University of Southampton

Faculty of Environmental and Life Sciences

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Using data science to optimise nurses' shift patterns in acute hospitals

by

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Abstract

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In inpatient hospital wards, registered nurses are often required to work in shifts that cover the 24-hour day. While shift work has previously been linked with increased fatigue, burnout, sickness, and work-life imbalance, consensus is lacking on how to reconcile these risks with competing scheduling priorities, e.g., meeting ward demands and accommodating nurses' working time preferences. This thesis aimed to address this gap through three interconnected studies.

Study 1 involved a thematic analysis of national survey data to identify the factors nurses prioritise when choosing their working hours. Findings stressed the importance of scheduling practices that support a good work-life balance, such as ergonomic shift planning, consistent/predictable patterns, and increased control over working hours.

Study 2 involved the analysis of 1.4 million historical roster records from two NHS hospital Trusts via logistic mixed regression models. Several adverse shift work variables, including long working hours, spells of consecutive working days, excessive night work, and insufficient rest periods were found to significantly increase the odds of sickness absence in both weekly and monthly exposure windows.

Study 3 integrated the findings of the first two studies to develop a novel mathematical optimisation model for nurse scheduling. Across a series of experimental scenarios, the model successfully generated rosters that minimised adverse shift configurations, incorporated nurses' general scheduling preferences, and satisfied minimum nurse staffing requirements.

This research makes significant contributions to both practice and policy, providing novel insights into nurses' working time preferences, the longitudinal effects of shift work on well-being, and innovative methods for automated rostering. This programme of work also offers a practical and adaptable methodology for prioritising nurse-centred outcomes in ward scheduling - a critical consideration given national challenges in nurse recruitment and retention.

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Research Thesis: Declaration of Authorship

Name: **Talia Emmanuel**

Title of thesis: **Using data science to optimise nurses' shift patterns in acute hospitals**

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

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3. Where I have consulted the published work of others, this is always clearly attributed;
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Signature: Date:

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Definitions & Acronyms

Definitions

Adverse Shifts .... Shift types, patterns, and configurations that pose negative impacts to nurse wellbeing, such as those that cause the accumulation of fatigue, increase the risk of sickness, or disrupt work-life balance

Bank Shifts........................ Shifts that cover temporary staffing shortfalls in settings that are different from one's "home" role or ward

Benchmark Instance .... A problem instance with pre-defined properties (sets, parameters, objectives) that serve as a reference point for assessing the performance of a solving technique/algorithm

Constraint........................ A logical/mathematical condition that any feasible or optimal model solution must satisfy

Coverage .... The number of staff needed over a particular planning period, i.e., minimum staff needed per hour, per shift, or per day

DTN Rotation.................... Day-to-night rotation; a shift pattern variable that is characterised by switching from a day shift to a night shift within a 7-day period

E-Rostering .... Electronic rostering software that enables automatic generation of staff rosters, where integration of historical/live views of ward demands and patient acuity, staffing levels and skill-mix, leave and absence records, and flexible working requests are possible

Feasible Solution .... A combination of decision variable values that satisfies all constraints of the problem but without necessarily achieving or proving optimality

"Inadequate Rest"........... Preference profile that involves heavier penalisation of assignments that result in interrupted rest and frequent rotations; is applicable to nurses who prefer schedules with meaningful rest periods and are more consistent and predictable (in terms of shift type and timing)

"Intense Shifts"................ Preference profile that involves heavier penalisation of long working hours and lengthy spells of consecutive working days; is applicable to nurses who prefer schedules that avoid the accumulation of fatigue or exhaustion

Intense Spell .... A shift pattern that is characterised by working 3 or more consecutive long or night shifts (i.e., long or night shifts that end and start <24 hours apart)

Long Shift......................... A shift type that is characterised by lasting 12 hours or more (including intra-shift breaks)

Long Spell .... A shift pattern that is characterised by working 6 or more consecutive shifts (i.e., shifts that end and start <24 hours apart)

Lower Bound .... In optimisation problems using branch-and-bound solving algorithms, the lower bound is the smallest confirmed value that an objective function can theoretically achieve while satisfying all constraints

