Health care modelling: opening the 'black box'

In the second of two articles, based on Professor Millard's recent lecture course, we explore the concept of "flow", i.e. how patients actually move through hospital beds. The use of mathematical models to describe flow is outlined, and examples are given of practical applications in health care management.

Dr Simone Ivatts is Specialist Registrar, St George's Hospital Rotation

Professor Peter Millard is Emeritus Professor of Geriatrics, St George's Hospital Medical School, Visiting Professor, Health and Social Care Modelling Group, University of Westminster

By Simone Ivatts and Peter Millard

Symptoms and signs are nature's expression of defence against disease. Trolley waits; cancelled operations; hospital-acquired infections; blocked beds; delayed discharges etc.: all are signs of 'sick' hospitals. Symptoms are parliamentary questions, public disquiet and complaints.

In factories, it is well recognised that the quality of the finished product decreases if the conveyor belt goes too fast. Yet, for the last twenty years and for the foreseeable future the basic premise is that hospital treatment can be forever sped up with impunity.

Now NHS performance tables (based on speed of treatment and death rates) are being published in national newspapers to 'name-and-shame' failing hospitals. Yet factors inside and outside hospitals influence speed of treatment.

For example, in English Health Authorities, there have been considerable differences in the outcome, discharged home and discharged to nursing home for patients admitted to hospital with stroke illness (Lee et al. 1998). Soon, articulate pensioners will want to know why?

Currently, a comment in the Department of Health's performance measure on length of stay states, "keeping people in hospital longer than is necessary can be an indicator of poor performance (Department of Health 1999)". So, the pressure is on to shorten length of stay, seemingly, irrespective of need and the outcome of the treatment.

Disease presents differently in older people, and often comes disguised as social problems. To an older person and their family, there is a considerable difference between the outcome discharge to nursing home without rehabilitation and safe return home following quality in-patient care. The population is ageing, and community care will fail if dependent older people with social problems which mask illness are denied access to 21st century acute hospitals.

In our previous article (Ivatts and Millard, 2002), we showed that the methods used to measure, compare, contrast and plan hospital in-patient activity are seriously flawed. We also argued that scientifically valid tools should be used to measure and model in-patient activity.

Starting from here

Our aim in writing these papers is to take the reader from Level Zero of Seymour's hierarchy of possible levels of understanding of modelling methods to Level A, where a few general rules of thumb or 'heuristics' are understood due to a general reading of the modelling literature (Seymour, 2001). References in this paper guide readers to recent research papers that underpin the concepts that we are developing.

In Level B of Seymour's hierarchy, understanding of clinicians' (and, we would add, managers') own data-set at one point in time is obtained, and simple "what-if" scenarios are constructed.

Information about the tools that we are using can also be obtained from the University of Westminster Health and Social Care Modelling Group web site, at **http://www2.wmin.ac.uk/hscmg**

In the first paper, we used a cube with black and white squares to illustrate the problem of "bed-blocking" (*Figure 2*,

BJHCMMillard251_5amend 29/7/02 9:16 am Page 2

paper 1). *Figure 1*, in this paper, further develops the modelling concept to show how simple algebra adds a further explanatory variable to explain 'bed-blocking'.

Models simplify complex systems

Toy trains are not real trains, but they do enable us to understand how real trains work. Changes made in the layout of a toy train track do not change the real world, but sharp corners explain what happens if trains go too fast.

We used a twenty-four hour train in our first paper (*Figure 1*, paper 1) to make the problem of measuring, modelling and planning hospitals easier to understand. By using the analogy of a train circling a track at constant speed, we can remove the emotion associated with discussion of patient care and focus on the problem of service improvement in a different way.

The train circles the track at a constant speed: time cannot be speeded up. To improve the passenger carrying performance of the train (hospital) one has several choices. To:

- add more carriages (more beds),
- stop passengers getting on board (reduce admissions in the over 75's)
- stop passengers staying overnight (more day patients)
- persuade passengers to get off the train early and continue their journey elsewhere (early discharge, intermediate care and transfer to social care homes).

The problem with all of the above methods of improving performance is that they take, as a given, that the clinical management of patients within the hospital is optimal and cannot be changed.

Yet *Figure 1* in this paper shows that the key explanatory variable associated with 'bed-blocking' is a medical decision, taken within the hospital, that no further actions can be taken within the hospital to solve the patient's problem.

Thousands of facts are collected in modern hospitals. The challenge is to find the minimum number of facts that are needed to determine how beds are actually used. Some of the necessary facts, like age, sex, specialty, diagnosis, admission and discharge dates and discharge destination are already collected. Others are not.

