Institution: Cardiff University

Unit of Assessment: Mathematical Sciences (10)

Title of case study: Improving patient outcomes and reducing healthcare costs in the UK and Germany

Period when the underpinning research was undertaken: 2009-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Daniel Gartner	Senior Lecturer	04/01/2016 – present
Paul Harper	Professor	01/09/2007 – present
Vincent Knight	Senior Lecturer	01/04/2009 – present
Tracey England	Research Associate	01/02/2011 – 31/10/2020

Period when the claimed impact occurred: 2015 – 2020

Is this case study continued from a case study submitted in 2014? No

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

Increasing demand on healthcare systems requires innovative resource management to improve patient outcomes while remaining cost-effective. Cardiff University research into queueing theory, optimisation methods, and scheduling enabled substantial efficiency gains in the healthcare sector. Through these mathematical methods, Cardiff's research was fundamental to healthcare improvement projects in the UK´s National Health Service (NHS) and within a university hospital in Germany. This included improvements in operating theatre efficiency for a new £350M hospital, cost reduction and environmental benefits for bronchoscopy device logistics, improving health outcomes within a community mental health service, and reducing instances of pressure ulcers through improved understanding of staff behaviours and care. The combined interventions for the NHS and the German hospital saved approximately £12.2M.

2. Underpinning research (indicative maximum 500 words)

Healthcare systems typically operate in environments of uncertainty and variability within highly complex and connected networks. Hundreds of patients may pass through different care pathways each day, each of whom require varying resources to treat them efficiently and effectively. The Cardiff Operational Research (OR) group investigates the application of mathematical modelling to improve health outcomes and service delivery. Modelling is used to forecast demand, schedule clinics, calculate the required workforce size and mix of skills to correctly roster staff, schedule operating theatres and assignment of surgeons, and reduce waiting times and cancellations, among other uses.

2.1 Meeting Healthcare Needs

Patient movements through healthcare systems can be represented by networks of queues constrained by available resources. The stochastic nature of demand on acute healthcare services and the consequences for resource requirements, required the development of complex methods and simulations by the OR group.

The Cardiff modelling approach combined machine learning and conditional phase-type models to capture resource needs and risk predictors enabling better prediction service times in healthcare settings **[3.1]**. Further research paired queueing theory with optimisation methods to determine (a) appropriate size and skill-mix of hospital staff **[3.2]** and (b) scheduling of hospital-wide resources in a flexible and agile manner by approximating patient length of stay and resource capacity across flexible variables using a rolling horizon approach **[3.3]**.

The Cardiff team also optimised use of equipment in healthcare settings. For example, the optimisation of order sets to reduce clinical workload in the care prescription process by using a Greedy algorithm **[3.4]** and determining the optimal mix of bronchoscopes through a

strategic decision support tool **[3.5]**. These methods can be performed quickly and efficiently and are designed for use by hospital planners without highly specialised expertise.

2.2 E-HOSPITAL

Healthcare settings require decision-making at every level, from strategic decisions around staffing levels and equipment, to effective triaging of patients day-to-day. The Cardiff OR group, in collaboration with healthcare providers at Aneurin Bevan University Health Board **[G3.1]**, worked extensively since 2014 to develop a software suite able to address the complex needs of healthcare providers. This research was extended by combining the underpinning methodological concepts into a novel comprehensive modelling platform known as E-HOSPITAL **[3.6]**.

E-HOSPITAL is the only platform which combines strategic, tactical, and operational decision levels for healthcare operations in one platform. It contains multiple planning approaches published in the literature, such as case mix planning on the strategic level, as well as scheduling problems on the tactical and operational level. It features real-world-motivated extensions of planning decisions (e.g. enabling incorporation of therapy planning in case mix decisions). These test cases are instanced and solved, and the results fed back to the graphical user interface to be reviewed.

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

[3.1] 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. doi: 10.1016/j.ejor.2011.10.035.

[3.2] Harper PR, Powell NP and Williams JE (2009). 'Modelling the Size and Skill-mix of Hospital Nursing Teams'. *Journal of the Operational Research Society* 61(5): 768-779. doi: 10.1057/jors.2009.43.

