Modelling Care Pathways: Case Studies

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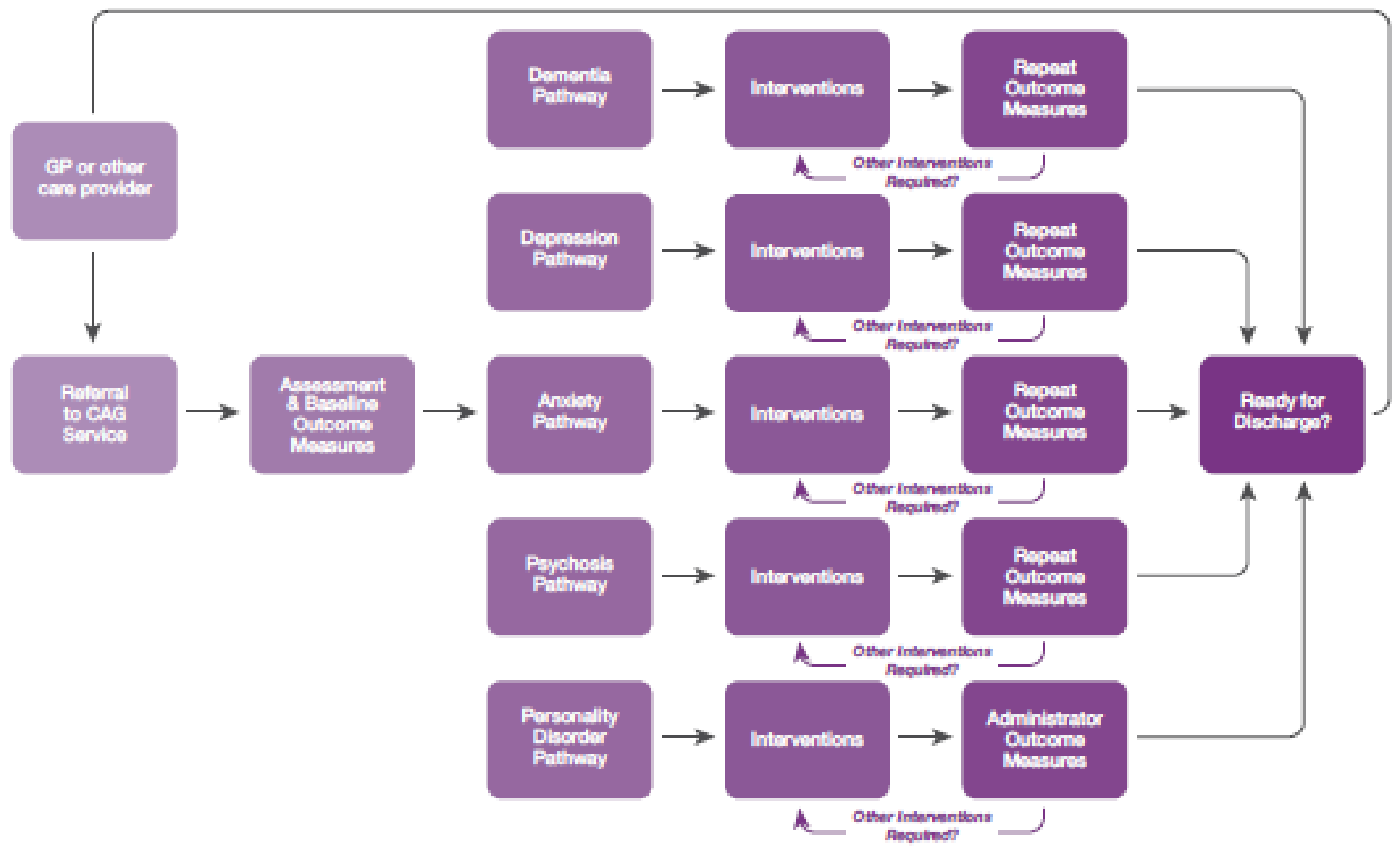
What is a Patient Pathway?

- The "**patient pathway**" is the route that a **patient** takes from their first contact with an NHS member of staff (usually their GP), through referral, to completion of treatment.

- **Clinical pathways**, also known as **care pathways**, **critical pathways**, **integrated care pathways** or **care maps**, are one of the main tools used to manage the quality in healthcare concerning the standardisation of care processes. It has been shown that their implementation reduces the variability in clinical practice and improves outcomes.
- When we propose new technology, it should be added to the pathway and evaluated as an addition/alternative.

Maudsley Care Pathways Overview

South London and Maudsley NHS
NHS Foundation Trust



KING'S HEALTH PARTNERS

Why use Modelling?

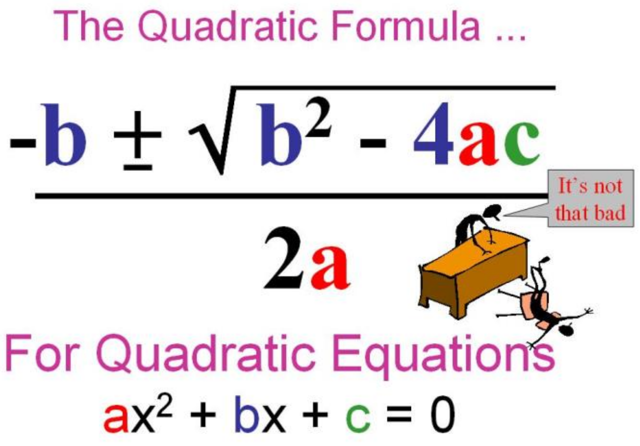
- Modelling can provide a framework for service design, an underpinning for process improvement and a scientific basis for decision making.
- A mathematical model is a simplified representation of a system.
- Simulation is the process of using the mathematical model to imitate important aspects of the behaviour of the system
- Therefore the model can be used to simulate the behaviour of the system that we may experiment without having to disturb the real-life set-up.

Correctness and Performance

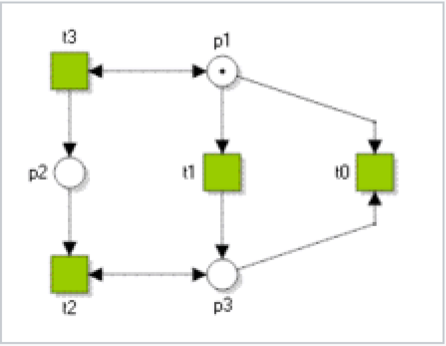
- Correctness and performance are two of the most important issues in the development of complex systems.
- Correctness describes the qualitative aspects of a system, such as liveness, safety, boundedness and fairness.
- Performance describes the quantitative, dynamic, time-dependent behaviour of systems, such as response time, system uptime and throughput.

Process Algebras

- Process algebras offer means for systematic, hierarchical modelling of complex systems, but they are only used for qualitative analysis (correctness) because they lack time and probabilistic information.
- Stochastic extensions of process algebra facilitate both qualitative and quantitative performance evaluation within a single, integrated modelling environment.



Petri Nets



A Petri net in which transition t_0 is dead, while for all $j > 0$, t_j is L_j-live

- Petri nets are high level formalisms that can also be used to model systems. A Petri net is one of several mathematical modeling languages for the description of distributed systems.
- Stochastic Petri nets, including Queueing Petri nets, can be used for quantitative performance analysis.
- Process Algebras and Stochastic Process Algebras are high level modelling languages that can be used to model a system.

Petri Nets: Definitions

- Petri nets are abstract formal methods, invented in 1962 by Carl Adam Petri, for the description and analysis of flow of information and control in concurrent systems.
- Like industry standards such as UML, Petri nets offer a graphical notation for stepwise processes that include choice, iteration, and concurrent execution. Unlike these standards, Petri nets have an exact mathematical definition of their execution semantics, with a well-developed mathematical theory for process analysis.
- Petri nets are graphically represented as collections of places drawn as circles, transitions drawn as rectangles, and arcs, which are drawn as arrows between places.

Process support for continuous, distributed, multi-party healthcare processes - applying workflow modelling to an anticoagulation monitoring protocol: Ian McChesney UU

- Workflow modelling has found relevance in the analysis and support of a range of healthcare processes,
- A trend in healthcare has been the move towards preventative treatments in primary care and through community care processes – processes which can be understood as continuous, distributed, multi-party workflow systems.
- A simple workflow modelling solution is based on coloured Petri Nets for an anticoagulation monitoring protocol.
- This has the value for workflow modelling for process understanding, simulation and implementation,
- Important characteristics of primary and community care processes can also be identified.