NHS England .... National Health Service; the publicly-funded health care system in England

NHS Trust .... An organisational entity within the NHS typically responsible for delivering healthcare services to a specific geographical region

Night Shift .... A shift type that is characterised by having an end-time of 08:00 AM or earlier (Dall'Ora *et al.*, 2020)

NP-*hard* .... Complexity classification for computational problems; no known algorithm is able to solve them in polynomial time (i.e., where problem complexity is a polynomial function of its input size)

NTD Rotation.................... Night-to-day rotation; a shift pattern variable that is characterised by switching from a night shift to a day shift within a 7-day period

NSP .... Nurse Scheduling Problem; type of employee scheduling problem studied in Operational Research (OR) that has an overall goal of assigning nurses to shifts according to a number of model constraints

Nursing Staff .... Staff responsible for the provision of care in health care settings through activities/tasks relating to monitoring, managing, and delivering medical interventions to patients; encompasses several roles including registered nurses (RNs), healthcare assistants or support workers, and nursing associates

Objective Function .... A mathematical representation of the overall goal in an optimisation model, i.e., the quantity to be minimised or maximised

Optimal Solution .... The combination of decision variable values that satisfies all model constraints and has been confirmed to be the best value of the objective function

Optimisation .... The mathematical process of selecting values for decision variables to maximise or minimise an objective function, given certain model constraints

Overtime.......................... Working in excess of 37.5 hours per calendar week when averaged over a certain reference period (NHS Employers, 2024)

Pragmatism .... A research philosophy that values interpreting reality through personal experiences, flexible methodological inquiry, as well as a ‘problem-solving’ approach to improving outcomes

Quick Return .... A shift pattern variable that is traditionally characterised as having ≤11 hours of rest between any consecutive shifts

Roster............................. Schedule detailing when employees work, i.e., the working hours they have been assigned

Self-Rostering .... A rostering method where an unassigned schedule containing all required shifts for maintaining continuity of care is made available to staff in order to bid for their preferred shifts

Shift Work .... Systems of work that occur outside of standard daytime hours (between 07:00 and 19:00, Monday-Friday) and can involve afternoon, night or weekend work, extended work shifts (e.g., ≥12-hour shifts), rotating hours, split shifts, overtime, and on-call duties (Health and Safety Executive (HSE), 2006)

Short Return..................... A shift pattern that is characterised as having ≤48 hours between a night-to-day (NTD) shift rotation

Sickness Absence .... Any period of absence from work due to sickness or ill health

“Social Disruption” .... Preference profile that involves heavier penalisation of shift assignments that can impact work-life balance, such as having too many working days or shifts that interrupt traditional social periods; is applicable to nurses who prefer schedules that enable longer periods away from work

Staffing Blocks .... Segments of the 24-hour ward day that require a minimum number of nurses

Upper Bound.................... In optimisation problems using branch-and-bound solving algorithms, the upper bound represents the best feasible objective function value that has so far been identified during solution search

Wellbeing......................... A positive state characterised by feelings of happiness and contentment, alongside functional aspects such as having good health, personal development, autonomy, purpose, and meaningful relationships (Ryff, 2013)

Work Fatigue.................... A state of physical, mental, and/or emotional exhaustion that results from repeated exposure to work demands (Frone and Tidwell, 2015)

WTD/WTR .... Working Time Directive/Regulations; legislation of working hours in the European Union that provides rules on daily/weekly rest periods, annual leave entitlements, length of working week, breaktime length and frequency, and special considerations for those working nights

Work-Life Balance............ The extent to which an individual is equally engaged in, and equally satisfied with, their work role and personal/family life (Kalliath and Brough, 2008)

Work-Time Control........... An employee's ability to control the duration, position, and distribution of their work hours, i.e., autonomy over working time