[3.3] Gartner D and Padman R (2019). 'Flexible Hospital Wide Elective Patient Scheduling'. *Journal of the Operational Research Society*, 71 (6): 878-892. doi: 10.1080/01605682.2019.1590509.

[3.4] Gartner D, Zhang Y and Padman R (2019). 'Reducing clinical workload in the care prescription process: Optimization of order sets'. *IMA Journal of Management Mathematics* 30(3): 305-321. doi:10.1093/imaman/dpy018.

[3.5] Edenharter GM, **Gartner D** and Pförringer D (2017). 'Decision Support for the Capacity Management of Bronchoscopy Devices: Optimizing the Cost-Efficient Mix of Reusable and Single-Use Devices Through Mathematical Modelling'. *Anesthesia & Analgesia*, 124(6):1963–1967. doi: 10.1213/ANE.0000000000001729.

[3.6] Gartner D and Padman R (2017). 'E-HOSPITAL – A Digital Workbench for Hospital Operations and Services Planning Using Information Technology and Algebraic Languages.' *Studies in Health Technology and Informatics* 245: 84-88. PMID: 29295057.

Selected grant:

[G3.1] Harper PR, **Gartner D**, **Knight VA** (Mathematical Modelling Research Unit), Aneurin Bevan University Health Board. June 2014 to December 2021, £685,163.

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

Cardiff researchers formed strategic alliances with multiple Welsh NHS health boards to engage healthcare professionals with Operational Research (OR). Application of the research outlined in Section 2: **1)** provided healthcare decision-makers with reliable modelling data to better provide service to patients, while training NHS staff to further improve their data analysis services. Through this engagement, the research led to: **2)** improved hospital designs; **3)** increased efficiency of frontline mental health services; and **4)** reduced instances of painful pressure ulcers.

4.1 Setting up dedicated modelling units in NHS Health Boards

Harper is a founding Director of the Health Modelling Centre Cymru (hmc^2), which works with clinicians and NHS managers to apply modelling techniques to healthcare settings. In 2014, hmc^2 partnered with the Aneurin Bevan Continuous Improvement Unit (ABCi), which provides mathematical modelling capability for the Aneurin Bevan University Health Board (ABUHB). To support this work, the Cardiff team established the Mathematical Modelling Unit within ABCi, additionally training NHS staff in how to apply OR models to develop and test alternative approaches to healthcare management. Trish Chalk, Clinical Futures Lead at ABCi said of the partnership: "*This unique and innovative partnership has delivered considerable impact in developing and applying OR methods for improving our NHS services and patient outcomes*" **[5.1]**.

In addition, hmc^2 initiated the novel researchers-in-residence programme in partnership with NHS Wales, supporting both Aneurin Bevan and Cardiff and Vale University Health Boards, which collectively serve over 1.1 million people. This programme embedded modelling techniques within the improvement work undertaken at the health boards, for example: modelling the dynamics of day surgery flow and clinic flow at Royal Gwent Hospital to advise on capacity needs and to reduce patient waiting times; analysing the effect of individuals presenting in A&E under the influence of alcohol and to subsequently contribute to planning of a mobile emergency unit in Cardiff city centre on Friday and Saturday nights to alleviate pressures on A&E and limit disruptive behaviours towards staff **[5.2]**; and development of a text mining tool to analyse a backlog of more than half a million outpatient letters, saving £630,000 that had been reserved for manual data entry **[5.3]**. Judith Paget, Chief Executive of the Aneurin Bevan University Health Board, praised the collaboration and the outcomes upon the work of both health boards: "*The modelling unit's work has led to better planning and better analysis: far better decisions are made as a result of the input of the modellers*" **[5.4]**.

In 2015, the collaboration between Cardiff research and NHS practice was recognised by the *Times Higher Education* Awards and received the award for 'Outstanding Contribution to Innovation and Technology' **[5.5]**. The panel noted that "*such mathematical modelling has never been used before in the UK healthcare system*" and that the judges were "*impressed by the range of innovations achieved in a subject area not renowned for this type of collaboration*" **[5.5**, p.31**]**. Harper also received the Companion of OR award from the Operational Research Society, the panel noting that his work has "*a vision for sustained impact*" and that the ABCi Mathematical Modelling Unit be "*praised and aspired to by the health OR community*" **[5.6]**.

