Institution: City, University of London

Unit of Assessment: UoA 10 Mathematics

Title of case study: A solution to staff rostering problems in hospitals by means of a 'fair' algorithm

Period when the underpinning research was undertaken:

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:
Professor Celia A. Glass	Professor of Operational Research	1999 – current

Period when the claimed impact occurred: 2010 - 2020

Is this case study continued from a case study submitted in 2014? Y

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

This case study charts the success of an innovative mathematical solution in targeting well-being and training of a hospital medical workforce. Developed in research at City, University of London, the e-rostering system was used at a major London NHS Hospital to reduce doctors' fatigue, resulting in improved staff morale and patient care, and increased efficiency of workforce utilisation, providing considerable costs savings. The research also informed the 2016 Junior Doctors' negotiation, provided evidence to a government inquiry into managing the supply of NHS clinical staff, helped to shape training capacity for Health Education England, and in 2020, helped a major London hospital redeploy junior medics as the COVID-19 pandemic evolved.

2. Underpinning research (indicative maximum 500 words)

Rostering is a complex combinatorial problem that affects hospital personnel on a daily basis all over the world. The need for quality software solutions is acute for a number of reasons, not least because a high-quality roster can lead to a more contented and thus more effective workforce, and better care for patients.

In 2005, Professor Celia Glass and her PhD student, Roger Knight, an expert in call centre workforce management, began to research staff rostering. Their approach had its origins in Glass' earlier research on comparative algorithms where she studied the performance of contemporary heuristics, such as Simulated Annealing, Tabu Search and Genetic algorithms, to understand the relative performance on a range of *NP-hard* combinatorial problems. Later she developed a parsimonious formulation of the scheduling problem and then exploited the relative simplicity of its solution space representation using an appropriate algorithm [3.1] [3.2]. Knight's research question was whether a rostering programme could be driven for employee well-being. The challenge involved capturing the following competing imperatives: maintaining sufficient staffing levels to cover demand without incurring the added costs associated with over-staffing or the use of agency staff; satisfying working practices and employment contracts; and having due regard for staff well-being and individual preferences.

Shift patterns can have a profound effect on well-being, especially if they include night shifts. Staff well-being had not previously featured within rostering software. Glass and Knight identified fatigue metrics from the Human Resources literature that would capture staff well-being and applied them in linear constraints within their rostering model. As it is not possible to satisfy all the constraints simultaneously, the Lagrange multiplier approach was adopted to reduce selected constraints to soft goals with measurements of their violation. The Call Centre Rostering problem was then amenable to an Integer Linear Programming (ILP)

formulation, albeit too slow to handle larger instances. The key advance was to capture the underlying features of call centre rostering in an implicit formulation which could then be used for optimisation [3.3]. Glass and Knight could thus produce a higher quality roster for benchmark real world call centre data compared to others in the literature or from commercially available off-the-shelf rostering packages. Their primary achievement was to solve the problem to optimality, in the face of contrary claims in the literature that such large instances of this NP-hard problem could only be solved approximately. The quality objective relating to staff fatigue and workplace risk makes the approach attractive. An additional benefit arose from the counter-intuitive outcome of being able to minimise cost without any quality-cost trade off [3.3]. Using the optimisation algorithm can provide a company with the cheapest possible solution, which offers the most employee-friendly low risk roster.

Armed with this general approach Glass and Knight then addressed the most studied rostering problem in the literature, that of Nurse Rostering. They found that their approach adapted well [3.3]. To prove its veracity, they focussed on producing a quality roster for three publicised, open benchmark problems, for which they were the first to solve to optimality [3.4].

In 2008, they extended the research in response to various real-world situations. Reformulation in each case produced a successful outcome and demonstrated the transferability of the implicit ILP approach. For trainee doctors, the additional features of fairness criteria, a longer time horizon and legal requirements were added to the roster optimiser. The working practice of using rotational rosters (rotas) in the NHS was reflected in an alternative variant of the ILP formulation. For care homes, additional constraints addressed the diverse levels of expertise of nurses and carers and pre-existing shift patterns.

There are two theoretical aspects which allow Glass and Knight's approach to handle larger problem instances than others. One is depicting the problem and its consequent representation in an implicit form, which reduces the solution space. The other is the use of a Totally Unimodular constraint matrix in an ILP formulation, for which there are efficient algorithms. It is particularly rewarding that the optimisation approach is strong enough to find solutions which minimise the staffing costs of the roster without compromising quality within (an originally) vast solution space. Further insights relate to the importance of grounding the problem formulation in context. For example, their nurse rostering algorithm considers month-on-month continuity, while the failure of earlier algorithms to do so provided poor solutions in practice [3.4]. The methodology also quantifies both the undesirable effects of a roster such as unconducive night shift patterns which affect both staff fatigue and workplace risk and the desirable effects from satisfying personal preferences and maintaining fairness between staff, both of which affect staff morale. This differentiates the work from both previous academic and other commercial approaches. The impact of the research flows from the robustness of the underpinning mathematical algorithm combined with a careful capturing of contextual aspects of the problem.