Acronyms

AIC .... Akaike Information Criterion

BIC .... Bayesian Information Criterion

CI .... Confidence Interval

FIOH .... Finnish Institute of Occupational Health

FRMS .... Fatigue Risk Management System

FTE .... Full-Time Equivalent

HCA................................. Health Care Assistant

HPPD............................... Hours Per Patient Day

HSE .... Health and Safety Executive

ICC .... Intraclass Correlation Coefficient

IQR .... Inter Quartile Range

MILP .... Mixed Integer Linear Program

NICE .... National Institute for Health and Clinical Excellence

NIHR ARC .... National Institute for Health Research Applied Research Collaboration

NSP .... Nurse Scheduling Problem

OR .... Odds Ratio

OR .... Operational/Operations Research

PP.................................... Preference Profile

RN .... Registered Nurse

SD .... Standard Deviation

TOIL................................. Time Off In Lieu

UK .... United Kingdom

VIF .... Variance Inflation Factor

Chapter 1 Introduction

1.1 Background

In modern health care systems, essential services such as acute ward care and emergency response involve the staffing of workers in shifts to meet fluctuating patient demand over the 24-hour day. This introductory chapter provides an overarching summary of how shift work is regulated and organised in the United Kingdom (UK) and includes operational definitions, common shift characteristics and patterns, and the associated risks and harms of working shifts. The chapter then narrows down to the features that influence the organisation of registered nurses' shift patterns specifically and highlights the complexities managers face when organising shifts into team rosters. Finally, the motivation for this doctoral research is described alongside a number of key points that support its overall aim: **optimising shift patterns for nurses working in acute hospital wards**.

1.1.1 Defining & Organising "Shift Work"

In the European Union (EU), legislation of working hours across all industries originates from the European Working Time Directive, which stipulates rules on daily/weekly rest periods, annual leave entitlements, length of working week, breaktime length and frequency, and special considerations for those working nights (European Commission, 2003). These rules are enforced in the UK by the Health and Safety Executive (HSE), a national-level regulator for occupational health, safety, and wellbeing. In 2006, the HSE released comprehensive guidance for employers on how they should manage working conditions for shift workers specifically. Although not compulsory, it is strongly recommended that employers follow these provisions as a method for ensuring good scheduling/rostering practice (Health and Safety Executive (HSE), 2006).

Throughout this guidance document, "shift work" is defined as all systems of work that occur outside of standard daytime hours (i.e., between 07:00 and 19:00, Monday-Friday) and can involve afternoon, night or weekend work, extended work shifts (e.g., ≥12-hour shifts), rotating hours of work, split shifts, overtime, and on-call duties. Given this definition, employers are encouraged to assess the major risks associated with shift work and identify sub-groups of employees who may be vulnerable, particularly as a result of disruptions to internal circadian rhythms (Knutsson, 2003). Such disruptions can significantly affect physiological functions such as hormone release, body temperature, and metabolism, ultimately leading to issues with sleep and recovery, appetite and digestion, and the ability to engage in personal activities outside of work. A considerable amount of research has demonstrated several consequences of shift work: increased fatigue and burnout, poor work-life balance, and development of chronic illness or cancer in the long-term (Grzywacz, 2016; Arlinghaus *et al.*, 2019; Moreno *et al.*, 2019). Consequences for performance and safety at work have also been found (Folkard and Tucker, 2003; Wagstaff and Sigstad Lie, 2011; Dall'Ora *et al.*, 2016), which pose knock-on effects for service productivity and end-users.

With this in mind, the HSE provide several recommendations for optimising working hours configurations, summarised in Table 1. Although the severity of these risks depend on the demands unique to each workplace or industry, the HSE highlight that simply complying with legal Working Time regulations is likely not enough to prevent or reduce shift workers' fatigue, and that employers should go beyond basic requirements to ensure work schedules are safe.