4.2 Improving the design and operation of hospitals

ABCi approached Cardiff University in 2016 requesting mathematical modelling support in the early-stage design of a proposed new hospital near Cwmbran, South Wales, which would serve a population of over 600,000. The E-HOSPITAL framework was used to assess the potential capacity and required capabilities of the hospital and optimise the flow of patients, reduce unnecessary surgical cancellations, reduce waiting times, and plan for safe care.

The ABCi unit specifically highlighted the role of the software in the development of the hospital plans: "*Dr Gartner and the team at Cardiff University School of Mathematics have been fundamental in helping us to design the new hospital using the E-HOSPITAL platform*" **[5.1]**. The proposed design, including the Cardiff-recommended structural changes, became the confirmed plans for the Grange University Hospital, a new 470-bed hospital supported by a £350M investment from Welsh Government. The hospital opened ahead of schedule on 17 November 2020 to assist the South Wales response to both Covid-19 and winter health pressures **[5.7]**.

Trish Chalk, Clinical Futures Lead at ABCi outlined the value of the E-HOSPITAL platform: *"Our provision was 32 operating theatres. Using E-HOSPITAL, you have helped us to identify smarter and more efficient scheduling of operating theatre sessions such that the total number of staffed operating rooms across ABUHB has been reduced by 2"* **[5.1]**. Chalk confirmed that this equates to a saving for the Health Board of around £900,000 each year, totalling £2.7M to date. Through early identification of surplus requirements, and the associated costs in

staffing operating theatres, the Health Board was able to reallocate resources previously earmarked for the surplus theatres: "*A substantial saving which means we can reinvest these funds into other aspects of our services*" **[5.1]**. The modelling was praised not only for the improved efficiency in financial costs, but also for maintaining the proposed level of service to the local population despite the reduced number of operating theatres: "*It should be noted that this reduction has been made possible even whilst accommodating for growth in demand"* **[5.1]**.

The Cardiff team also applied E-HOSPITAL to identify cost savings for University Hospital Munich. The platform was able to determine the optimal mix and inventory control of disposable and reusable bronchoscopy devices, eliminating the need for single-use disposable bronchoscopy devices. Dr Günther Edenharter, Specialist in General Medicine at University Hospital Munich, stated: "*Before your [Dr Gartner]'s work, we disposed of 950 units per year. Thanks to your work, we have removed entirely the need to dispose these units"* which has *"resulted in substantial environmental and economic savings*" **[5.8]**. CO_2 emissions have been reduced by six tons each year together with annual cost savings of €182,350 (around £152,252).

4.3 Supporting mental health outreach teams

Cardiff research supported the provision of mental health services across South Wales, focussing on Assertive Outreach Teams (AOTs). AOTs are a novel patient-led service which enable mental health professionals to identify and more readily respond to the needs of severely mentally ill adults, placing them on an appropriate care pathway to avoid progression of the patient's condition to the point of hospitalisation. At Aneurin Bevan University Health Board, however, AOTs were perceived as a costly service with poorly understood benefits; these were due to be cut.

Modelling and statistical analysis work from the Cardiff group quantified the benefits achieved by AOTs, which supported the business case made to the health board to continue to fund these teams. The Cardiff team developed a caseload management tool, incorporating clinical, demographic and staffing variables, such as medical history, specific patient needs, staff skill-mix, resource levels and availability, and geospatial demand and travel times. This enabled AOTs to better coordinate complex caseloads with further benefits for patients and the health board, as noted below **[5.9]**. Dr Izabela Spernaes, ABCi Mathematic Modelling Unit Lead, explained that AOT services were at great risk of closing and that *"the analysis and modelling provided by the School of Mathematics resulted in significant benefits of AOT services"* **[5.9]**. The benefits identified as a result of the Cardiff research include **[5.9]**:

- *"Improved patient outcomes measured by a reduction in the Adult Camberwell Assessment of Need (CANSAS) per patient by an average of 51%."* The CANSAS measures severe needs for mentally ill adults across a range of physiological and psychological factors, such as psychological distress, self-care, and physical heath.
- A reduction in *"ineffective and unnecessary acute hospital admissions by 79%."* Acute admissions are those which require diagnostic tests, treatment, and follow-up care. There was also a 66% reduction in the number of crisis admissions (hospital stays when the patient is highly vulnerable) from 2.76 stays on average per patient to 0.93. The mental wellbeing benefits to the patients are difficult to quantify, but savings to the NHS Board were calculated at £7.3M per annum from crisis admission reduction alone.
- *"A 65% reduction in time taken off work by patients due to severe mental health episodes."* Days off due to severe mental health episodes went from an average of 41.8 days per patient per year to 14.6 days.

