Institution: Cardiff University

Unit of Assessment: 10

Title of case study: Mathematics and Healthcare: Saving Lives and Reducing Costs

1. Summary of the impact (indicative maximum 100 words)

Research conducted at the School of Mathematics at Cardiff University has engineered lifesaving, improvements to UK healthcare systems. New mathematical models, accounting for the complexity and diversity of the health system, have been created and applied in a variety of contexts to markedly enhance the efficiency and effectiveness of a wide range of healthcare services - at policy, commissioning and operational levels. The extensive benefits include:

- Reducing the mortality of trauma patients across South London by 54% (equating to 0.7 additional survivors out of every 100 patients for the period 2010-2012, rising to 4.2 in 2013)
- Reducing the mortality of stroke patients across South London by 60% through the creation of a new Stroke Unit, based on the research findings (the services were rated as the best in the country by the National Sentinel Audit 2010 organised by the Royal College of Physicians).
- Realising net efficiency gains of £1.6m per year in the emergency department at University Hospital of Wales;
- Provision of hospital capacity planning tools in use across the UK

This work has been disseminated nationally and internationally, in the media and at a range of events designed to engage the public with Mathematics. Therefore the impacts claimed in this case study are health, economic benefits and public engagement.

2. Underpinning research (indicative maximum 500 words)

Modelling health systems requires the development of suitable mathematical models that are able to account for dynamic processes, stochastic conditions, and high levels of complexity. This has been achieved by the Operational Research (OR) group at Cardiff University from 1993-2012. The range of methodologies employed may be categorised as follows:

Queueing Systems (*Griffiths, Harper, Williams and Knight)*

Patient movements through healthcare systems (care-pathways) can be represented by flows through networks of queues constrained by available resources. Previous contributions in queueing theory have focussed on bulk service queues and time-dependent queueing models. Theoretical work has made significant progress with the transient solution of queueing systems and the time-dependent nature of queues including multi-server queues with priority (3.1) The stochastic nature of demand on acute hospital services and the expected consequences on resource requirements, taking into consideration both intra week and monthly seasonality, required the development of a complex simulation packages by members of the OR group. These packages enable simulation studies to be performed quickly and efficiently, without highly specialised expertise and extensive configuration times (3.2).

Exploiting known information on patient characteristics, such as age, gender, socio-economic status etc, can allow for predictions on individual patient resource needs and outcomes. Novel work on developing a discrete conditional phase-type framework demonstrated the benefits of Coxian phase-type distributions interfaced with classification tree algorithms. Underpinning work also embedded Coxian phase-type service time fits within *M*/*PH*/*c*/*NPRT* priority queueing and simulation models (3.3).

Behavioural Modelling (*Harper, Griffiths, Williams and Knight)*

It is well observed that individual behaviour can affect the efficiency of queueing systems. To address such issues, using theoretical insights from routing game theory, algorithmic approaches for obtaining the price of anarchy were proposed. Theoretical results were obtained as to the demand and worth of service. It was shown that in a public service system, with an adequate capacity to provide the perceived worth of service, a high price of anarchy is to be expected (3.4).

Recognising that the structure of social networks also play an important role in the dynamics of healthcare processes, research explored small world principles to capture disease propagation dynamics as well as agent based simulation investigations into the consequential effects of social networks and behavioural (3.5). For the first time in the literature, formal psychological models (such as theory of planned behaviour) were integrated with physiological parameters within the same clinical model to provide greater understanding of the importance of human behaviour in healthcare simulations.

Facility Location (*Harper and Knight)*

The research considered the development of mathematical models for locating facilities, including those within hierarchical systems. The novelty and contribution of this work was to incorporate both equity and efficiency parameters into proposed classes of optimisation model, thus permitting decision making when considering both 'fair' and 'efficient' locations. Other research proposed new mathematical formulations for locating emergency medical services that incorporate the survival of heterogeneous patient classes. An extended iterated method of solving the model was developed that uniquely takes in to account the reactive nature of the stochastic conditions (3.6).

Key staff contributing to the research: Professor Jeff Griffiths (academic staff 1964-), Professor Paul Harper (academic staff 2007-), Dr Janet Williams (academic staff 1988-2013) and Dr Vincent Knight (research associate 2009-2011, academic staff 2011-).