Table 1. Recommendations for shift work (Health and Safety Executive (HSE), 2006)

Risk Category	Recommendation
High-risk shifts	Permanent night shifts and split shifts should be avoided.
Weekly working hours	Legally limited to a maximum of 48 hours per week (averaged over a four-month period). Workers can opt out of this limit via written agreement.
Rotating shifts	Adopt forward rotating (i.e., chronologically moving from morning-evening-night) schedules that either rotate quickly (every 2-3 days) or slowly (every 3-4 weeks) to avoid disruption to circadian rhythms.
Shift start times	Avoid shift start times before 07:00.
Shift length	Shift length may be optimised at 8-hours, but some workers prefer working 12-hour shifts to enable compressed working weeks; avoid shifts longer than 8 hours when work is demanding, safety-critical or monotonous.
Consecutive working days	Limit the number of consecutive working days to 5-7 days; limit the number of consecutive 12-hour shifts, night shifts and/or shifts with early starts to 2-3 days.
Rest between shifts	Ensure a minimum of 11 hours of rest time between shifts.
Rest days	Rest days should allow employees to recover, take part in social/domestic activities, and adjust to a new work schedule if necessary; when working multiple 12-hour shifts, night shifts or shifts with early starts, 2-3 rest days should be allocated.
Worker preference	Ask shift workers about their preferences, particularly in relation to fixed vs. rotating shifts and shift length.

These recommendations are made further applicable to healthcare workers in England's National Health Service (NHS) through several working groups, like the National Quality Board (NQB; a national controller of patient care quality) and NHS Employers (responsible for negotiation of terms and conditions applicable to all NHS staff). In their guidance published for caring staff, the NQB provides recommendations on ideal staff deployment in 24-hour care settings, primarily focusing on how to ensure that staffing levels are met on a shift-to-shift basis (National Quality Board, 2013;2016). They additionally recommend that these settings use electronic rostering technology, which enable managers to bring together information from multiple routine sources to quickly build rosters that prioritise meeting patient demand. In contrast, recent guidance published by NHS Employers focuses more on 'ergonomic' shift pattern planning by applying several HSE recommendations to the context of healthcare staff and patient wellbeing (NHS Staff Council, 2020). They additionally recommend that wards analyse data trends on staff absenteeism and turnover, qualitative data from staff regarding fatigue and safety, and timing of care errors to identify any potential issues with the working patterns used in staff rosters.

Guidance and advice for nurses themselves largely comes from public service and nursing staff unions. For example, in their "Guide to Negotiating on Shift Work", UNISON (2013) provides an overview of various shift systems across different industries, including the 2-shift and 3-shift systems usually seen in hospitals. They also highlight the concept of self-rostering - where shift workers take an active role in the planning of their shifts - but preface that this must be carried out cautiously so that service is always maintained. Workforce standards published by the Royal College of Nursing (2021a) provide similar guidance in Standard #11, stating: "*Rostering patterns for the nursing workforce will take into account best practice on safe shift working. Rostering patterns should be agreed in consultation with staff and their representatives*". They additionally emphasise the need for clear rostering policies and procedures within workplaces.

1.1.2 What shift patterns are nurses working in England's NHS?

Given the abundance of resources available for both employers and employees, the shift patterns worked by NHS nursing staff in hospitals should, in theory, be limited to those that are safe for both staff and patients. However, acquiring the data to confirm how guidance has shaped the actual shift patterns worked by nurses is not straightforward, as information on their working hours are not routinely collected through official or centralised mechanisms (Ball *et al.*, 2015). Alternatively, examination of nurse-reported data from large-scale surveys and administrative data from cross-sectional and longitudinal research studies can offer some insight.