A Petri net for anticoagulant monitoring

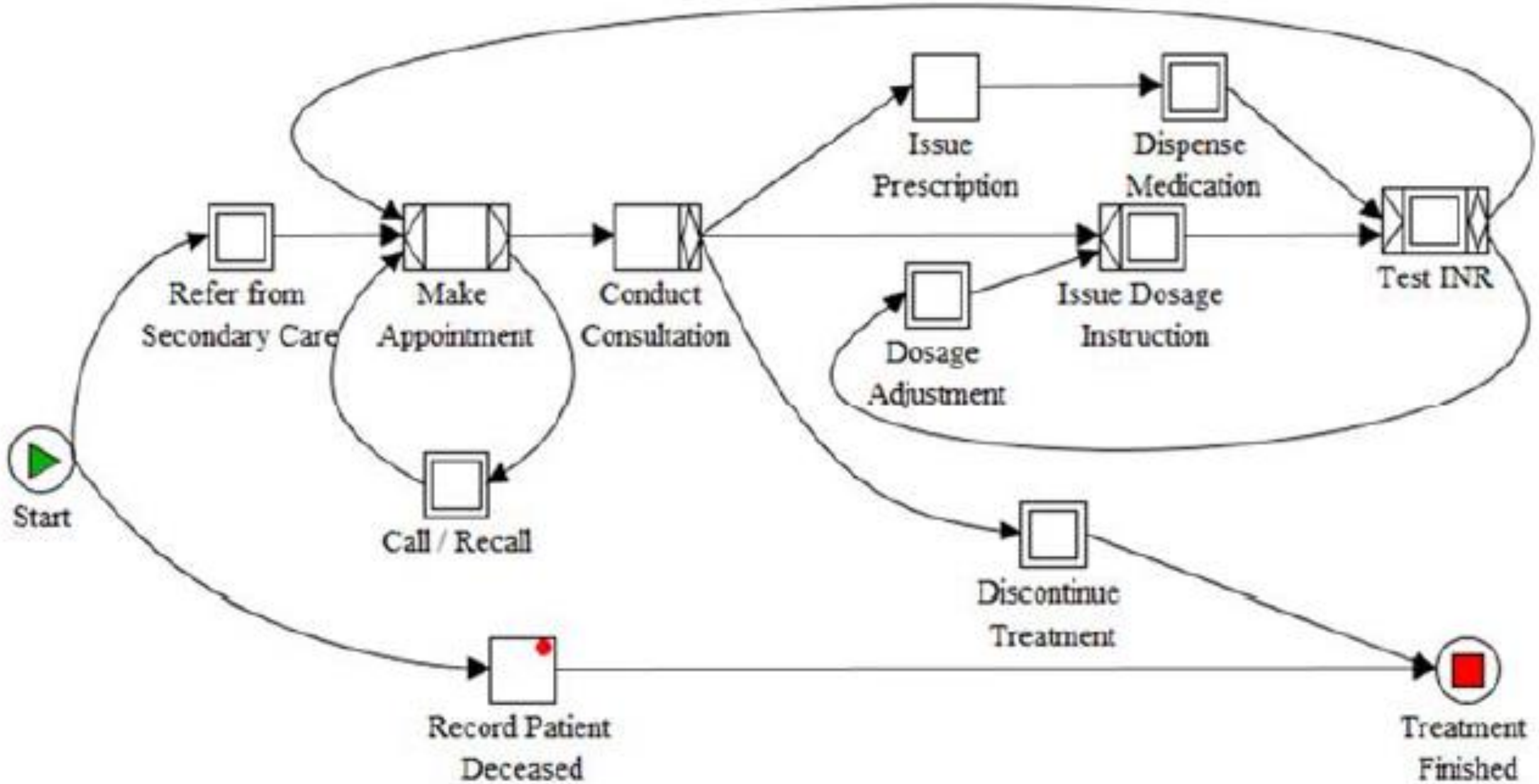
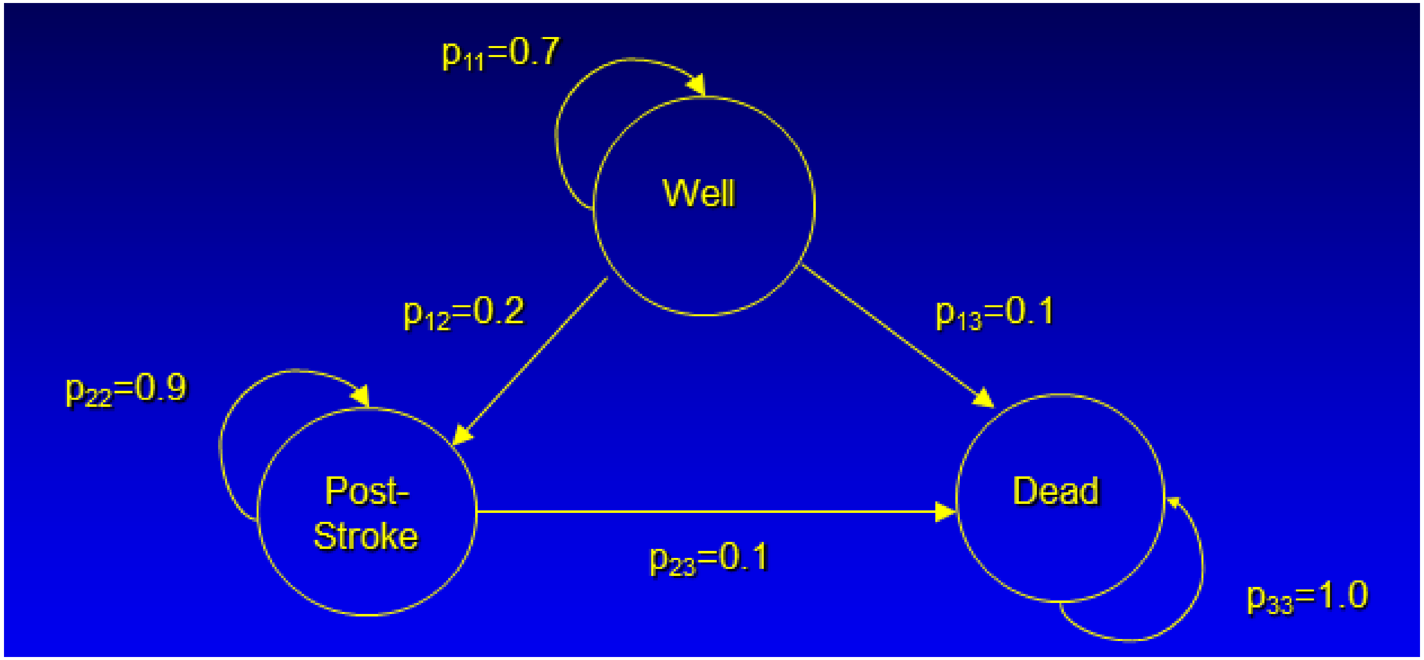


Fig. 1. Top level workflow net for anticoagulant monitoring

McChesney, I. (2016). Process Support for Continuous, Distributed, Multi-party Healthcare Processes-Applying Workflow Modelling to an Anticoagulation Monitoring Protocol. In *Ubiquitous Computing and Ambient Intelligence: 10th International Conference, UCAmI 2016, San Bartolomé de Tirajana, Gran Canaria, Spain, November 29–December 2, 2016, Proceedings, Part I 10* (pp. 255-266). Springer

Markov Models

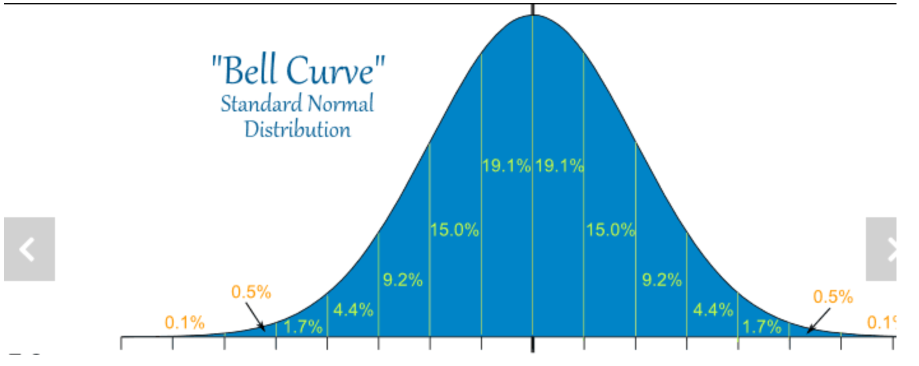
- A Markov model is a stochastic model used to model systems where it is assumed that future states depend only on the current state not on previous events (the Markov property).
- This assumption facilitates predictive modelling and probabilistic forecasting Markov property.



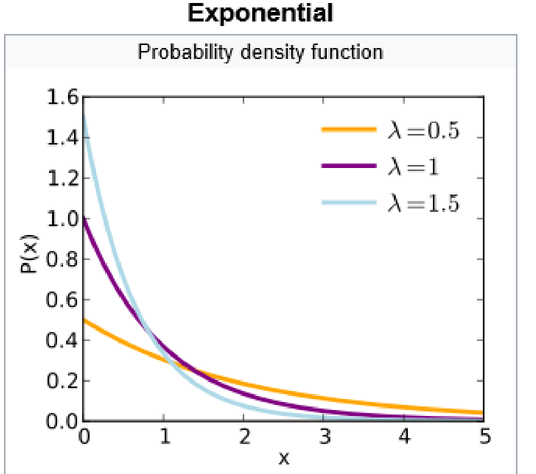
Continuous-time Markov Chains (CTMCs)

- CTMCs are commonly used in stochastic modelling.
- State durations are described by exponential distributions (the Markov property).

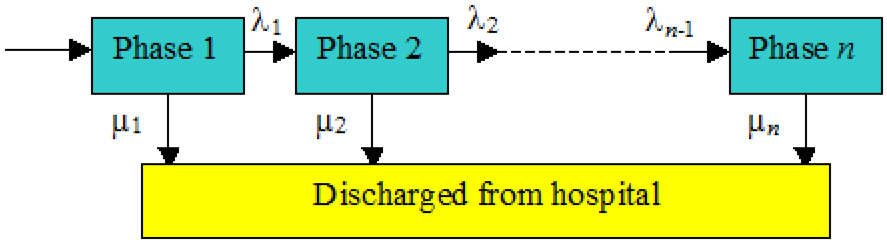
- In Statistics, the Normal (Gaussian) distribution is most useful. $N(\mu, \sigma^2)$



- For durations, the exponential distribution is most useful. $\text{Expo}(\lambda)$



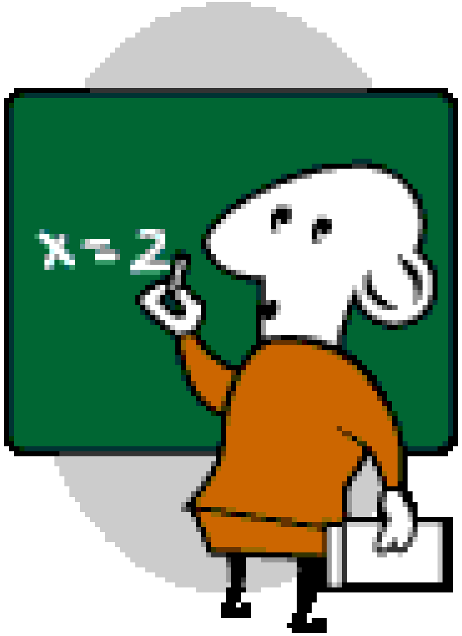
Towards developing Models



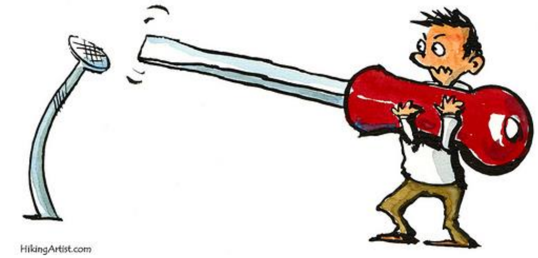
- A multi-phase (Markov) approach to pathway management facilitates the study of both the specific elements of a patient pathway, and its overall impact.
- This is important since previous healthcare solutions, for practical reasons, typically dealt with specific elements of the pathway (e.g. emergency care).
- A joined-up approach is particularly significant in services for older people since this patient group predominates.
- In this way we can develop mathematical models of the whole system and try to optimise criteria such as waiting lists, costs, or QALYS.

The role of Mathematics

- We cannot use mathematics to predict individual patient behaviour with any accuracy.
- Instead the model shows us typical or average behaviour thus allowing prediction of capacity requirements, summarising outcomes and forecasting future costs and QALYS.
- Likewise an equation cannot replace the professional's expert knowledge but can provide decision support.
- Such an approach is ideally suited to complex systems such as Health, Social and Community Services.



Solving the models



Performance evaluation using discrete-event simulation, in general requires very long runs to obtain results of good accuracy.

Analytical analysis, on the other hand, though it is fast and accurate, allow for only highly restricted Markov Chains.

Therefore, the most promising method of performance evaluation is numerical analysis, which is more accurate than simulation, more flexible than analytical methods, and provides what-if analysis (perturbation, sensitivity, optimisation).

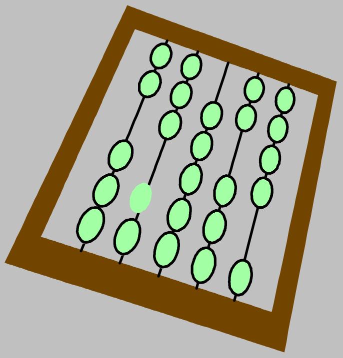
Key concepts of Multi-phase Modelling

- Sophisticated tools are needed to describe patient pathways for patient-centred care.
- A multi-phase approach allows us to quantify durations and costs of stages on the patient pathway.
- This approach can be based on readily available hospital and social service data.
- Better decisions can then be made, for patient-centred care and optimal use of health service resources.