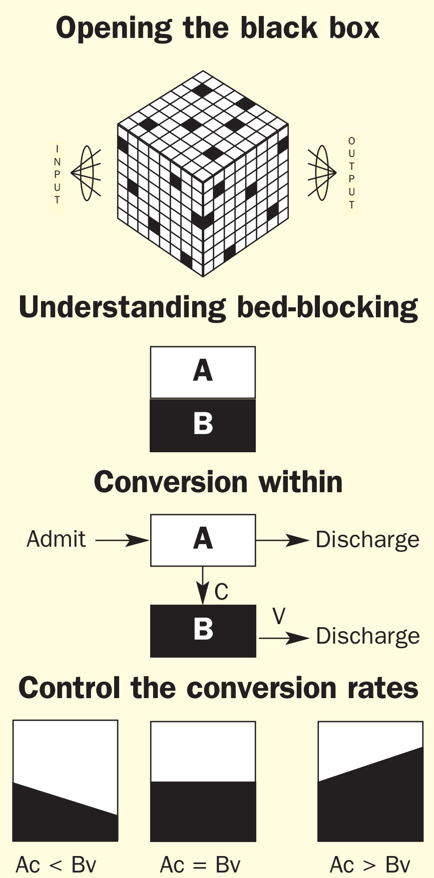


Figure 1
The figure shows why the key to solving 'bed-blocking' may lie within the hospital. Assuming that a hospital has no empty beds, on any day new patients can only enter if other patients leave.
Patients designated as 'bed-blockers' change their status from active intervention to passive compliance. The patient recognises their changed status because the consultants and their teams pass by; the therapists move on to more rewarding patients; and the nurses still tend, but they do no longer actively encourage self-help.
In modelling terms, the patient has crossed a catastrophe hypersurface, a local behaviour-related decision-making threshold over which the patient had no control. And everyone waits for someone else to solve the problem.
Algebraically, the stable state equation is $Ac = Bv$, i.e. the stable state depends on the conversion rate within the hospital being the same as the rate of discharge of 'bed-blocking patients'.
When $Ac > Bv$ the hospital will slowly have fewer beds to meet acute care needs. Vice versa, if the hospital staff could change their learnt behaviour such that $Ac < Bv$ then over weeks and months, more beds become available for admissions.

Figure 2 shows part of the problem that needs to be solved.

Model building (Bartholomew et al. 1991)

Models are built in four stages.

- Model-building is the role of the scientist
- Model-solving involves mathematicians
- Model testing requires applied research
- Model implementation involves decision makers

In the decade since Harrison and Millard (Harrison and Millard, 1991) reported a mathematical solution to a two-compartment model of flow in departments of geriatric medicine, a world-wide group of mathematicians; decision scientists; computer experts; health business analysts; care providers and clinicians have been working together to validate, expand and test new methods of measuring and modelling health and social care systems.

A scientifically-valid model of the interactions between health and social care is the gold standard for which we must aim. Stages 1, 2 and 3 have already been achieved. The time is now right for stage 4 (operational planning) to begin.

Operational Planning (Feldstein, 1963)

Key features of operational planning are:

- An operational model of the problem
- Implementation of the model with statistical evidence
- Solution of the problem by finding the alternative policy, which maximises a particular equation in the model

Human activity systems (McClean & Bustard 1997)

Hospitals are human activity systems. In human activity systems, human beings undertake some activity to achieve a purpose, e.g. a factory or a university.

Professors McLean and Bustard from the School of Information and Software Engineering at the University of Ulster defined the properties of a full geriatric care system as:

- Ongoing purpose – care of the elderly
- Mechanism for control – government control

- Sub-systems – hospital, nursing homes
- Interacting sub-systems – patient flows
- Wider system – National Health Service
- Boundary – catchment area
- Resources – budget
- Expectation of continuity – hopefully.

An important point about systems is that they form hierarchies. The authors also define a typical system hierarchy of health care as:

- Level 1: Health Authority / Region
- Level 2: Hospital
- Level 3: Department
- Level 4: Ward

Key points concerning a systems approach are:

- The aim is to optimise performance
- The approach takes a broad view, embracing social and political aspects
- Optimum parameters are needed for the design, construction and operation of the system
- Control is dependent on the feed back of accurate information
- Performance measures typically focus on productivity, responsiveness and utilisation
- Performance indicators are frequently interdependent
- Changes in one part of the system can have a detrimental effect on other parts.