For example, one can specifically look at trends in distribution of the shift lengths worked by nurses. Traditionally, shift patterns were based on 3-shift systems, with each shift lasting ≥8 hours each and three handovers occurring during a 24-hour ward day. But over time, 12-hour shifts have become increasingly popular due to perceived benefits like improved continuity of care for patients and better work-life balance for nurses (Dall'Ora, Ejebu and Griffiths, 2022). In a research funder report on the prevalence of 12-hour shifts in the UK, Ball *et al.* (2015) compared data collected by annual employee surveys distributed by the Royal College of Nursing (RCN), the largest nursing-specific trade union in the UK. They noted that over a 4-year period, there had been a considerable increase in members working 12-hour shifts in NHS hospitals: 31% in 2005 vs. 52% in 2009. Griffiths *et al.* (2014) reviewed working hours from 2568 nurses in England (as part of the Nurse Forecasting in Europe (RN4CAST) survey distributed in 2010), stating that 32% of day shift workers and 36% of night shift workers worked ≥12 hours on their last shift. They additionally found that England was unique in shift length distribution – while other European countries demonstrated the use of uniform patterns, England used a mix of 8-hour, 12-hour and other shift lengths, and that this mix also often varied between wards within the same hospital. In a longitudinal study of nursing staff sickness absence rates from administrative records, Dall'Ora *et al.* (2019a) found that 38% of 601,282 shifts worked in a large acute hospital (between 2012-2015) were ≥12 hours. Moreover, cross-sectional administrative data collected in 2017 from 81 wards across 4 hospitals found that 72% of shifts were ≥12 hours, but this proportion varied significantly between wards and hospitals (i.e., ranging from 36% to 95%) (Saville, Dall'Ora and Griffiths, 2020).

Although these examples of shift length distribution over the years are not directly comparable due to heterogeneity in study setting and purpose, they do offer a rough overview that is helpful for understanding how nurses' shifts are likely to be organised. In general, rather than a uniform group of working patterns, the UK appears to employ a variety of shift lengths (and therefore systems) that significantly vary between wards, hospitals, and specialties. Therefore, examining the benefits and drawbacks of using these different systems of shift work, particularly in terms of minimising risks to staff, is of critical importance.

1.1.3 Nurses' shift patterns from different perspectives

The organisation of nurses' working hours involves a number of features that exert influence at the staff-, ward- and organisational-level. For individual nurses, preferences for different shift types and patterns often arise from one's personal priorities in and outside of the workplace, such as work-life balance, childcare responsibilities, and remuneration. For example, some nurses may prefer to work long shifts (i.e., shifts lasting 12 hours or more), as they enable more days off from work when compared to working short shifts (i.e., shifts lasting 8 hours or less).

However, research has also shown that working long shifts can lead to increased burnout and job dissatisfaction (Dall'Ora, Ejebu and Griffiths, 2022). Although honouring working time preferences and flexible working requests has the potential to improve outcomes for nurses (NHS Staff Council, 2021b), these practices must be implemented and used carefully so that service is maintained and shift preference disputes are avoided or resolved quickly.

At the ward-level, having sufficient numbers of nursing staff is critical for maintaining safe and effective care environments. Many cross-sectional and longitudinal studies have demonstrated a clear link between higher nurse staffing levels and improved patient outcomes including shorter lengths of stay, fewer complications, and reduced risk of death (Dall'Ora *et al.*, 2022; Drennan *et al.*, 2024). Developing safe staffing targets requires analysis of expected patient numbers, characteristics, and levels of acuity/ dependency. While some flexibility is allowed to accommodate expected staff absences (also known as 'headroom', which covers annual or study leave entitlements, etc. (NHS, 2020)), ward managers must ensure wards are continuously staffed with "the right people, with the right skills, in the right place at the right time" (National Quality Board, 2013). However, deploying the nursing workforce with this single-minded goal in settings that are resource-constrained naturally leads to more difficult shift configurations: longer shifts, increased weekly working hours, and more overtime (Ball *et al.*, 2015; Royal College of Nursing, 2023), all of which are harmful stopgaps that are not sustainable for long term use.

Hospital-level considerations also play a critical role. Effective rostering policies and practices are essential for ensuring compliance with labour laws and union contracts and minimising reliance on costly temporary staff (Silvestro and Silvestro, 2000; Drake, 2019). They should additionally provide guidance around distributing shifts equitably among staff while taking into account any previously agreed working requests. Newer electronic rostering technologies can be leveraged to enforce such considerations, with the ultimate aim of reducing operational inefficiencies while also tracking key performance indicators around workforce wellbeing (e.g., rates of sickness absence) and patient care quality (e.g., number of adverse events). However, findings from the Carter Review on NHS hospital productivity and performance highlight significant variation in organisational rostering policies, as evidenced by disparity in managing annual leave, shift patterns and flexible working (Carter, 2016). Moreover, they found disparity in the use of e-rostering technology, with many hospitals using it superficially (e.g., transferring manual paper rosters to e-rosters) and others only starting to use its data integration features.

