Institution: Cardiff University

Unit of Assessment: Mathematical Sciences (10)

Title of case study: Transforming emergency and urgent care services through mathematical modelling

Period when the underpinning research was undertaken: 2012 - 2018

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:
Paul Harper	Professor	01/09/2007 - present
Vincent Knight	Senior Lecturer	01/04/2009 - present
Geraint Palmer	Lecturer	18/09/2017 - present
Tracey England	Research Associate	01/02/2011 - 31/10/2020
Daniel Gartner	Senior Lecturer	04/01/2016 - present
Jonathan Gillard	Reader	01/10/2007 - present

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)

Urgent and emergency healthcare requires accurate forecasting to ensure the rapid deployment of both medical resources and patients to the correct healthcare pathway. Cardiff's Operational Research group developed forecasting models for time-dependent scenarios that were applied across multiple NHS settings. The research was key to the Welsh Government's £4M investment in the Single Cancer Pathway, which improved nationwide urgent cancer treatment. The group's research also supported emergency healthcare by forecasting staffing requirements for the London Ambulance Service, as well as informing the staff profile required to launch the Welsh NHS 111 service. Recent impact involved modelling Covid-19 transmission amongst student populations, which guided Welsh and UK national policies during the 2020 winter.

2. Underpinning research (indicative maximum 500 words)

Urgent and emergency medical services play a critical role in providing healthcare. Access to pre-hospital treatment, timely provision of care, and ensuring the correct healthcare pathway for patient needs can be the difference between life and death. Healthcare pathways typically include stochastic and time-dependent queueing systems with distinct priority classes (e.g. patient urgency).The healthcare research of the Operational Research (OR) Group at Cardiff focuses on modelling these healthcare pathways with the aim of addressing critical bottlenecks in care delivery, applying resource where it is most valuable, and identifying opportunities for improvements.

2.1. Accounting for Variable Priority Levels

To date, only approximation methods have been explored to generate staffing requirements for time-dependent dual-class services, limiting the realism and accuracy of modelling. Cardiff developed a numerical approach using mixed discrete-continuous time Markov chains that can, unlike previous methods, account for the variable levels of urgency healthcare staff may be dealing with. The Cardiff methodology was embedded in an extension of the Euler method, coined Euler Pri. This method can cope with different priority patient classes and **has been shown to successfully establish safe minimum staffing levels for emergency medical service providers [3.1]**. The OR Group subsequently developed a comprehensive Discrete Event Simulation to identify service levels and staffing for a proposed 111 service for Wales. The detailed model quantified staffing requirements and economic savings needed under different demand scenarios and optimal service configurations **[3.2]**.

The group also **developed decision models on how to optimally locate and deploy ambulances**. Parameters included the most efficient allocation of emergency vehicles to

available bases and stand-by points within a region, accounting for predicted demand and patient needs, traffic congestion and routing, and vehicle/paramedic availability. Cardiff research further explored allocations based on minimising response times or maximising patient outcomes/survival. These emphasised the importance of explicitly modelling response times using survival probabilities by permitting multiple survival functions in order to accommodate diverse patient classes and reflect different outcome measures within the population **[3.3]**.

2.2. Accounting for external variables such as weather and seasonal effects

Using data from the Welsh Ambulance Service, Cardiff researchers determined that **forecasting emergency ambulance demand** with Singular Spectrum Analysis methods was more flexible, and provided superior forecast performance, compared to conventional time series methods. The latter do not account for seasonal variations and other irregular effects, which can cause inaccuracies in the predictions **[3.4]**. **Short-term forecasting of emergency hospital admissions** also incorporated weather information using Hierarchical Bayesian models, in collaboration with the Met Office **[3.5, G3.1]**.

2.3. Detecting Deadlock

Open restricted queueing networks give rise to deadlock, whereby patients may be unable to leave a server due to upstream blocking, preventing them from moving to the next stages of treatment in the system. This can be very difficult to detect and resolve in a model, while in real life it will often be detected and dealt with by the staff within the system. To improve model accuracy, Ciw, an open source simulation Python library, designed and developed by the Cardiff OR group, incorporates **novel deadlock detection** by combining Markov models, state digraphs and linear algebraic techniques on transition matrices **[3.6]**. This brought the models more in line with observed behaviours, thus incorporating greater realism.