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

3.1.Gerodimos A.E., **Glass C.A.** & Potts C.N. (2001) Scheduling of Customized Jobs on a Single Machine under Item Availability. *IIE Transactions,* **33**(11) 975–984.

3.2. **Glass C.A.** & Prugel-Bennett A. (2005) A polynomially searchable exponential neighbourhood for graph colouring, *Journal of the Operational Research Society*, **56**(3) 324-330

3.3. Knight, R.A., (2008) *Optimisation methods for staff scheduling and rostering: an employee-friendly approach*. Unpublished PhD thesis, Awarded by City University London [Now City, University of London]. **Supervised by Professor Celia Glass**.

3.4. **Glass C.A.** & Knight R.A. (2010) The nurse rostering problem: A critical appraisal of the problem structure, *European Journal of Operations Research*, **202**(2) 379-389

3.5. Kim E.-S., **Glass, C. A.** (2015), Perfect periodic scheduling for binary tree rooting in wireless networks, *European Journal of Operational Research*, **247**(2) 389-400

Indicators of quality for underpinning research:

Four outputs were published in prestigious academic journals which apply a rigorous peer-review process prior to acceptance of papers. Output 3.5 was supported by an EPSRC Standard Research Grant: *Integrated Scheduling for Wireless Mesh Networks*, 1 November 2009 - 31 October 2012. Principal Investigator: Celia Glass. Funding value: £244,232. Grant number EP/G036454/1.

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

Fair staff rosters at a large NHS Hospital

The Emergency Department at London's NHS Whittington Hospital had been using ergonomic rosters for junior doctors since February 2016. These rosters were produced by a research team led by Professor Glass using their e-Rostering Software. The Whittington Hospital provides community care services to 500,000 people and an income of £295 million.

The introduction of software to produce e-rosters uses algorithms to prioritise staff ergonomics (adhering to best practice from the literature in terms of fatigue minimisation so improving safety and efficiency at work) and work/life flexibility (e.g. annual and study leave preferences, exams, personal commitments and less than full time trainees) within the roster. In this way, individualised rosters are produced for each doctor which meet their particular needs, protect patients and doctors through fatigue reduction, ensures fair total hours distribution across the duration of their placement and fits work around life. [1]

There was an increase in junior doctor overall satisfaction with roster vs rota, and all doctors reported improved morale working on this roster. This was achieved both through the consideration of doctors' priorities and the other specified quality measures in the design of the roster, which cannot be accounted for by traditional patterns of a fixed rota. All junior doctors reported reduced fatigue on the roster compared to on a rota. This has an obvious and direct relationship to patient safety. [1]

Each request for annual leave or study leave was assigned a priority by the doctor. Every doctor on the roster was guaranteed their first priority annual and study leave requests. The software was able to handle a variety of specifics including protected weekends either side of leave weeks, and requests to work only during the daytime on a particular date. Doctors reported that this significantly reduced the stress of waiting for leave approval or fixed date allocation, and directly contributed to improved sense of autonomy and morale. The roster was carefully controlled for fairness, ensuring trainees were allocated a very similar number of total and anti-social hours. This removed the unfairness of some doctors working more antisocial shifts than others dependent on indiscriminate allocation of which line of the rota they commenced their placement on. [2]

The software also delivered a range of organisational improvements. The software was able to design rosters which were fully compliant with the legal requirements of the Working Time Regulations, and with the New Deal and the 2016 Junior Doctors' Contract. This removed the risk of fines and additional banding supplements. Moreover, the New Contract obliges that Doctors should now be paid for the actual hours worked. Equitable distribution of work between doctors is guaranteed by the roster which results fairer pay rewards. [2]

The software has also delivered financial savings to the department. e-rosters improve cover and reduce locum requirements during changeover of one cohort of junior doctors with the next. Reducing locum requirements during the December 2016 changeover and induction period, when 5 doctors rotated, meant that the department saved the cost of 8 locum shifts, the equivalent of £6000. Planning shifts around study leave, some of which are mandatory training meant that the department saved the cost of providing locum cover for two nightshifts

rather than one day shift, saving £900 each time. Currently there are around 30 of these kind of study-leave requests in 6 months, and it is reasonable to assume that around 5 of these would have been during nights on a rota, a total saving of £4500. Considerable further savings were made in the rota manger's time (over 10%). [2]

This rostering system can improve patient safety by objectively and subjectively reducing the fatigue of doctors on it, and through improving morale. Furthermore, although registrars were rostered separately, the software was able to ensure that at least one more experienced junior doctor was rostered during the vulnerable nightshift periods. Having more seniority around when there are fewer doctors on the floor improved the safety of the nightshift. [2]

The pilot implementation at Whittington Hospital's A&E was selected as an exemplar initiative for supporting doctors in training by *NHS Improvement* [3], noting that the optimised rostering system reduces fatigue for staff, protects staff and patients, reduces locum spend through redeployment of existing staff, honours training & personal commitments, while maintaining full-service cover.

