPS and the Sorensen models provide information about patient numbers, the number of required beds and other statistical information of interest to health service managers, planners and clinicians. Neither provides explanations as to why the statistics exist. As with many tools, both models provide insights into portions of the health system, but they cannot be used in a void. Clinical explanations for the reasons why various patient groups exist may enhance understanding of the dynamics of the health service by managers and planners (Watt 1995).

Resistance to change

While models such as those developed by McClean and Millard, and Sorensen, are designed to appeal to hospital managers or health planners, it is considered likely that health workers will resist the use of such methods and continue to use rule of thumb models (Xiao-Ming 1995). Bed numbers can be determined by rule of thumb modelling, but the information gained is limited and provides the manager and clinician with little, if any, useful insight into the dynamics of bed usage. The provision of education regarding the benefits of more sophisticated bed modelling together with financial imperatives would be necessary for the widespread take-up of bed modelling.

Future research directions

The use of modelling packages or methods such as those described in this article represent a quantum leap from the days of management by rule of thumb to more sophisticated management. The application of such models is not just limited to the scenario to which the models were applied, but should be considered when looking at health care services from a variety of perspectives including demographic, unit or service level. The what-if facilities that can be used in modelling should enable health care workers to gain an appreciation of how internal and external changes to service delivery affect bed requirements, bed numbers and the time needed for changes to stabilise.

Work has commenced to apply the modelling techniques referred to in this article to the strategic planning process occurring in a regional setting within South Australia. It is hoped that the adoption of these techniques will facilitate the increased understanding and acceptance of bed modelling.

The use of BOMPS methodology in conjunction with simulation software is already being used to increase the sophistication of the modelling (El-Darzi et al. 1998). While simulation software is expensive when compared to the cost of standard spreadsheet and database software, it can provide models that incorporate a visual model of the actual health unit using various icons, thus further increasing understanding of the way different policies influence bed usage and occupancy.

Conclusion

The management of hospital beds is crucial in times when hospitals are under ever increasing pressure to do more with fewer resources. Financial management must occur hand in hand with appropriate planning of inpatient health services.

The use of basic information is no longer sufficient to supply the information health managers and planners should use to manage and plan inpatient activities. The use of bed modelling tools such as those considered in this article should complement the armoury of tools at the disposal of health planners and hospital managers. It is incumbent upon senior management to encourage staff to seek out such tools and provide them with the necessary opportunities to acquire the skills to incorporate those tools into everyday planning work.

Acknowledgements

Mark Mackay thanks Chris Vasilakis of St George's Hospital, London, for his support with the analysis of the data using BOMPS. The authors thank the referees and Marisa Maio Mackay for their suggestions regarding the structure of the article.

Note

The views expressed in this article are those of the authors and do not necessarily represent those of their employers. Further information regarding BOMPS can be obtained from Professor Millard by email (p.millard@sghms.ac.uk) or from the Internet site http://www.sghms.ac.uk/depts/gm/index.html.

References

Clerkin D, Fos PJ & Petry FE 1995, 'A decision support system for hospital bed assignment', *Hospital and Health Services Administration,* vol 40, no 3, pp 386–400.

Duckett SJ 1995. 'Hospital payment arrangements to encourage efficiency: The case of Victoria, Australia', *Health Policy*, vol 34, pp 113–34.

Duckett SJ 1998 'Casemix funding for acute hospital inpatient services in Australia', *Medical Journal of Australia*, vol 169, supplement pp S17–21.

Gove D, Hewitt D & Shahani A 1995, 'Towards a model for hospital caseload decision support', *IMA Journal of Mathematics Applied in Medicine and Biology*, vol 12, pp 329–38.

El-Darzi E, Vasilakis C, Chaussalet T & Millard PH 1998, 'A simulation modelling approach to evaluating length of stay, occupancy, emptiness and bed-blocking in a hospital geriatric department', *Health Care Management Science*, vol 1, pp 143–9.

Harrison GW 1994, 'Compartmental models of patient occupancy patterns', in PH Millard & SI McClean (eds), *Modelling hospital resource use: a different approach to the planning and control of health care systems*, Royal Society of Medicine Press, London, pp 53–61.

Harrison GW & Millard PH 1991, 'Balancing acute and long-term care: The mathematics of throughput in departments of geriatric medicine', *Methods of Information in Medicine*, vol 30, pp 221–8.

McClean SI & Millard PH 1995a, 'Modelling inpatient bed usage behaviour in a department of geriatric medicine', *Methods of Information in Medicine*, vol 32, pp 79–81.

McClean SI & Millard PH 1995b, 'A decision support system for bed-occupancy management and planning hospitals', *IMA Journal of Mathematics Applied in Medicine and Biology*, vol 12, pp 249–57.

Millard PH 1998, 'The anatomy, physiology and biochemistry of health care for an ageing population', *Health and Hygiene*, vol 19, pp 49–60.

Pendergast JF & Vogel WB 1988, 'A multistage model of hospital bed requirements', *Health Services Research*, vol 23, pp 381–99.

Sorensen J 1996, 'Multi-phased bed modelling', *Health Services Management Research*, vol 9, pp 61–7.

Watt S 1995, 'The bed occupancy management and planning system (BOMPS)', *The Lancet*, vol 345, pp 243–4.

Williams A 1995, 'The role of quantitative modelling in health care' [editorial], *Health Economics*, vol 4, pp 1–6.

Wyllie JH, Kidson IC & Wyllie DH 1988, 'Pursuing efficiency in surgical practice', *British Medical Journal*, vol 297, pp 1368–71.

Xiao-Ming H 1995, 'A planning model for requirement of emergency beds', *IMA Journal of Mathematics Applied in Medicine & Biology*, vol 12, pp 345–53.