As such, the OR Group at Cardiff developed expertise and a portfolio of methodologies for accurate modelling of emergency and urgent care healthcare systems as they operate in the real world, which have been adapted and applied to the problems faced by healthcare staff **[G3.2]**.

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

[3.1] Vile JL, **Gillard JW**, **Harper PR a**nd **Knight VA** (2017), "A queueing theoretic approach to set staffing levels in time-dependent dual-class service systems". *Decision Sciences* 48(4): 766-794. https://doi.org/10.1111/deci.12236

[3.2] Tuson M**, England T** *et al*. (2018), "Modelling for the proposed roll-out of the '111' service in Wales: a case study". *Health care Management Science*. 21(2): 159-176. https://doi.org/10.1007/s10729-017-9405-7

[3.3] 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: 918-926. https://doi.org/10.1016/j.omega.2012.02.003

[3.4] Vile J, **Gillard J, Harper PR and Knight VA** (2012), "Predicting Ambulance Demand Using Singular Spectrum Analysis". *Journal of the Operational Research Society*. 63: 1556-1565. http://dx.doi.org/10.1057/jors.2011.160

[3.5] Sahu SK, Baffour B, **Harper PR,** Minty JH and Sarran C (2014), "A Hierarchical Bayesian Model for Improving Short-Term Forecasting of Hospital Demand by Including Meteorological Information". *Journal of the Royal Statistical Society*, *Series A*. 177: 39-61. https://doi.org/10.1111/rssa.12008

[3.6] Palmer GI, Harper PR and **Knight VA** (2018), "Modelling Deadlock in Open Restricted Queueing Networks". *European Journal of Operational Research*. 266(2): 609-621. https://doi.org/10.1016/j.ejor.2017.10.039

Selected grants:

[G3.1] PI: Harper; EPSRC EP/H010637/1 (MetSim: a Hospital Simulation Support Tool Using Meteorological Information to Improve the Planning and Management of Health Services, £341,363, Met Office 2010 – 2012

[G3.2] PI: Harper, Gartner; C66656/A27882 (Analysis and Modelling of a Single Cancer Pathway Diagnostics Phase); £133,278, Cancer Research UK 2019 – 2021

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

Cardiff's Operational Research (OR) group applied their research expertise, as described in Section 2, to significantly improve healthcare pathway allocation and patient outcomes across NHS urgent and emergency care services in Wales and England.

4.1. Streamlining pathways to cancer diagnosis and treatment

Five-year cancer survival rates in Wales are poor compared to other developed nations. The NHS identified that this difference was related to how the system detected patients and started their treatment. Wales had two established diagnosis and treatment pathways for cancer. When a patient's GP saw obvious red-flag cancer symptoms the patient entered the 'urgent' pathway, and treatment was required to start within 62 days. When symptoms were present which could indicate either cancer or some other condition, patients enter the 'non-urgent' pathway, for which a treatment deadline was only set once cancer was confirmed through diagnostic tests. This system had been criticised for complicating cancer statistics and inaccurately recording the waiting time of patients on the 'non-urgent' pathway, who could be waiting for months before cancer was confirmed and a treatment deadline was imposed. Patients on this 'non-urgent' pathway represent 60-70% of total cancer patients.

In 2016, the OR Group was enlisted by the Wales Cancer Network and the Welsh Government to test the feasibility of a single cancer pathway (SCP) **[5.1]**. Through the SCP, patient waiting times are measured from when cancer is first suspected (for example, by their GP), not when first referred to hospital, and aims to provide a clear target to speed up diagnosis times and improve survival rates.