3. References to the research (indicative maximum of six references)

3.1. **Griffiths JD, Leonenko G and Williams JE** (2006)**,** "The Transient Solution to M/Ek/1 Queue". *Operations Research Letters*, 34(3): 349-354. http://dx.doi.org/10.1016/j.orl.2005.05.010 Copy held by HEI, available on request.

3.2. **Griffiths JD, Knight VA and Komenda I** (2013), "Bed Management in a Critical Care Unit". *IMA Journal of Management Mathematics*. 24(2): 137-153. http://dx.doi.org/10.1093/imaman/dpr028 Copy held by HEI, available on request.

3.3. **Harper PR, Knight VA** and Marshall AH (2012), "Discrete Conditional Phase-type Models Utilising Classification Trees: Application to Modelling Health Service Capacities". *European Journal of Operational Research*. 219(3): 522-530. http://dx.doi.org/10.1016/j.ejor.2011.10.035 Copy held by HEI, available on request.

3.4. **Knight VA and Harper PR** (2013), "Selfish Routing in Public Services". *European Journal of Operational Research*. 230(1): 122-132. http://dx.doi.org/10.1016/j.ejor.2013.04.003 Copy held by HEI, available on request.

3.5. Vieira IT**,** Cheng RCH, **Harper PR** and de Senna V (2010), "Small World Network Models of the Dynamics of HIV Infection". *Annals of Operational Research*. 178: 173-200. http://dx.doi.org/10.1007/s10479-009-0571-y Copy held by HEI, available on request.

3.6. **Knight VA, Harper PR** and **Smith L** (2012), "Ambulance Allocation for Maximal Survival with Heterogeneous Outcome Measures". *OMEGA: The International Journal of Management Science*. 40(6): 918-926. http://dx.doi.org/10.1016/j.omega.2012.02.003 Copy held by HEI, available on request.

4. Details of the impact (indicative maximum 750 words)

The mathematical models developed by the OR group at Cardiff University have been applied to a wide range of healthcare services, in a variety of hospitals, across the UK. The impacts directly

arising from the research are highly significant and include:

Health Benefits

The research has been used in a major new trauma centre that opened in 2010, at St George's Hospital in London (a capital investment of £3.6m). The models were used to create service level agreements (annual capacity planning) with commissioners over several years and, importantly, informed the required patient-flows and resourcing levels for the centre. This enabled patient waiting time to be reduced and better levels of patient care achieved through improved resource management and greater efficiency. The result has been an observed increase in survival rates of 54%. Jen Goddard, Business Analyst at St. George's Hospital, stated, "The research and tools that Cardiff University provided have been extremely useful to St George's, enabling us to understand and model our data and use it to significantly improve patient care and resource management. Mortality rates have fallen as a consequence of the implementation of the Major Trauma Centre and the Hyper Acute Stroke Unit." (5.1)

The models were similarly utilised by a new hyper-acute stroke unit covering the South London area. The new unit and stoke care service were rated as the best in the country by the National Sentinel Audit 2010 organised by the Royal College of Physicians. The outcomes were again lifesaving; significantly lowering risk-adjusted mortality for stroke patients to 60%. This is verified by data comparing mortality rates pre and post the implementation of the research (provided by Jen Goddard, St. George's Hospital). (5.1)

Patient care and hospital resources have also been significantly improved, through the work of the OR team, at a major neurological rehabilitation hospital in South Wales (Rookwood Hospital, Cardiff). Previously the complex scheduling of inpatient physiotherapy sessions was undertaken manually which was time consuming and amounted to a clinician spending one day per week assembling the following week's timetable. The research enabled the scheduling process to be automated; the computerised new system has been implemented since January 2011. It produces a vastly enhanced schedule within minutes, enabling clinicians to devote more time to assessing patients' needs and delivering medical care. Jakko Brouwers, Senior Service Improvement Programme Manager at the Hospital commented, "Your research work with our Department of Specialist Physiotherapy and Rehabilitation at Rookwood Hospital has had a huge impact on how we utilise our resources. … The automated computer scheduling creates a fairer system for patients as it takes into account what treatment the patient received the previous week." (5.2)

The work at Rookwood Hospital also included a detailed queueing analysis of their patient admission and discharge process, with particular emphasis on tailoring physiotherapy treatment to the needs of the patient. This optimised the length of stay in the unit and provided improved quality of life for patients. Jakko Brouwers added, "The service modelling work has been a real asset in that it has opened the eyes of the operational service manager to the issues regarding patient flow. These insights are now used on a regular basis in waiting list management and admissions meetings." (5.2)