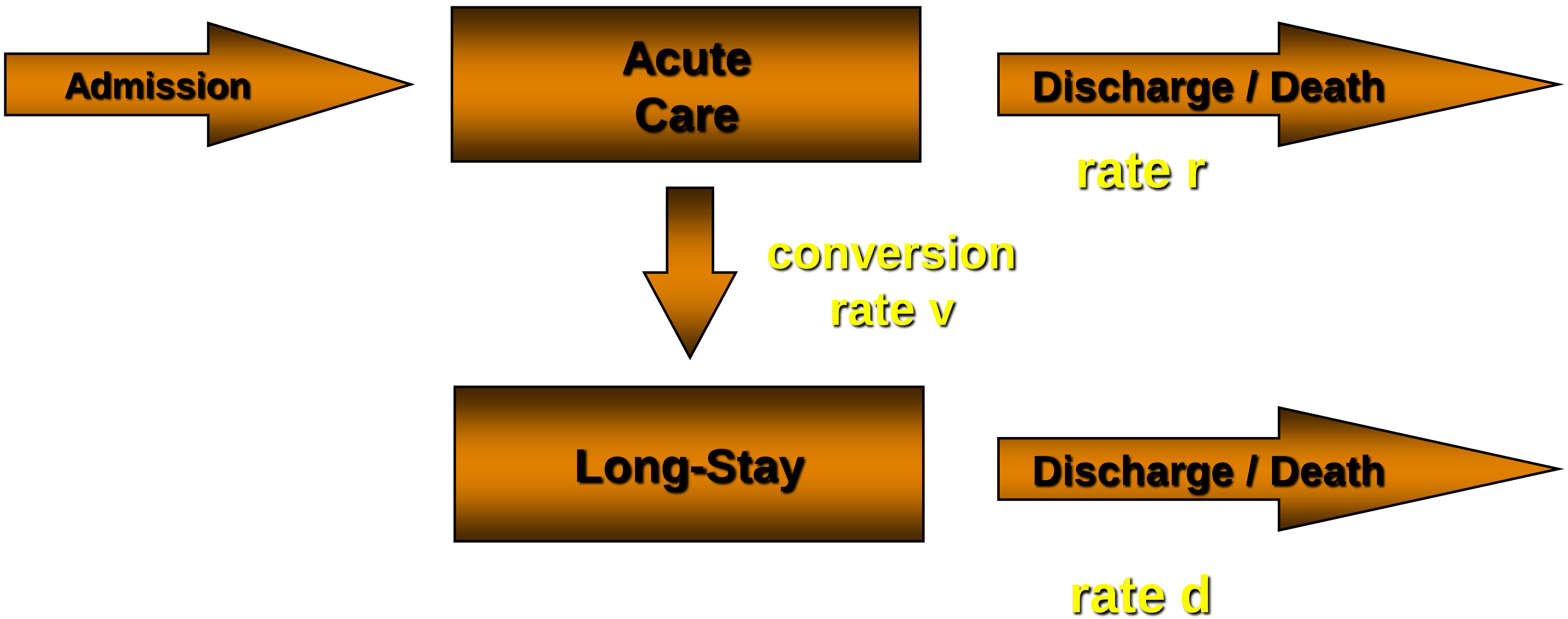
The need for modelling

"People who don't count, won't count"

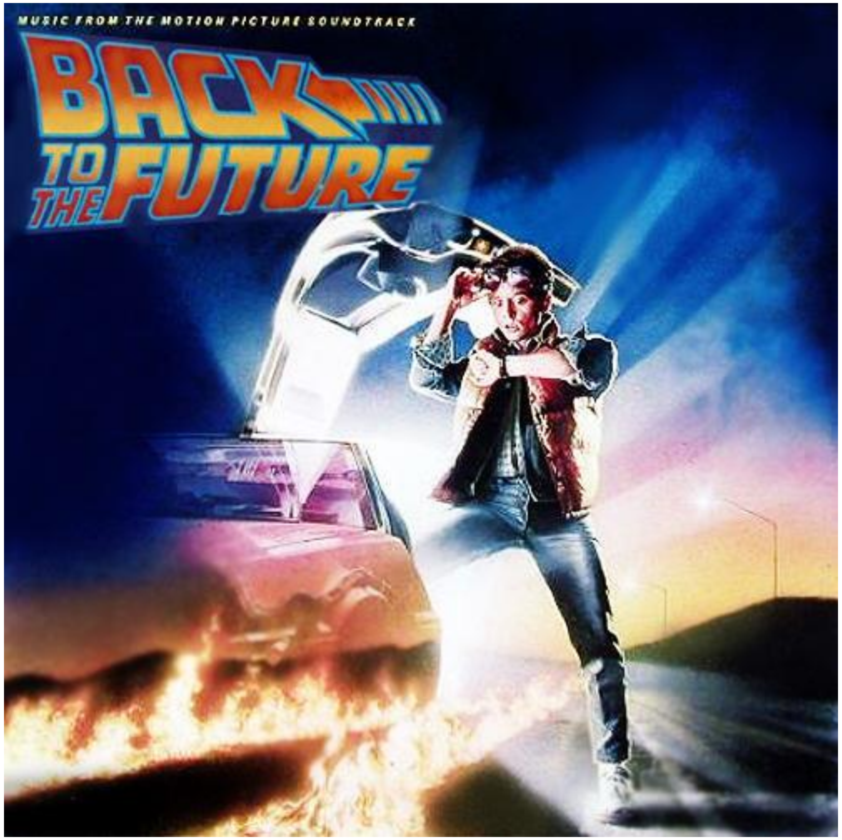
Anatole France



Patient Flows



Millard P, and McClean S, eds. (1994). Modelling hospital resource: a different approach to the planning and control of health care systems, Royal Society of Medicine Press, London.



J. R. Statist. Soc. A
(1976), **139**, *Part* 2, p. 205

The Two-Stage Model of Personnel Behaviour

By Sally McClean

The New University of Ulster

Summary

A stochastic two-stage model describing the way in which personnel behave during employment, and leave from a company is presented. The model is fitted to observed leaving patterns for several companies and compares favourably with the well-established lognormal and transition models. Recruitment is described as either being Poisson or dependent on the size of the company. Deterministic and continuous time stochastic models of company behaviour are developed which combine these recruitment patterns with two-stage leaving. These models are tested against the observed growth patterns of several companies and the results show good agreement.

Keywords: TWO-STATE MODEL; LABOUR TURNOVER; WASTAGE, PERSONNEL BEHAVIOUR; COMPANY GROWTH; COMPANY BEHAVIOUR; MANPOWER PLANNING MODEL; CONTINUOUS TIME STOCHASTIC MODEL

1. Introduction

It is now a firmly established result that, for a company, propensity to leave is highly dependent on length of service. In general, as an employee's tenure in a company increases, he becomes more committed to that particular firm and is consequently less likely to leave. This relationship between leaving and tenure has been described by the lognormal law, and the lognormal distribution has been fitted to length of service on leaving for a wide range of firms with great success. The main shortcoming of this lognormal hypothesis, however, is that there is no satisfactory model of leaving which explains its use in terms of the internal behaviour of staff in a company.

Bartholomew (1959, 1971) suggested the mixed exponential distribution to describe the distribution of the completed length of service (CLS) on leaving. Therefore the p.d.f. of CLS is $f(t) = p\lambda_1 e^{-\lambda_1 t} + (1-p)\lambda_2 e^{-\lambda_2 t}$, where $\lambda_1, \lambda_2 \geqslant 0$ and $0 \leqslant p \leqslant 1$. He suggested (1971) that an explanation for this is that leaving is exponential with rates λ_1 and λ_2 from two groups which are present in the proportions p and $1-p$ (Fig. 1).

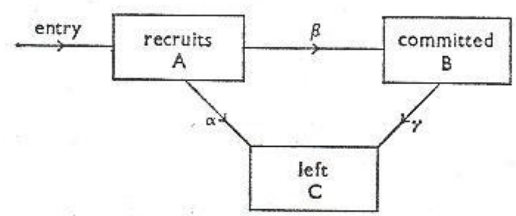
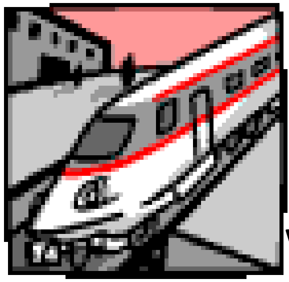


Fig. 1. The mixed exponential model.

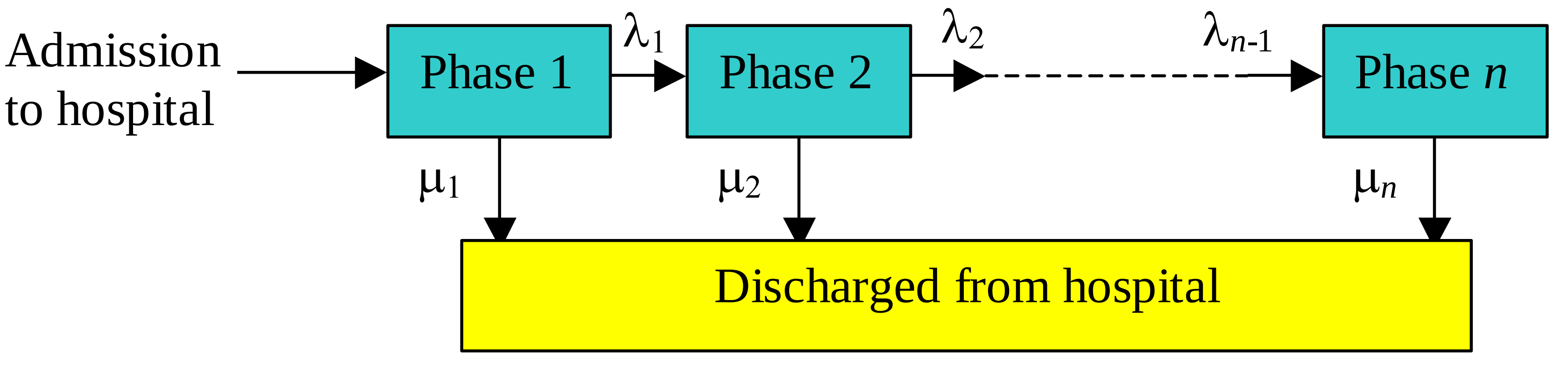
Bartholomew (1959) fitted this distribution to data from three companies and in all cases it was found that λ_1 was considerably greater (of the order of ten times) than λ_2. This would suggest that some people (those in group 1) are more mobile than others (group 2) who have a much smaller turnaround. This hypothesis is consistent with the so-called "mover–stayer" model of labour mobility which postulates that a certain proportion of employees (the "stayers") do not change their job while others (the "movers") tend to move around from



The Coxian Phase Type Distribution

(with Gordon Taylor, Malcolm Faddy, Adele Marshall, Mary Shapcott, Lalit Garg, Jennifer Gillespie and……Peter Millard)

Patient flow can be modelled as an *k* state Markov process with Coxian phase type distributions



The λ's and μ's are rates of moving between states.

McClean, S.I. and Millard, P.H. (2006), Where to Treat the Older Patient? Can Markov Models Help us Better Understand the Relationship Between Hospital and Community Care?, Journal of the Operational Research Society, 58 (2), pp. 255-261, ISSN 0160-5682.