Care must be taken when instituting change in human activity systems, because sub-systems interact horizontally as well as vertically. Activity in hospitals cannot be considered alone, because hospital and community services interact.

To improve patient care, hospitals need to slow down

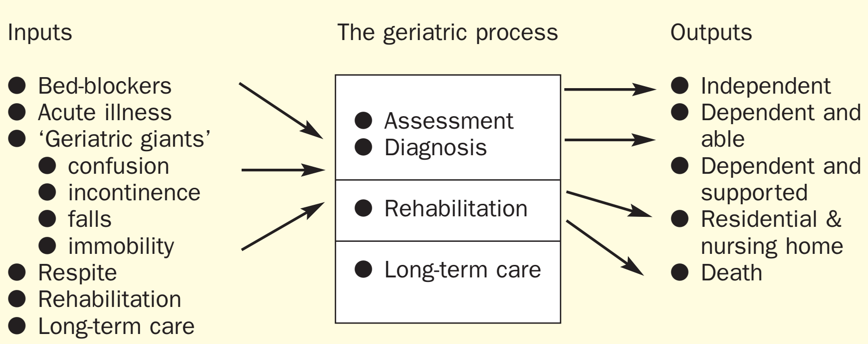
Treatment in acute hospitals cannot forever be speeded up without deleterious consequences on patients, staff and carers.

To escape from the conveyor belt mentality, performance measures are needed that take into account the biological, psychological and social characteristics that determine a patient's length of stay.

In **biological** terms:

- Patients have simple, difficult or complex problems
- They are ill and likely to recover, or they are not
- They can walk or they cannot
- They are continent or they are not.

Figure 2



Geriatric medicine is a complex service in need of measurement. Not one of the indicators in current data sets takes account of the input and output characteristics of the patients that used to be (and in some places still are) referred to geriatricians. Patients flow through departments of geriatric medicine in three different streams of flow: the technical name for this process is progressive patient care. As time passes staff interventions change from treatment and active intervention, to rehabilitation, motivation and encouragement, to supportive care. These stages take different times. Active intervention takes days and weeks; 50% leave by death or discharge within 21 days; rehabilitation lasts for weeks and months; long term care lasts for months or years. Flow models help us understand the process of care because they enable us to see how the three streams interact.

Reprinted with permission of publisher Cambridge University Press
Millard PH, O'Connor M, McClean SI. (1998) *Measuring and modelling patient flows through rehabilitation and continuing care.* Reviews in Clinical Gerontology 1998; **8**: 345-352 Cambridge University Press

In **psychological** terms:

- They have good mental function, or not
- They want to return home, or not
- They co-operate with staff, or not, etc.

In **social** terms:

- They can have good or bad home circumstances
- Their partner (if any) can be alive or dead
- Their neighbours may be supportive, or not
- Their relatives may support a home discharge, or not
- The early discharge (intermediate care) team may or may not have places.

Unless the interactions between hospital and community care are taken into account, we reach the absurd situation in which the hospitals that institutionalise sick people in nursing homes without any rehabilitation get praised.

Meanwhile, the hospitals that minimise the need for long-term care, by giving sick people time to recover, get punished.

Uncertainty (Marshall et al. 2001)

In medicine, there are no certainties: just interacting probabilities.

Bayesian Belief Networks model the causal relationship between variables, where one variable is viewed as having a direct influence on another.

Although age is an explanatory variable for increasing length of stay, age alone does not determine how long a patient will occupy a bed.

For example, a male patient who lives alone admitted with stroke illness is most likely to spend over 50 days in the department of geriatric medicine, irrespective of his actual age.

Marshall's cited study used Bayesian Belief Networks (BBN's) to analyse a database concerning 4,722 patients admitted to the department of geriatric medicine at St. George's Hospital, London.

The analysis showed that personal details interacted with admission reasons to determine dependency, and these factors interacted to determine length of stay.

Using Bayesian Belief Networks based on local data, clinicians and hospital managers could gain knowledge of the

> **'The creation of a scientifically-valid model that shows the interactions between health and social care is the gold standard for which we must aim.'**

patient sub-groups, their likely duration of stay and destination at discharge. Thus facilitating the planning of services.

Modelling hospital flow (Harrison, 2001)

Prof Harrison, from the College of Charleston, South Carolina, US developed the mathematical solutions to the two compartment (Harrison and Millard, 1991) and three compartment (Harrison, 1994) models of flow through health and social care services.