Using its Ciw software, the OR Group modelled the resources needed to meet the proposed SCP waiting time targets. This involved analysis of more than 6,000 cancer referrals, across 10 different types of cancer, for 30 defined categories of diagnostic tests, using data from a trial in Cwm Taf University Health Board. The OR group's report outlined the impact of a SCP, identified the need for a 20% increase in diagnostic resources to meet proposed treatment timescales, and indicated that rollout of "rapid diagnostic hubs" (where patients with suspected cancer could have a range of cancer screenings undertaken with a single trip) would help achieve the project's goals **[5.1]**. Professor Tom Crosby, National Cancer Clinical Director for Wales and Clinical Lead Transforming Cancer Services, stated that the results "*provided the underlying business case to implement the single cancer pathway (SCP)"* **[5.1]**.

The findings were used to advise Vaughan Gething, the Welsh Government Minister for Health and Social Services, who "*was assured that implementation of the SCP was feasible and 'the right thing to do'*" **[5.1]**. As a result, Gething "*released an additional £3 million of funding earmarked to provide the operational and diagnostic support required to transfer to the Single Cancer Pathway in line with Professor Harper's modelling*" **[5.1]**. The Welsh Government confirmed that the £3M was invested in Health Boards and Velindre NHS Trust to initiate the single cancer pathway and to support performance and quality improvements in the pathways of care. **[5.2]**. The Welsh Government also provided Cwm Taf Morgannwg and Swansea Bay University Health Boards with an additional £1M in funding to pilot rapid diagnostic hubs **[5.1]**.

As a result of Cardiff's extensive research contribution, Wales is the first UK nation to introduce a single waiting time target for cancer patients. The SCP changes the diagnosis and treatment pathway for the approximately 60% of cancer patients in Wales who would previously have been placed on the 'non-urgent' suspected cancer pathway **[5.1]**. Crosby stated that the immediate benefits *"are naturally hard to quantify, but we have no doubt that they are significant, both for those patients who are now told they do not have cancer more rapidly,*

and for those who are diagnosed with the disease they can begin effective treatment promptly" **[5.1]**.

4.2 Supporting the London Ambulance Service

The London Ambulance Trust is responsible for responding to urgent and emergency medical situations within the UK's busiest ambulance service. It receives 1.9M 999 calls, and responds to over 1.2M incidents, annually. The efficient allocation of support and frontline staff is essential to avoiding unnecessary burden on emergency departments **[5.3]**.

Since 2015, the OR Group worked closely with the London Ambulance Service Forecasting & Planning team (F&P), led by Dr Leanne Smith. Smith stated that systems thinking and research from the Cardiff OR Group "*informed my approach to implementing a successful and valuable modelling team, and has helped shape the type of work conducted*" **[5.3]**. She cites Cardiff's direct influence on successful F&P projects, which include **[5.3]**:

- **Development of a forecasting suite** that predicts resource requirements as far as 14 days in advance. The forecasts *"are used on a daily basis to make decisions around staffing, escalation procedures, and anticipated system pressures*" and enables informed and proactive decisions at local levels, identification of performance and potential risks, and retrospective insight to enhance learning and efficacy.
- **Enhanced modelling annual contract evaluation:** Annual contract negotiations for the London Ambulance Service (approximate value £370M) were previously based on unconfirmed estimates and averages. By working with the Cardiff team, the F&P team has "*improved the offering of the financial year forecasting, allowed for operational planning to occur much further in advance, with recommended flex for seasonal demands*". This has allowed the Service to agree to contracts with a fairer financial risk share.
- Increased assurance around demand and performance enabled the **more effective use of approximately £10M of staff overtime per annum.** This included budget savings in lower demand periods "*that could be instead used at times of greater pressure, ultimately resulting in a more equitable and safe delivery of service to patients".*

Within three years of collaborating with the OR Group, the London Ambulance Trust had been transformed into "*a data-driven organisation, with Strategic and Operational decision making across various teams now supported with analytical evidence and the supporting "what-if?" modelling"* **[5.3]**. The F&P team subsequently invested in five full-time staff to facilitate its expanding remit to embed modelling and forecasting in decision-making throughout the London Ambulance Service **[5.3]**.

4.3. Designing and launching the NHS 111 Service

In 2015, NHS Wales commissioned the OR Group to analyse national NHS Direct and Out-of- Hours data to model a proposed 111 service across Wales**.** The service sought to combine the functionalities of the NHS Direct call-centres with the Out-of-Hours GP phone service and differs from other national 111 services by employing a greater proportion of clinical staff. The Cardiff group evaluated different ways of providing the complex new service and forecasting the optimal staffing size and skills required to support it **[5.4]**.