The Deterministic Solution

$$A(s+1) = A(s) - vA(s) - rA(s)$$

acute at day s+1 — *acute at day s* — *conversions* — *death / discharge*

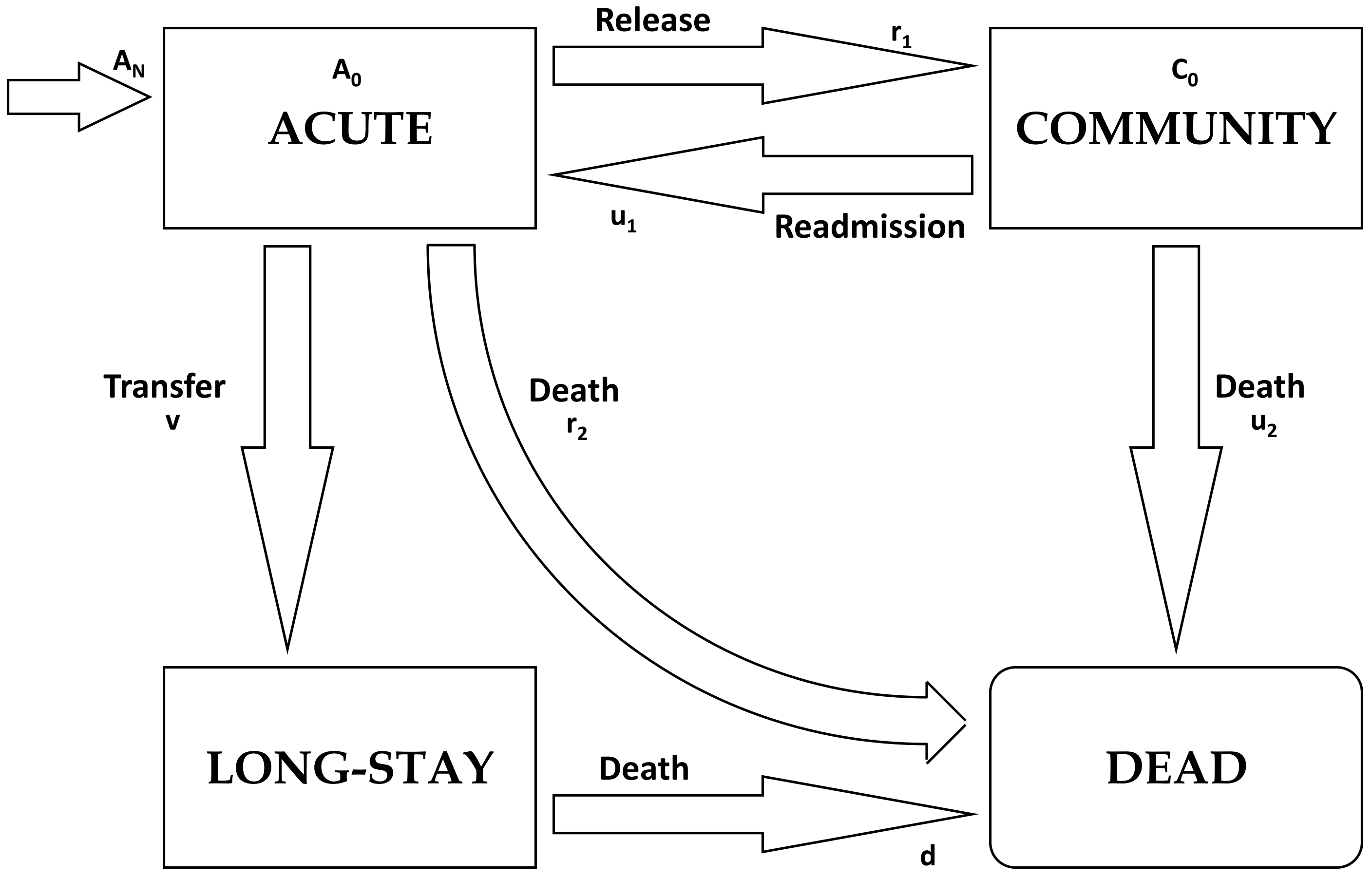
$$L(s+1) = L(s) + vA(s) - dL(s)$$

long-stay at day s+1 — *long-stay at day s* — *conversions* — *death / discharge*

The Solution is a mixed exponential expression

Three Compartment Model (Taylor et al.)

G. J. Taylor S. I. McClean P. H. Millard (2001). Stochastic models of geriatric patient bed occupancy behaviour, Journal of the Royal Statistical Society: Series A, Volume 163, Issue 1, pages 39–48, 2000, Wiley.



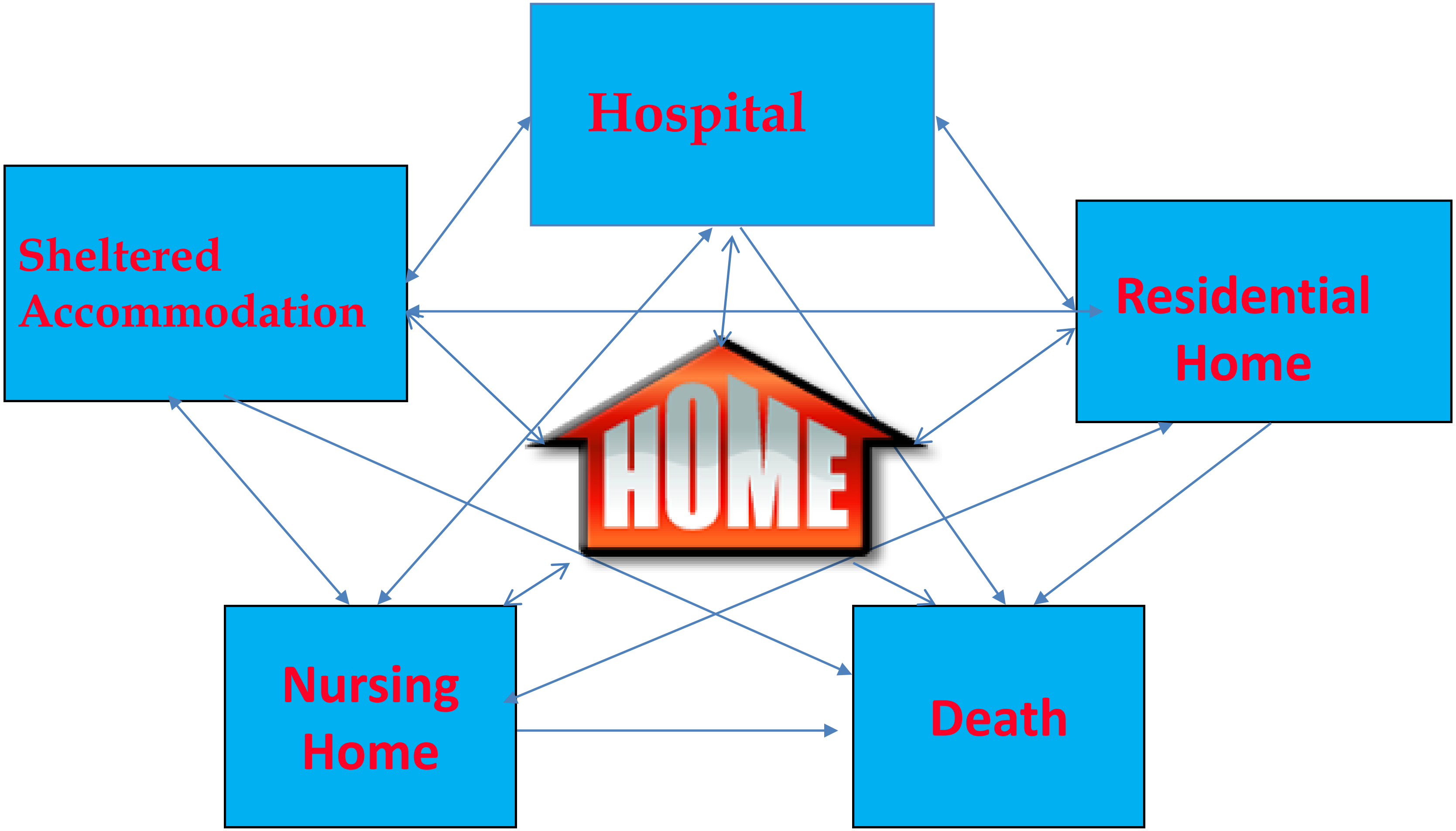
Belfast Health and Social Care Trust

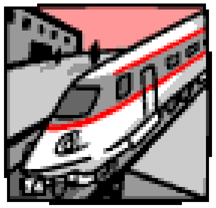
St George's University of London

The Ulster Stroke Exemplar

- Champions
  - Dr Ken Fullerton, Belfast City Hospital
  - Dr Ivan Wiggam, Belfast City Hospital
  - Dr David Wilson, Queen's University Belfast
  - Maria Kinnaird, Belfast City Hospital
  - Professor Peter Millard, St. George's, University of London
- Research Questions?
  - What are the major pathways for Belfast City Hospital stroke patients in terms of survival distributions, outcome probabilities, and pathways, taking account of the phases of care from referral to admission and discharge, movements between hospital, different social care options and readmissions?
  - Can we develop and use models to predict and compare outcomes and costs of rehabilitation and care options for Stroke patients?

The Integrated Patient Care System





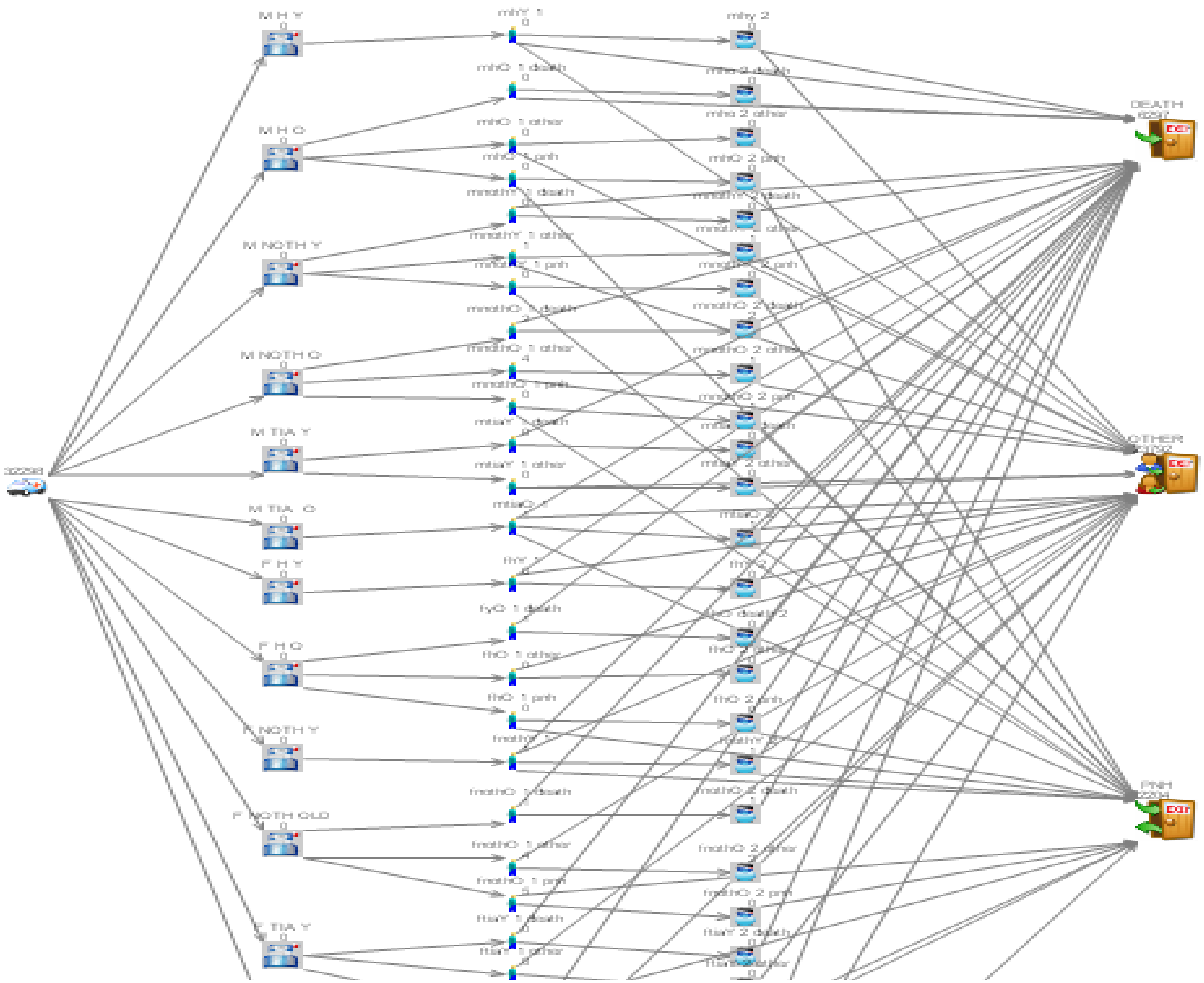
The multiple class, multiple absorbing state, phase-type model

- As well as multiple states and phases within hospital care (for different diagnoses, male and female, and different discharge destinations), we also have different outcomes (usual residence, private nursing home, death etc.).