The models that Harrison developed are analogous to the compartmental models that are used to measure the absorption, distribution, metabolism and excretion of drugs. The difference between pharmacological models and Harrison models is that pharmacological models analyse the clearance of drugs, whereas Harrison model analyse the pattern of accumulation of patients.

Figure 3 illustrates the concept of one, two and three streams of flow and shows the services that are associated with the different models of flow. The only service that we have examined so far, in data sets from different parts of the world, that did not have an exponential fit to its occupancy data is learning difficulties.

The benefit of using exponential models of the flow of inpatients through health and social care systems is that decision makers can better understand the process of care (McClean and Millard, 1993a, 1993b). Also the short and long term outcome of possible decisions can be tested.

In future years, as the biopsychosocial nature of hospital human activity systems becomes better understood, clinicians and managers will discuss length of stay in hospitals in terms of streams of flow and half-lives. Single averages of complex systems will be placed in the dustbin of history.

Mixed exponential distributions in bed occupancy data imply:

a) That the length of stay of current in-patients is much longer than the length of stay of discharged patients
b) That the average stay of a group of discharged patients will not correctly indicate the resources that are used for rehabilitation and long-stay care
c) That the expected additional days' stay of an in-patient increases dramatically the longer they occupy a bed

Practical application

Several researchers have been able to apply these models to practical problems in the health service. Examples are.

- Explaining the Christmas bed crisis (Vasilakis et al, 2001)
- Queuing models of emptiness and occupancy (Gorunescu et al, 2002)
- Modelling the total system of care (Millard et al, 2001)
- Bayesian Belief networks in predicting length of stay (Marshall et al, 2001)
- A mathematical solution to six compartment model of the hospital and community system of geriatric medical care can be found in (Taylor et al, 2000)

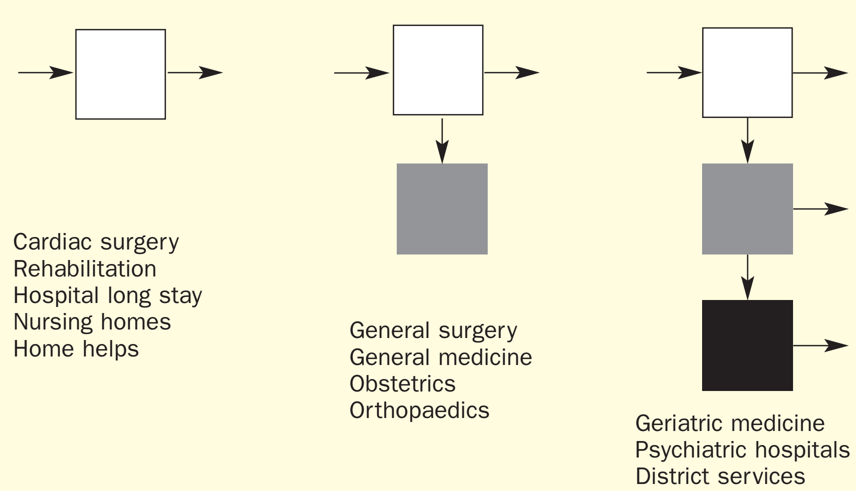
Papers describing newer methods of analysing hospital activity include:

- Bed usage by stroke patients (Lee et al. 1998)
- Use of surgical beds (Millard et al, 2000)
- Use of medical beds (Christodoulou and Millard, 2000)
- Models that incorporate discharge destination (Mackay and Millard, 1999)
- Practical experience of modelling (Mackay, 2001)

Conclusion

Mathematical models are only as good as the theory on which they are based and the accuracy of the statistical evidence that is used. Linear models are now used to plan health and social care services. These models are based on concepts of pressure and force (MacStravic, 1984). In future years behavioural flow models will be used instead.

Figure 3
Streams found in different services



Flow modelling identifies the presence of the different streams of flow and measures the contribution that each stream within the system gives to the whole process of care. One, two or three streams of flow with different dimensions of time occur in services dependent on the nature of the patients being admitted, the characteristics of the patients who are admitted e.g., pregnancy can be normal or associated with complex problems that require hospitalisation, so the beds in the obstetric department are mainly occupied by longer term patients while the day to day workload is delivering babies.