4.4 Reducing pressure ulcers

Pressure ulcers, which can occur when patients spend significant time in bed, are painful, impair mobility, and diminish a patient's quality of life. Low staff morale has been identified as causing lapses in care, leading in increased instances of pressure ulcers (among other unintended consequences), which then further decreases staff morale, generating a negative feedback loop. Pressure ulcers are also costly to health boards; for example, pressure ulcers

costed Aneurin Bevan University Health Board more than £500,000 per annum in compensation to affected patients.

To address this problem, Cardiff researchers embedded within ABCi developed a comprehensive simulation (system dynamics) model of the health board's Unscheduled Care (USC) system. This modelled staff wellbeing and its impact on clinical performance and identified that current measures being implemented by the Trust would not be sufficient to reduce health acquired pressure ulcer incidences at the Royal Gwent Hospital.

The model was used to identify negative feedback loops, including understanding and quantification of dependencies between staff behaviours and factors, such as resource utilisation, morale, sickness rates and use of agency staff. Consequently, joint learning sessions with Cardiff University researchers and ABCi staff were developed to help Unscheduled Care staff understand the complex dynamics of the health system. In addition, spreadsheet-based monitoring tools were developed together with a Consultant Clinical Psychologist in order to track staff wellbeing. These interventions helped prevent negative feedback loops occurring and transformed patient care from potentially harmful to safe **[5.10]**. As a result, "*within two years, up to ten frontline teams prevented (at least) 265 pressure ulcers and averted more than £1.5 million in cost while securing better quality care for patients and improved patient experience*" **[5.10]**. The approach won the NHS Wales Award 2019 in the category Improving Patient Safety.

In summary, Cardiff research into mathematical modelling techniques was used by Welsh NHS Health Boards to improve patient outcomes and the delivery of services. Close collaboration through the Cardiff-NHS Wales innovative researchers-in-residence programme, and via international partnership with University Hospital Munich, enabled efficient design of hospitals, improved the efficiency and effectiveness of mental health outreach teams, and reduced pressure ulcers. This led to direct cost savings of at least £12.1M for the NHS, as well as ~£150,000 savings for the University Hospital Munich hospital in Germany.

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

[5.1] Testimonial from Trish Chalk, Aneurin Bevan Clinical Futures Lead for Radiology, Pathology and Theatre Services

[5.2] Harper P (2020). 'Healthy O.R. in Wales', *Impact*, 2020 (2): 28-32, doi:10.1080/2058802X.2020.1768684.

[5.3] Jennifer Morgan, Paul Harper, Vincent Knight, Andreas Artemiou, Alex Carney & Andrew Nelson (2019) Determining patient outcomes from patient letters: A comparison of text analysis approaches, Journal of the Operational Research Society, 70:9, 1425-1439, DOI: 10.1080/01605682.2018.1506559

[5.4] Video interview with Judith Paget, Chief Executive of the Aneurin Bevan University Health Board corroborating the use and impact of the models for the Aneurin Bevan University Health Board.

[5.5] *Times Higher Education* Awards 2015

[5.6] Citation for the Companion of OR 2018 for Professor Paul Harper, The OR Society

[5.7] Grange University Hospital opening webpage

[5.8] Testimonial from Dr Günther Edenharter, University Hospital Klinikum rechts der Isar, Technische Universitat Munchen (TUM)

[5.9] Testimonial from Dr Izabela Spernaes, Unit Lead, Aneurin Bevan Continuous Improvement

[5.10] Winner of NHS Wales Award 2019: How to avoid Health Acquired Pressure Ulcers (HAPUs): Using System Dynamics to identify the Leverage Point