- These can be incorporated into the phase-type models as additional phases.

McClean, S. I., Barton, M., Garg, L., & Fullerton, K. (2010). Combining analytical and simulation approaches to model patient flows. the ACM Transactions on Modelling and Computer Simulation (TOMACS).

The multiple class, multiple absorbing state model



Costing the Models

- We have extended the Markov model of patient flows to a Markov system where admissions of new patients are modelled by Poisson arrivals and the state space is expanded to include spells in the community.
- By assigning costs to the various states of the model, we may determine the overall costs involved in treating cohorts of patients.
- Using locally obtained transition rates and costings, hospital planners may thus identify cost-effective strategies that balance differential costs in the various components of the system.

Modelling Thrombolysis

- In collaboration with Dr Ken Fullerton and colleagues at the Belfast City Hospital, we have developed a detailed model of thrombolysis.
- Costs are assigned to thrombolysis and to rehabilitative care within the community.
- The model also includes differential lengths of stay and probabilities of outcomes for thromolysed and non-thrombolysed patients
- Results indicate that thrombolysis is cheaper, and affords substantial improvements in quality of life.
- The experience gained and techniques learned are likely to be relevant to health and care of older persons in general.
- Current interest in both health and social care of older persons demonstrates the importance for future planning that this work could have.

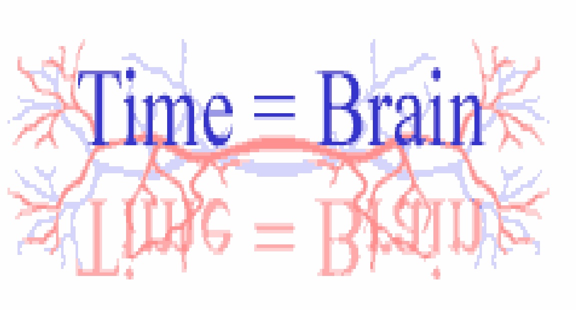
Thrombolysis for acute ischaemic stroke

- A "clot-busting" drug, licensed for use in UK in 2003 for treatment of acute ischaemic stroke for appropriate patients
- Stringent criteria (eligibility)
  - Must present within 3hr window
  - Patients aged ≤ 80 years
  - Must have brain imaging to eliminate diagnosis of intra-cerebral haemorrhage and severe stroke

    (also must not show any medical contraindications to the drug e.g. seizure at onset of stroke, low blood glucose, heparin within previous 48 hrs)

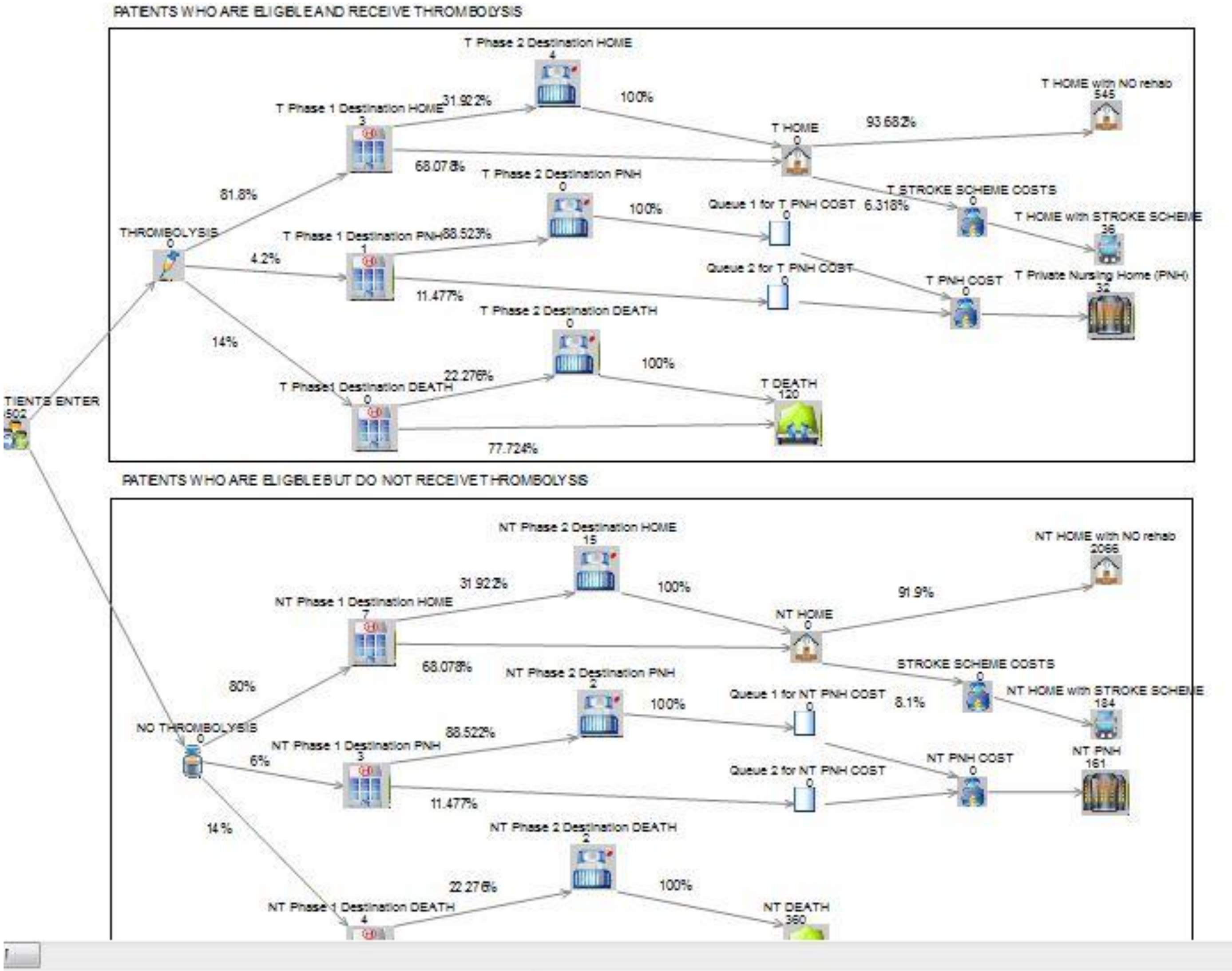
Thrombolysis for acute ischaemic stroke

- National Stroke Strategy
  - 24hr access to stroke care
  - 24 hr access to diagnostic scan



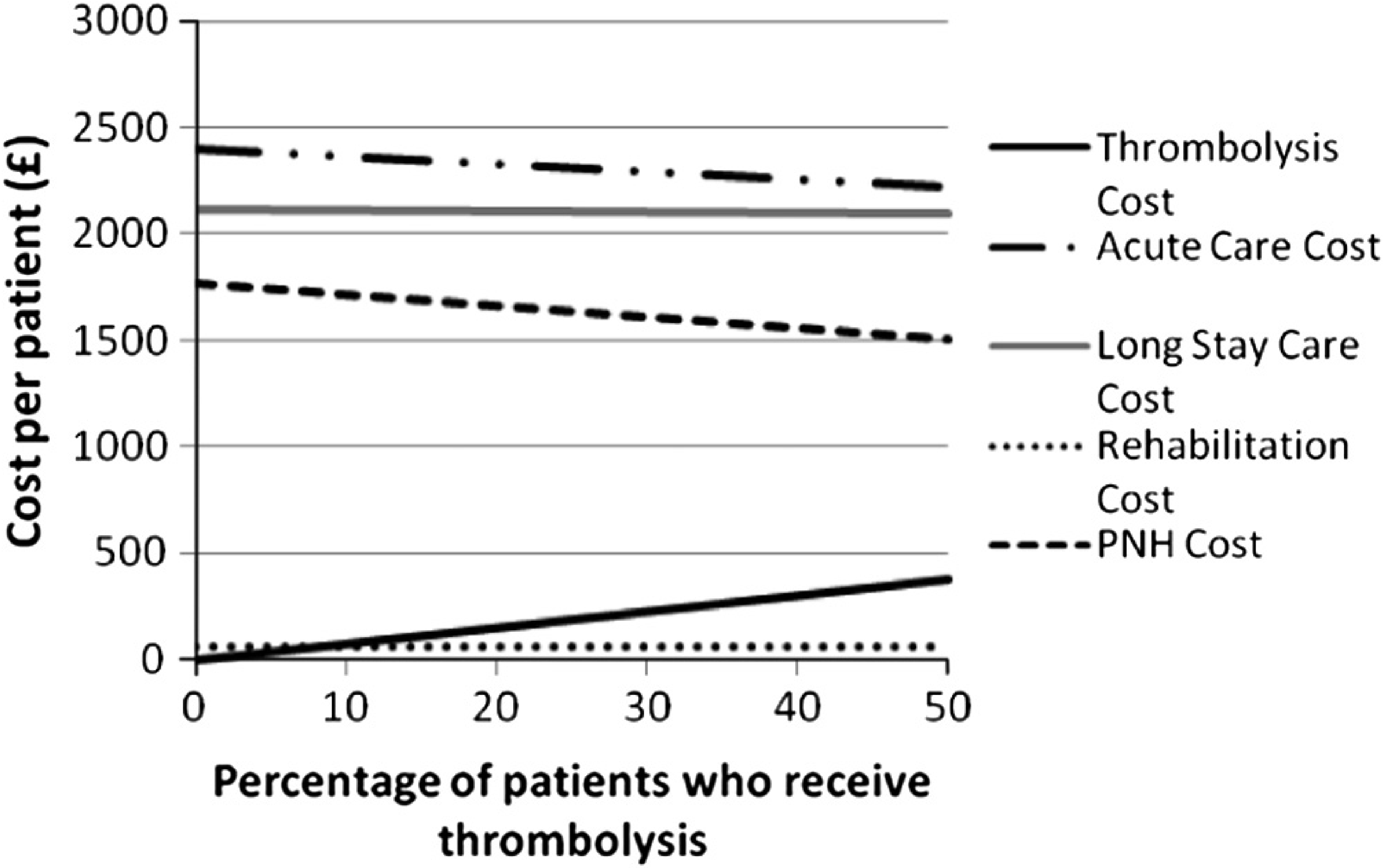
  - This requires a major overhaul of stroke services
  - It is crucial that the development of thrombolysis services are not at the expense of post stroke services in the community.