The OR analysis found that an effective combined service required increased staffing of nurses and call-handlers but revealed that fewer GPs could be used in the service. The analysis also provided information about resource allocation and predicted impact on service delivery to the 111 Project. Richard Bowen, National Lead of the 111 Project praised the OR group's contribution: "*The analysis was highly valued, and led to key changes in the operational rollout of the 111 service, particularly in the combining of existing resources under the new structure and the placement of staff within that new structure*" **[5.4]**. As the analysis undertaken by Cardiff indicated increased staffing would be required, Bowen also confirmed that this additional resourcing was secured to meet the expectations outlined in the model **[5.4]**.

These recommendations were implemented via a 2016 pilot launch across the Abertawe Bro Morgannwg (population 499,400), Hywel Dda (population 375,000), and Powys (population

133,000) Health Board areas, with significant evidenced benefit to the NHS. For example, within six months, in the Abertawe Bro Morgannwg Health Board, the service received 71,853 calls: 404 calls per day at the weekend and 802 calls per day on bank holidays. This resulted in 1,343 fewer hospital emergency visits and 1,291 (29%) fewer ambulance callouts. By avoiding unnecessary emergency journeys, **savings of £642,120 were generated over the six month monitoring period [5.5**, p.9**]**.

Based on the success of the pilot schemes, the Welsh Government announced in 2018 that **the service would be expanded to the entire population of Wales** (~3M people) **[5.6]**.

4.4. Modelling student infections during the Covid-19 pandemic

The Welsh Government asked the OR Group to forecast the impact of students moving from their University halls of residence to their permanent home addresses during the Covid-19 pandemic. Using data from Cardiff University's asymptomatic Covid-19 testing service, the group modelled secondary infection numbers if students returned home and created a new online app to estimate secondary infections for a specific region, given local values for returning student numbers and prevalence of Covid-19.

This analysis informed the Welsh Government's Technical Advisory Cell and Higher Education Task and Finish Group dealing with Covid-19. Specifically, during the Welsh firebreak lockdown, enacted on 23 October 2020, the Welsh Government advised universities to stay open, with specific advice to students to remain at their university rather than returning home **[5.7]**. Huw Morris, the Welsh Government Director Skills, Higher Education and Lifelong Learning, stated that, following the OR Group's results*, "there was evidence that encouraging students to return to their permanent home address from university residences would create greater risks than encouraging students to remain located close to their university of study*". Morris also confirmed that the Cardiff research was communicated to colleagues in UK, Scottish and Northern Ireland Government and that it influenced the development of policy across the UK on students returning home safely for the Christmas vacation **[5.7]**.

4.5 Summary

Cardiff OR research transformed cancer services in Wales, improved the efficiency of the London Ambulance Service, supported the design and roll-out the new Wales NHS 111 service, and informed (and continues to do so) Welsh Government policies on student movements between home and university during the Covid-19 pandemic.

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

[5.1] Testimonial from Professor Tom Crosby, National Cancer Clinical Director for Wales, Clinical Lead Transforming Cancer Services, Wales Cancer Network

[5.2] Welsh Government Cabinet Statement 'Single Cancer Pathway public reporting' from Vaughan Gething MS, Welsh Government Minister for Health and Social Serviceson Welsh Government's website to corroborate the implementation and impact of the national single cancer pathway

[5.3] Testimonial from Dr Leanne Smith, Head of Analytics, London Ambulance Service,

[5.4] Testimonial from Richard Bowen, Project Director, 111, NHS Wales, corroborates the involvement in the '111' modelling work

[5.5] Independent report by NHS Wales – *'Review of the 111 Pathfinder: Final report*' (November 2017)

[5.6] Health in Wales news item – '111 to be rolled out across Wales' (5 April 2018)

[5.7] Testimonial from Huw Morris, Director Skills, Higher Education and Lifelong Learning (SHELL), Welsh Government