KEY POINTS

- **New methods of assessing in-patient activity are required**
- **Hospitals are complex human activity systems**
- **Older patients have a heterogeneous mix of biological, social and psychological problems**
- **Bayesian Belief Networks, based on local data, can help managers predict outcomes in patient care**
- **Patients progress through hospitals in streams of flow**
- **Models can be applied to services, in order to analyse current activity and predict impact of proposed changes**
- **Scientifically-valid models need to be created to underpin decision making in health and social care**

Linear models have served us well. But, the *reductio ad absurdum* of linear thinking is that no beds will eventually be needed to treat patients. Clearly, that conclusion is absurd.

Mathematically, as well as clinically, a forgotten key component that controls availability of resources in all other parts of the system is the decision that a patient needs long-term care.

The creation of a scientifically-valid model that shows the interactions between health and social care is the gold standard for which we must aim. If such a model were created, decision-making should improve. Policy makers could predetermine the results of proposed changes without continually experimenting with the real world (McClean and Bustard, 1996).

Acknowledgements

Thanks to Dr. Mark Kinirons; the material used is based on Professor Millard's contribution to the KCL Health Informatics Course at St. Thomas's Hospital.

Countless people living and dead have contributed their thoughts to the concepts we describe.

Without the enthusiastic co-operation of academics, colleagues, researchers, collaborators, family and friends the work outlined in this paper would not have been achieved.

References

Bartholomew DJ, Forbes AF, McClean SI (1991) Statistical techniques for manpower planning. 2 edn. John Wiley, Chichester

Christodoulou G, Millard PH (2000) Measuring and modelling patient flow. *British Journal of Health Care Management 6:* 463–8

Department of Health (1999) Improving quality and performance in the new NHS clinical indicators and high level performance indicators

Feldstein MS (1963) Operational research and efficiency in the Health Service. *The Lancet* **i:** 491–493

Gorunescu F, McClean SI, Millard PH. (2002) A queueing model for bed-occupancy management and planning of hospitals. *Journal of the Operational Research Society* **53:** 19–24

Harrison GW (1994) Compartmental models of hospital patient occupancy patterns. In: Millard PH, McClean SI, eds. Modelling hospital resource use: a different approach to the planning and control of health care systems. Royal Society of Medicine, London

Harrison GW (2001) Implications of mixed exponential occupancy distributions and patient flow models for health care planning. *Health Care Management Science* **4:** 35–43

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* **30:** 221–8

Ivatts S, Millard P (2002) Health care modelling – why should we try? *British Journal of Health Care Management* **8:** 212–6

Lee C, Vasilakis C, Kearney D, Pearse R, Millard PH (1998) An analysis of admission, discharge and bed occupancy of stroke patients aged 65 and over in English hospitals. *Health Care Management Science* **1:** 151–7

Mackay M (2001) Practical experience with bed occupancy management and planning systems: an Australian view. *Health Care Management Science* **4:** 47–56

Mackay M, Millard PH (1999) Application and comparison of two modelling techniques for hospital bed management. *Australian Health Review* **22:** 118–43

MacStravic R (1984) Forecasting the use of health services: a provider's guide. Aspen (ISBN 0-89443-857-3)

Marshall A, McClean SI, Shapcott CM, Hastie IR, Millard PH (2001) Developing a Bayesian belief network for the management of geriatric hospital care. *Health Care Management Science* **4:** 23–30

McClean S, Bustard D (1996) A Systems Approach to Healthcare Planning. In: Millard PH, McClean SI, eds. Go with the flow: a systems approach to health care planning. Royal Society of Medicine Press Limited, London: 15–20

McClean SI, Millard PH (1993a) Modelling in-patient bed usage behaviour in a department of geriatric medicine. *Methods of Information in Medicine* **32:** 79–81

McClean SI, Millard PH (1993b) Patterns of length of stay after admission in geriatric medicine: an event history approach. *The Statistician* **42:** 263–74

Millard PH, Christodoulou G, Jagger C, Harrison GW, McClean SI (2001) Modelling hospital and social care bed occupancy and use by elderly people in an English health district. *Health Care Management Science* **4:** 55–60

Millard PH, Mackay M, Vasilakis C, Christodoulou G (2000) Measuring and modelling surgical bed usage. *Annals of the Royal College of Surgeons of England* **82:** 75–82

Seymour DG (2001) Health care modelling and the National Health Service. Theoretical exercise or practical tool? *Health Care Management Science* **4:** 5–10

Taylor GJ, McClean SI, Millard PH (2000) Stochastic models of geriatric patient bed occupancy behaviour. *Royal Statistical Society: Series A* **163:** 39–48

Vasilakis C, El-Darzi E, Millard PH (2001) A simulation study on the winter bed crisis. *Health Care Management Science* **4:** 29–34