The SIMUL8 Simulation Model



Sally I. McClean, Jennifer Gillespie, Lalit Garg, Maria Barton, Bryan W. Scotney, Ken Fullerton: Using phase-type models to cost stroke patient care across health, social and community services. European Journal of Operational Research 236(1): 190-199 (2014)

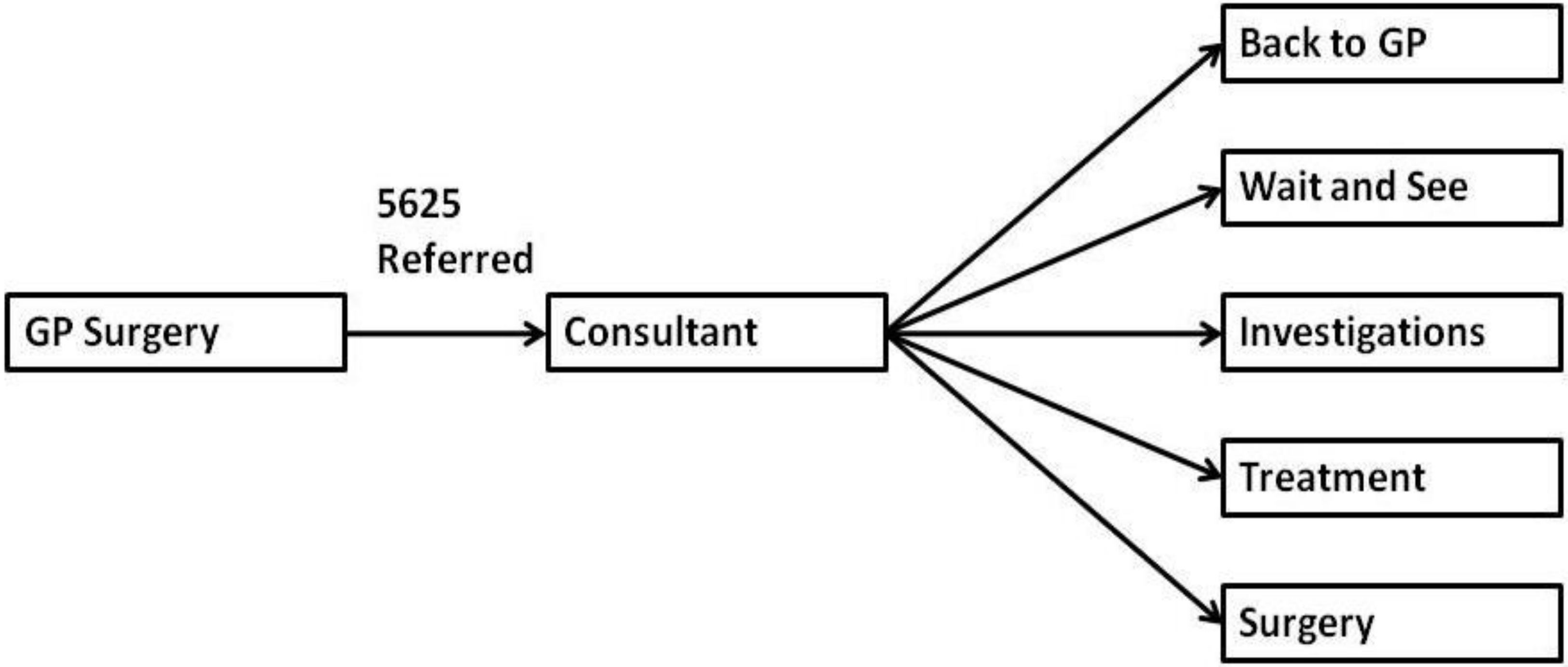
Thrombolysis costs



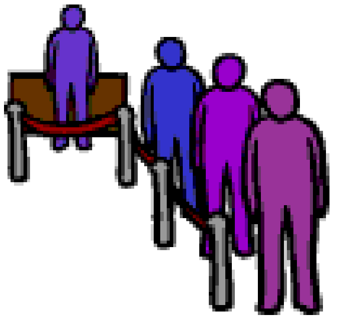
Barton Maria, McClean Sally, Gillespie Jennifer,, Lalit Garg, David Wilson, Ken Fullerton (2012). Is it beneficial to increase the provision of thrombolysis? – A discrete-event simulation model. QJM, Oxford Journals 2012.

A Case Study: Modelling Orthopaedic ICATS

The Orthopaedic Process in the UK before ICATS was introduced



The Problem

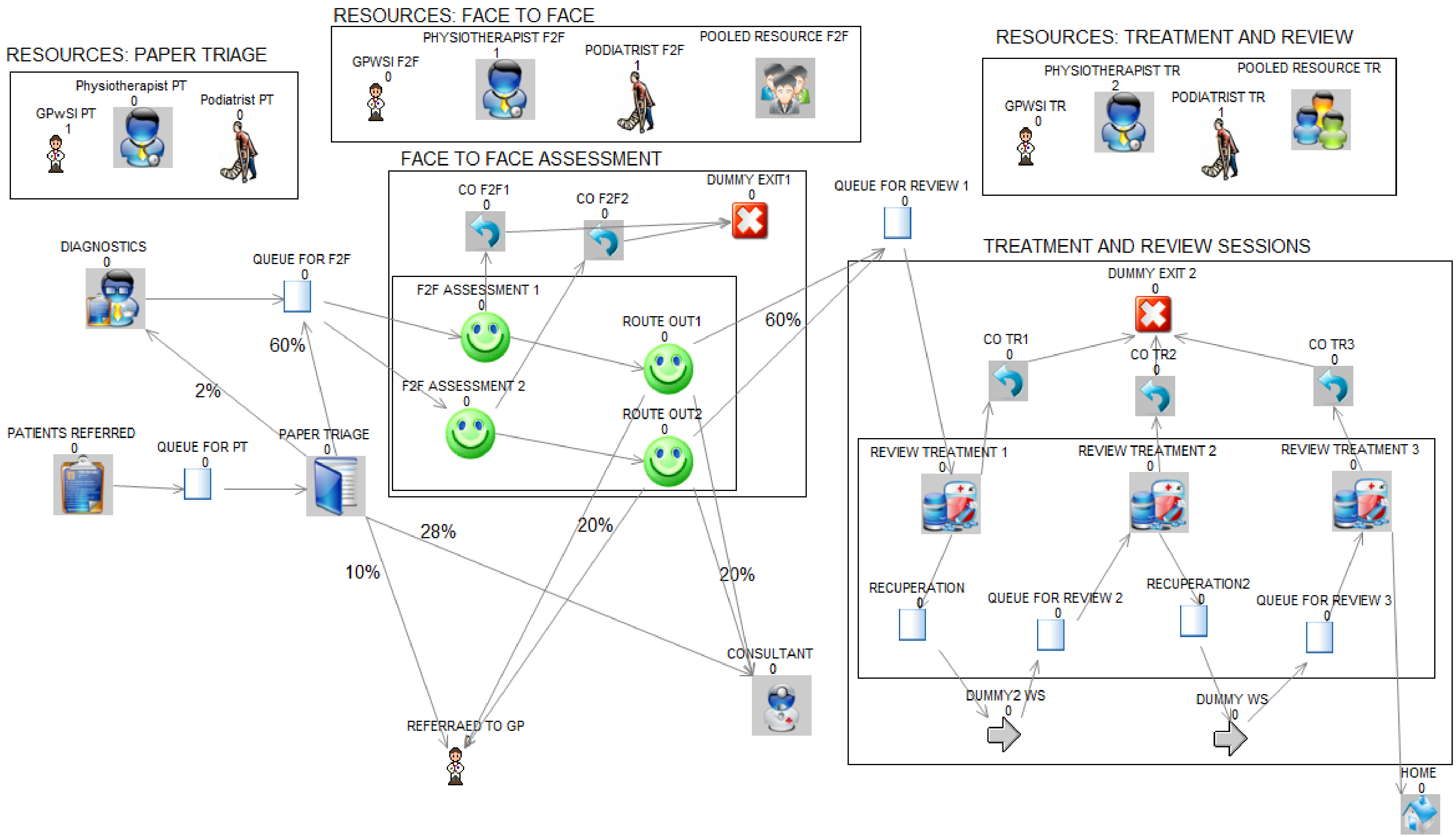


- Due to all patients having to wait for an appointment with an orthopaedic surgeon a bottleneck was created.
- Patients had a waiting time of up to 52 weeks.

The Solution

- To introduce a new system, ICATS, to manage orthopaedic referrals.
- Introduced in 2005 to GB.
- Introduced in 2007 to Northern Ireland.

The Final ICATS Simulation model



Towards an evidence-based decision making healthcare system management: Modelling patient pathways to improve clinical outcomes

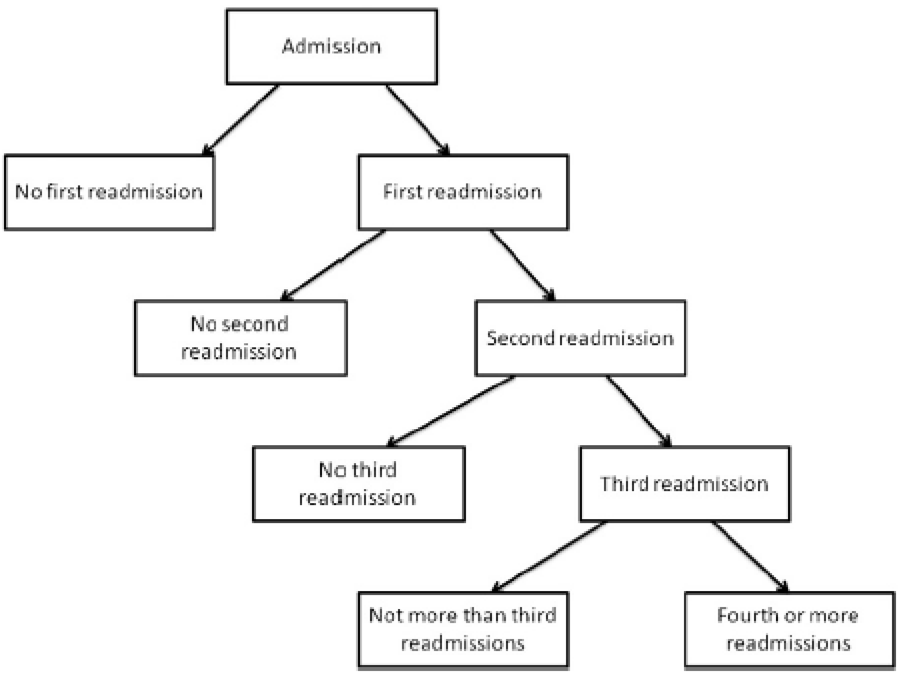


Fig. 1. Multiple readmissions as disease progression.

Shola Adeyemi, Eren Demir, Thierry Chaussalet

Decision Support Systems 55 (2013) 117–125

- We study individual clinical pathways for chronic obstructive pulmonary disease (COPD).
- Data were extracted from the national English Hospital Episodes Statistics dataset.
- First readmission signifies a problem in the process of care may be the beginning of many subsequent readmissions.
- This model could be a valuable tool for informed decision making in the management of diseases.