The research has been particularly significant to the Welsh Ambulance Service Trust (WAST). Like all Emergency Medical Services WAST is under increasing pressure to provide wide geographical coverage and improve performance to meet Government set response times. The work at Cardiff University has helped WAST by forecasting 999 calls by category of call and providing valuable evidence to confirm the importance of ambulance allocations based on patient outcomes for different conditions (using survival probabilities) as opposed to only those based on hard time targets (e.g. 8 minute response). This means that extra lives can be saved. Researchers at Cardiff University have quantified the relationship between overall service performance and changes to durations in each phase. Critically, the findings show that reducing the time of the patient handover from ambulance to the emergency department at hospitals makes the biggest impact on overall WAST performance. Richard Whitfield, the Research and Development Manager at WAST stated that "the work is an extremely relevant contribution to implementing policy and procedural changes at WAST." (5.3)

Financial Benefits

The research entailed modelling the Emergency Unit (EU) at the University Hospital of Wales (UHW). This enabled the hospital to examine the reconfiguration of services and identify problems in the system. Subsequently major changes were implemented, based on the results of the research, leading to a huge alteration in patient flows in the EU. This meant that the hospital was able to reduce staffing levels and the number of trolleys by 43%, amounting to a net efficiency gain of approximately £1.6m. Andrew Nelson, Director of Acute Services, Cardiff and Vale University Health Board, commented, "The modelling work provided by the Maths school has been the basis of our plans for the current major re-design and refurbishment of the Accident and Emergency Department at the University Hospital of Wales. This is the second major change resulting from the work undertaken by the maths school to improve our knowledge of demand and capacity within the department and how we can best equip the department to improve performance and overall cost effectiveness". (5.4)

The models were used to evaluate the impact of the South Wales Development Programme, leading to a £4.2 million investment in system wide capacity. This has allowed Cardiff and Vale University Health Board to better align resources with the needs of patients. Moreover, it has formed the basis of a successful joint bid with Social Services for a £2.5 million invest-to-save scheme with the Welsh Government to improve non-emergency transport services for hospital patients. (5.4)

Public Engagement

The research has been widely disseminated in the UK and overseas and has led to a significant level of public engagement. Examples of this include a series of four radio programmes that were aired on BBC Radio Wales (2010) as part of its weekly programme called 'Science Cafe'. Seminars have been given in America at Princeton University, New Jersey; Columbia University, New York; Baylor University, Texas. The audiences comprised of a mixture of nonspecialists, teachers and students. Professor Griffiths has also spoken at the Cardiff Scientific Society, which seeks to extend interest in the application of Science to everyday life. His latest talk in October 2012 was entitled "Some Queues I've enjoyed". Professor Harper has also given a wide range of public talks including speaking at the Cardiff University's Innovation Network event in April 2013. This was attended by 70 delegates, including health care professionals, who scored the event 4.2 out of a possible 5. (5.5)

Outreach activities, where the healthcare modelling research has heavily featured, have involved over 500 school children. Regular sessions are given, for example, at the Monmouth Science Initiative (www.monmouth-science.co.uk). (5.6) Online resources, concerning healthcare modelling topics, have also been created for teachers and students, and are also part of national initiatives such as that by the OR Society (www.learnaboutor.co.uk). (5.7)

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Business Analyst, Strategy, St George's Healthcare Trust, London. *Corroborates the use and impact of the models at St George's Hospital.*
5.2 Senior Service Improvement Programme Manager, Rockwood Hospital. *Corroborates the use and impact of the models at Rockwood Hospital.*
5.3 Clinical R&D Manager, Welsh Ambulance Service NHS Trust. *Corroborates the value of the research to WAST.*
5.4 Director of Acute Services, Cardiff and Vale University Health Board. *Corroborates the use and impact of the models at the University Hospital of Wales.*
5.5 http://www.innovation-network.org.uk/events/innovation-in-healthcare-wed-17-apr-2013.aspx *Provides an example of the public talks given as a result of the research.*
5.6 http://www.monmouth-science.co.uk/programme/physics/ *Confirms Cardiff's involvement in outreach activities, stemming from the research.*
5.7 http://www.profpaulharper.com/home/school-outreach
Confirms that online resources for teachers have been developed from the research.