2015-16 junior doctors contract dispute in England

The research informed the policy debate surrounding the 2016 junior doctors contract dispute in England and helped shape, in part, the government policy and subsequent NHS Junior Doctor's Contract. Armed with nine years research and preliminary findings from the Whittington emergency department experience Glass provided written evidence to the National Audit Office NAO) report, *Managing the supply of NHS clinical staff in England*, making particular reference to the increases in the number of night and weekend shifts proposed in the new contract which would increase disruption of junior doctors' sleep patterns. Her evidence was discussed at the Public Accounts Committee held on 23rd February [4] and later prompted questions in the House of Commons. For example: Dr Philippa Whitford (SNP, Central Ayrshire) *"Has he [Secretary of State for Health] seen the analysis by Cass Business School suggesting that it is impossible to avoid high levels of fatigue under the new contract?"* [5]

Glass's evidence to the NAO was cited first by: The British Medical Association as it concluded that the Health Secretary was imposing on junior doctors a contract that was "*far from ready for implementation*" [6]; then by Dr Phil Hammond, NHS Doctor and commentator, who expressed serious concerns about stress and fatigue of junior doctors on shift work and recommended "*a rigorous feasibility study of the new contract prior to implementation to ensure safety*" [7]; and finally by the BBC's Andrew Neil in an interview with the Health Secretary about the proposed 7-day NHS on BBC Sunday Politics show: "*To stretch the non-emergency, five-day service within the current funds over seven days. It just isn't feasible, as the Cass Business School told the Public Affairs Committee last week. Ultimately, this isn't about patient safety. It isn't about patients at all, this is about money."* [8]

Other impacts

In 2018, the research team was commissioned to support Royal College of Surgeons and Health Education England as part of a study to improve the training of surgical junior doctors, by ensuring at least 60% training time was under a specialist consultant, thus improving access and continuity of training opportunities for surgical trainees. The mechanism under investigation is training personalisation of training rotas, and how this can be achieved without compromising on well-being or compliance. Two pilot sites engaged with this consultancy project, namely, King George's Hospital, and Croydon University Hospital and the Royal College of Surgeons plan to use this project to share best practice across the whole of London. [9]

In 2020, Professor Glass advised Guy's and St. Thomas' Hospital on staff roster design during the COVID-19 Pandemic. In particular, demonstrating, through rotas for a group of anaesthetists, how junior doctors can be redeployed to meet the requirements in the next phases of the pandemic. The feedback from the consultant and senior registrar handling the

rotas was very positive: *'She [Glass] incorporated the recommencement of training for our registrars into flexible emergency rosters. The analysis and options presented by the team gave us valuable insights and suggestions in how best to proceed with for staff deployment as the COVID-19 pandemic evolved."* [10]

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

[5.1] Carmichael, Duncan, (2017) Emergency Department e-Rostering Software Report. Whittington Health. (February). [A report by Consultant in Emergency Medicine, Whittington Hospital]

[5.2] NHS Improvement (2017) Fatigue-minimising, flexible e-rostering in the Emergency Department: A Case Study of Whittington Hospital (Published 27 June)

[5.3] NHS Improvement (2017) Seven exemplary case studies that explore initiatives in engaging, supporting and valuing doctors in training: improving wellbeing and support. (Published 27 June)

[5.4a] Written Evidence from City University London to the Public Accounts Committee 'Managing NHS clinical staff numbers inquiry' and discussed Tuesday 23 February 2016, and later acknowledged in the [5.4b] House of Commons Committee of Public Accounts Managing the supply of NHS clinical staff in England Fortieth Report of Session 2015–16

[5.5] UK Parliament Commons Chamber Oral Answers to Questions: Health (10 May 2016), p.13-14

[5.6] Cooper, Charlie (2016) Junior doctors: new contract 'risks disrupting medics' sleep patterns', *The Independent*, (26th February)

[5.7] Hammond, Phil (2016) The junior doctors dispute explained simply but in detail… A blog post by physician and broadcaster, Dr Phil Hammond, March 9, 2016 @ 7.41am.

[5.8] BBC1 Sunday Politics, London. Episode: Sunday 6th March 2016. Transcript of programme. Available on request.

[5.9] Brecknell, J. (2018) *Improving Surgical Training*, End of Project Report for Royal College of Surgeon (RCS), Health Education South London (HESL).

[5.10] Doctors.UK.Net – member feedback and testimony [received 24th June 2020, available on request]

Notes: Some sources refer to Cass Business School or Nightglass Medical Rostering Ltd. Cass Business School is the old name of the Business School of City, University of London where Glass as on faculty. Nightglass Medical Rostering Ltd is a spin out company that holds the intellectual property stemming from the underpinning research.