Reduced outpatient waiting times with improved appointment scheduling

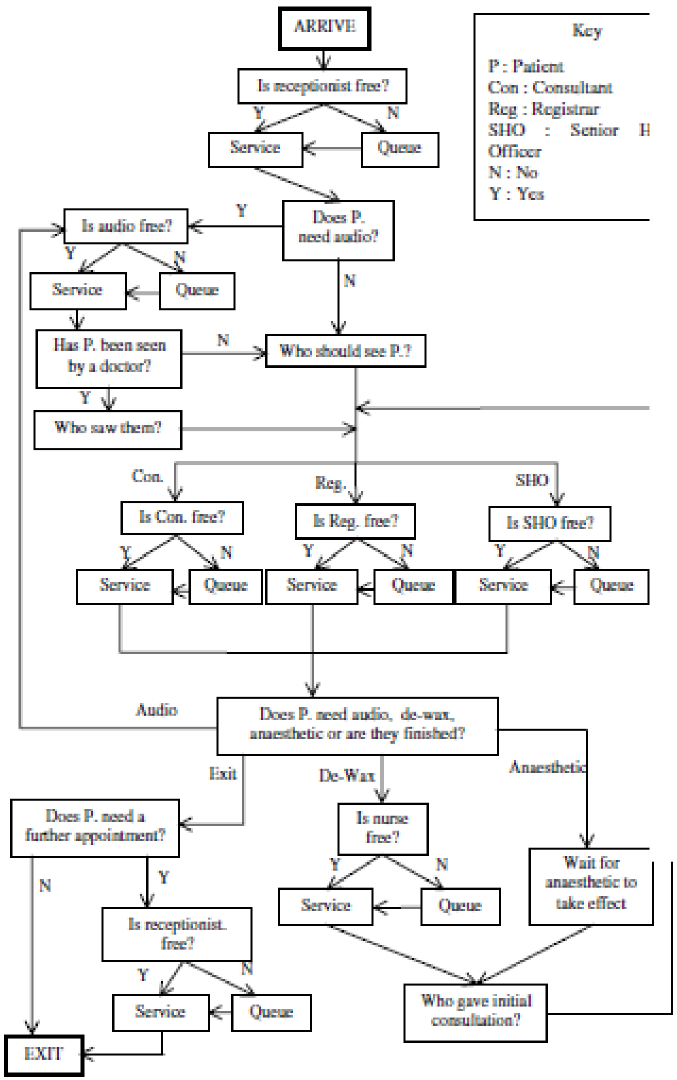


Fig. 2. Patient flows through the ENT clinic

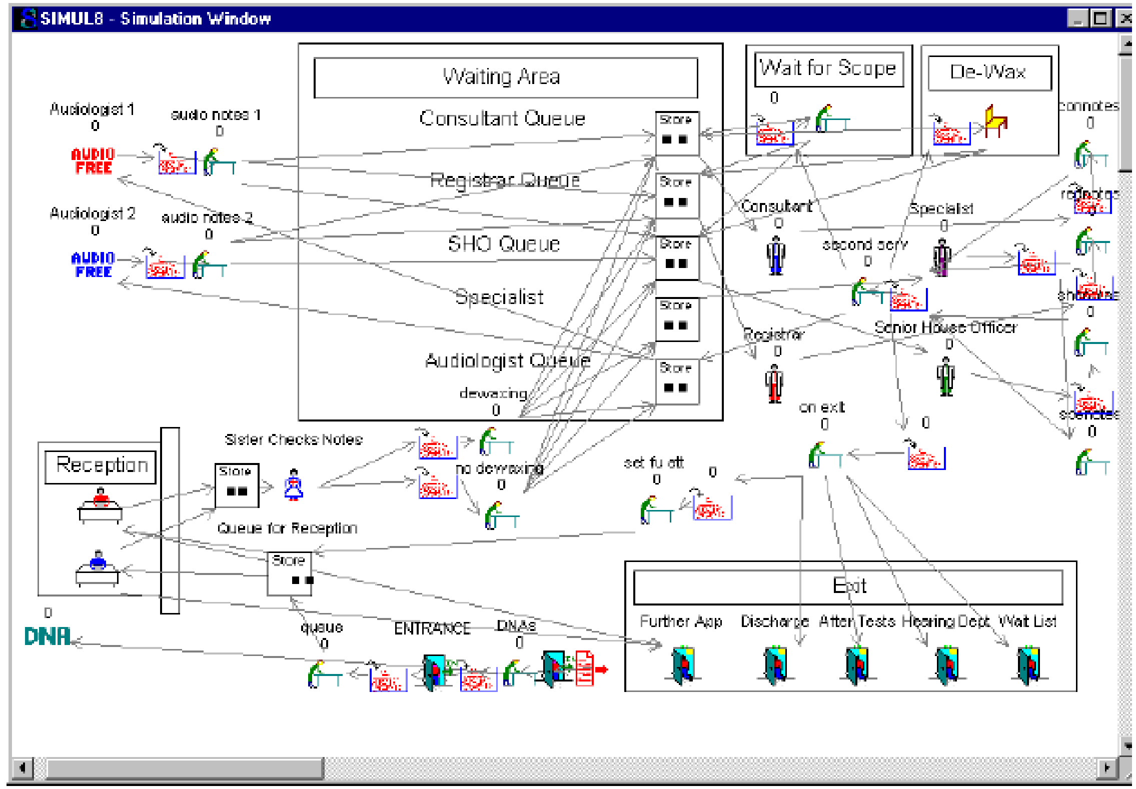


Fig. 5. Simul8 screenshot showing patient pathway routing arrows within the clinic

P.R. Harper and H.M. Gamlin

OR Spectrum (2003) 25: 207–222

Evaluating knee replacement surgery

Based on early short-term results, the model suggests that, in the longer term, computer-assisted TKR is highly likely to be cost-saving and to offer a small QALY advantage.

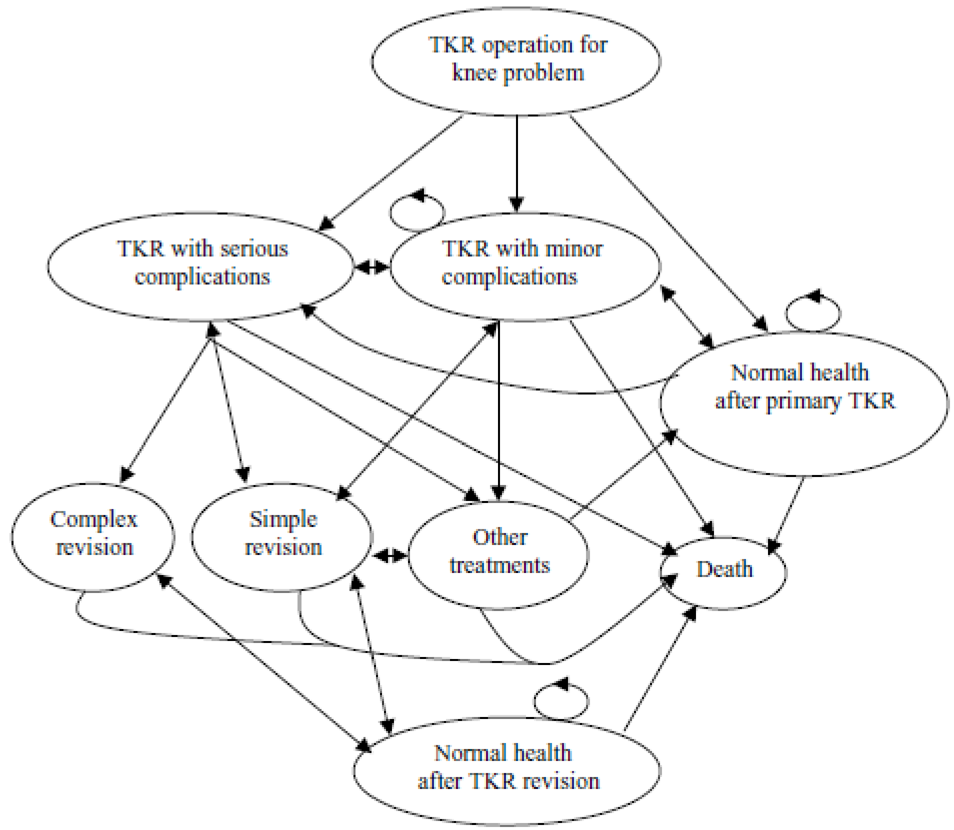


Figure 1. Markov state transition model for total knee replacement (TKR).

Hengjin Dong, Martin Buxton (2006) Early assessment of the likely cost-effectiveness of a new technology: A Markov model with probabilistic sensitivity analysis of computer-assisted total knee replacement. International Journal of Technology Assessment in Health Care, **22:2** (2006), 191–202.

Patient Pathways can be at different levels of detail

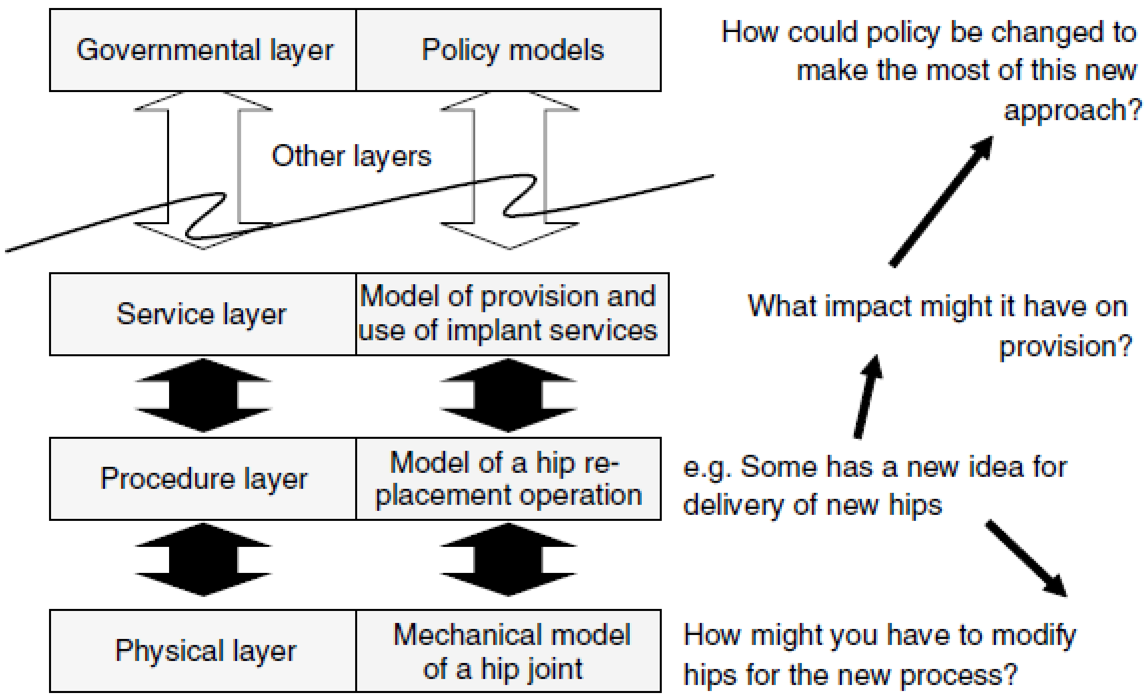


Figure 2 An example of multi-layered modelling.

T Eldabi, RJ Paul and T Young (2007) Simulation modelling in healthcare: reviewing legacies and investigating futures. Journal of the Operational Research Society 58, 262 --270

- Figure 2 shows various perspectives on hip replacement—from the physical aspects of technology and placement, through to policy and national provision.
- There are appropriate modelling techniques for each of these, although policy models, for instance, would tend to be quite different from physical models of hip behaviour.
- Process models addressing the intermediate layers might focus on logistics or service provision.

Meeting the four-hour deadline in an A&E Department

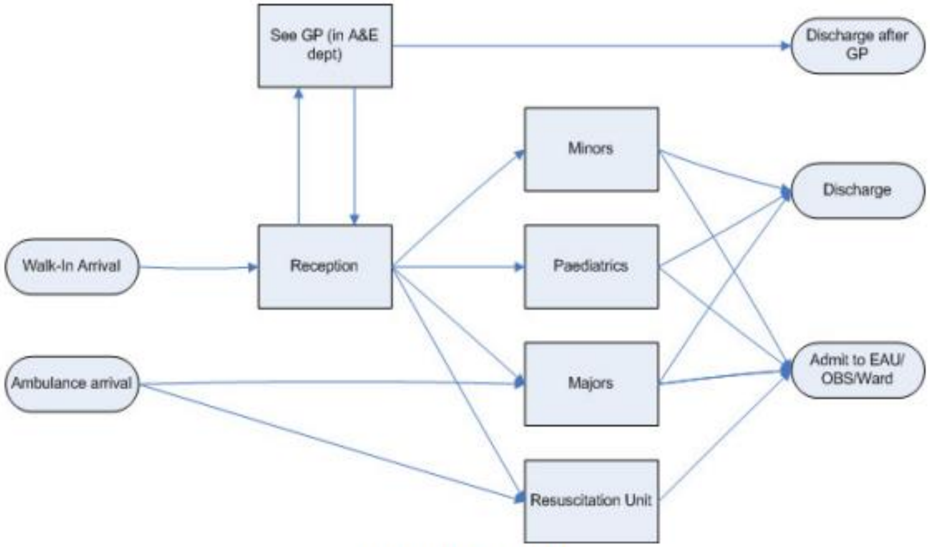


Fig. 1 Overview of model

The simulation demonstrates the coping strategies, such as re-prioritising patients based on current length of time in the department, have an impact on LoS of patients and therefore need to be considered when building predictive models.

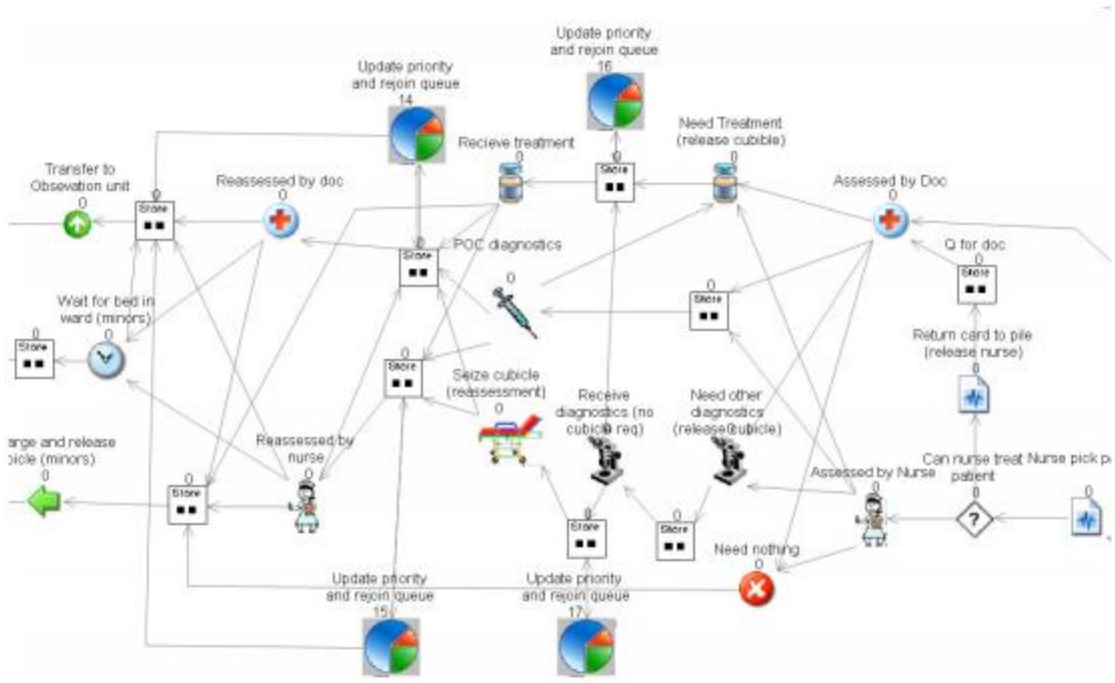


Fig. 2 Minors area of model

Eatock, J., Clarke, M., Picton, C., & Young, T. (2011). Meeting the four-hour deadline in an A&E department. *Journal of health organization and management*, *25*(6), 606-624.

Performance Evaluation Process Algebra (PEPA)

- The PEPA language serves two purposes:
  - as a formal description language for system models to predict performance.
  - As a description of behaviour where the model can reason about functional behaviour (e.g. deadlocks).
- Reasoning in PEPA models uses derivation graphs to represent the state transition diagram of the underlying Markov model.
- The PEPA Workbench is a prototype tool which supports checking of the well-formedness of the PEPA model through the creation of state The tool is implemented in Standard ML.

Gilmore, S., & Hillston, J. (1994). The PEPA workbench: A tool to support a process algebra-based approach to performance modelling. *Computer performance evaluation modelling techniques and tools*, 353-368.

Modelling and Performance a Analysis of clinical pathways using PEPA

- The Imperial Clinical Pathway Analyzer (ICPA) simulates stochastic behaviours of a clinical pathway by extracting information from public clinical databases .
- The performance of this clinical pathway, including KPIs such as throughput, resource utilisation and passage time can be quantitatively analysed using PEPA.
- By constructing the stroke clinical pathway, ICPA can use PEPA to analyse the performance in terms of KPIs such as throughput and passage time.

Simplified Stroke Clinical Pathway

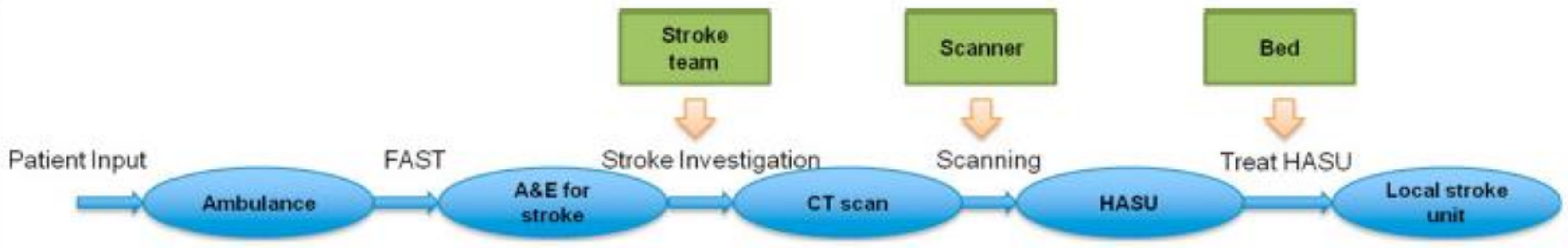


Figure 9 Simplified stroke clinical pathway.

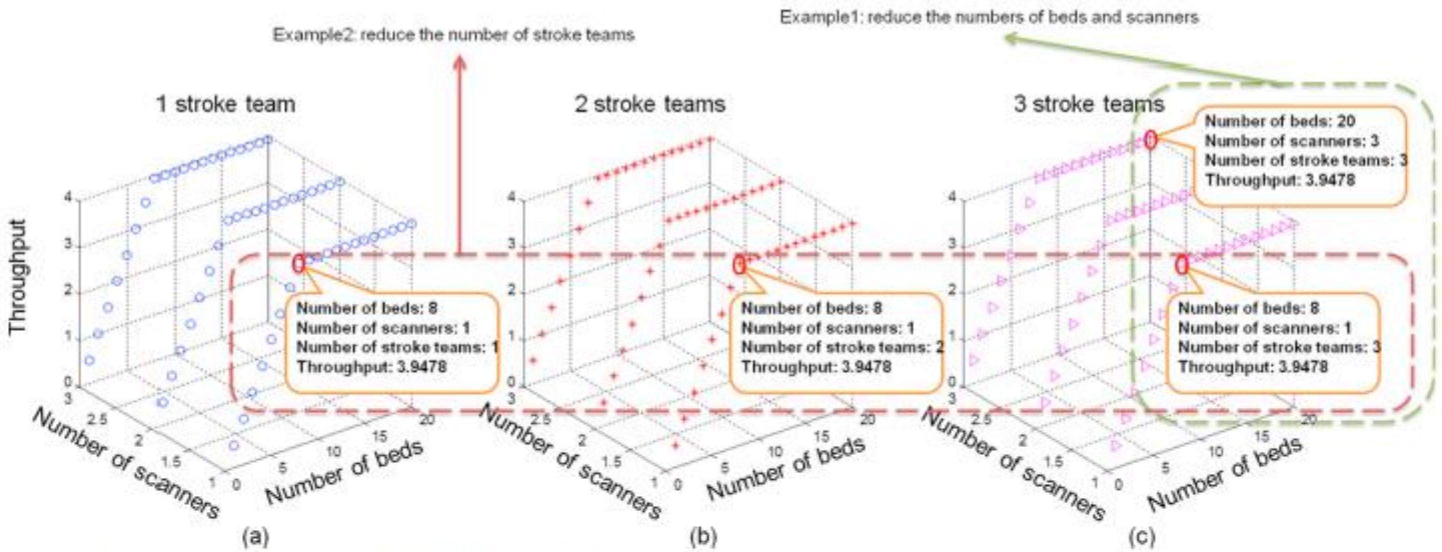


Figure 10 Resource optimization of clinical pathway. The number of scanners varies from 1 to 3 and the number of beds ranges between 1 and 20 in each graph. The number of stroke team is set to 1 in (a), 2 in (b) and 3 in (c) respectively. The maximum throughput of 3.95 can be achieved in (a), where there are 1 stroke team, 1 scanner and 8 beds.

Yang, X., Han, R., Guo, Y., Bradley, J., Cox, B., Dickinson, R., & Kitney, R. (2012). Modelling and performance analysis of clinical pathways using the stochastic process algebra PEPA. *BMC bioinformatics*, *13*(14), S4.

Future directions

(Mahmoud Elbattah and Owen Molloy NUIG, 2015)

- The paper aims to convey considerations in relation to improving the modeling and simulation of clinical pathways (CPs). We formulate our view based on observations and findings stemming from a systematic literature review.
- A clear finding of the review is that there is a need to establish a common research agenda for modeling and simulation of CPs, and for future studies to pay particular attention to fit their research methods to the state of prior work.
- Suggested future directions are:
  - Development of a conceptual reference model for Clinical Pathways
  - Adoption of a multi-perspective modeling approach that can integrate clinical, operational, financial and demographic dimensions of CPs.
  - Development of a generic semantic-based modeling that can realise higher semantic abstraction of CPs.
  - Adoption of Linked Data concepts and principles.

Elbattah, M., & Molloy, O. (2015). Towards Improving Modeling and Simulation of Clinical Pathways: Lessons Learned and Future Insights. In *SIMULTECH* (pp. 508-514).

Advances in Quantitative Verification for Ubiquitous Computing

Marta Kwiatkowska (Oxon)

- Rigorous model-based design methodologies are required for Ubiquitous Computing to ensure the safety and reliability of software embedded in devices
- Quantitative verification is a powerful technique for analysing system models against quantitative properties such as “the probability of a data packet being delivered within 1ms to a nearby Bluetooth device is at least 0.98“
- The probabilistic model checker PRISM has proved useful by detecting and correcting flaws in a number of ubiquitous computing applications.

Key limitations of current techniques

- Poor scalability of quantitative verification;
- Lack of effective methods for integrating discrete, continuous and stochastic dynamics;
- Poor efficiency of quantitative runtime verification.

- The scale and complexity of the ubiquitous computing scenarios are so great that the challenges that remain seem prohibitive. We anticipate that following topics will be particularly difficult:
  - scalability of quantitative verification; compositional quantitative frameworks; effective runtime steering; quality assurance for embedded software;
  - efficiency of strategy synthesis for autonomous control in dynamic scenarios; and
  - quantitative verification for stochastic hybrid systems.

Kwiatkowska, M. (2013, September). Advances in quantitative verification for ubiquitous computing. In *International Colloquium on Theoretical Aspects of Computing* (pp. 42-58). Springer Berlin Heidelberg.

Modelling Care Pathways in a Connected Health Setting

- In a connected heath environment, stakeholders can struggle to make best use of this information coming from a variety of sources.
- This paper investigates the challenge of how to use available information to make informed decisions about the care pathway which the patient should follow to ensure that prevention and treatment services are efficient and effective.
- Empirical evidence can be used in the development of the models through following an evolutionary multi-method research approach.
- Further research is needed to support the definition of what, when and how tasks are used for specific contexts, domains or organization in the Connected Health setting.

O'Leary, P., Buckley, P., & Richardson, I. (2013, August). Modelling care pathways in a connected health setting. In *International Symposium on Foundations of Health Informatics Engineering and Systems* (pp. 32-40). Springer Berlin Heidelberg.

Conclusion

- Care Pathways can be used for:
  - **Correctness**: does the pathway make sense
  - Predicting **performance**
    - Durations of pathway
    - Success rates
    - Compliance with requirements
    - Pathway restructuring
    - Assessing new processes.
    - Assessing new technologies
      - The business case.