Therefore, while shift planning is inherently complex, various challenges at every level further increase the difficulty of developing effective nurse rosters. Reconciling nurses' individual shift preferences with operational needs is a time-intensive process that can lead to staff dissatisfaction if not managed carefully. At the ward level, planning nursing establishments that solely prioritise patient demand forces reliance on problematic shift configurations such as longer shifts and overtime. At the hospital level, while e-rostering technology has the potential for creating data-driven rosters, many hospitals fail to fully use these systems (for reasons explored further in section 2.2.2.3), risking operational inefficiencies and poor shift planning.

1.1.4 Research Motivation

The implications of poorly planned shift patterns are evident in multiple contexts. Frequent news articles recount nurses' ongoing challenges with working shifts, e.g. "Nursing staff are frequently unable to take their breaks, are having to stay behind at the end of work and are being given "barbaric" rotas with back-to-back day and night shifts, which is putting both them and their patients at risk…" (Merrifield, 2017). These anecdotes are supported by national routine data collected over the last decade that show increased rates of nurses' sickness absence (particularly as a result of anxiety, stress, depression, and other psychiatric illness), higher reporting of feeling unwell as a result of work-related stress specifically, and an increasing proportion of nurses citing "work-life balance" as the reason for leaving their job (NHS Digital, 2022; NHS Staff Survey, 2023).

Despite all of this, shift work is a necessary feature of 24-hour acute care wards, where pressures are continuously placed on both individual nursing staff and ward-level resources. As previously discussed, the risks associated with working shifts are well-documented and should be carefully balanced with accommodating nurses' shift preferences and meeting patient demand. This difficult 'balancing act' is further complicated by a lack of consensus around how to reconcile these priorities when creating rosters in practice.

There is a clear and compelling case for improving this difficult status quo. This doctoral research sought to address this problem by exploring how to optimise the shift patterns of registered nurses working in acute hospital wards. Taking inspiration from current trends in working time organisation (i.e., employing data-driven rostering technology, using flexible and nurse-driven approaches to accommodating shift preferences), three research studies using a combination of qualitative thematic analysis, quantitative regression modelling, and mathematical optimisation modelling were undertaken. Specific details for each study are included in Chapter 3 (Project Methodology), as well as in each study chapter respectively: Chapter 4, Chapter 5, and Chapter 6.

1.2 Thesis Outline

This thesis proceeds with the following chapters:

Chapter 2 includes the results of a scoping literature review that explored and critiqued multiple connected topics: the impact of shift configurations on patient- and nurse-related outcomes, how nurses' rosters are created in practice, and an overview of the 'nurse scheduling problem' in the Operational Research (OR) domain.

Chapter 3 reviews the theoretical and conceptual underpinnings that informed the overarching approach of this research (objectives, questions, and data analysis strategies), as well as the specific approaches used in each study (a mix of qualitative, quantitative, and optimisation methods).

Chapter 4 reports the results of the first study, which aimed to gain a deeper understanding of the factors that lead nurses to prefer certain shift types or patterns through a cross-sectional analysis of closed- and open-ended survey data.

Chapter 5 reports the results of the second study, which explored the associations between 'adverse' configurations of working hours and odds of nurses' sickness absence through a longitudinal analysis of historical rostering data.

Chapter 6 reports the results of the third and final study, which integrated findings from the previous two studies to formulate and solve a novel nurse scheduling model that generates rosters that inherently prioritise nurses' preferences and wellbeing using mathematical optimisation methods.

Chapter 7 concludes the thesis with a summary of the aim, questions, and findings of this research, as well as with a discussion around the strengths, limitations, and implications of this programme of work.

Chapter 2 Literature Review

This chapter contains the results of a scoping literature review of two key subjects related to nurses' shift patterns and the organisation of their working hours: 1) shift characteristics and patterns that are known to influence patient and nurse-related outcomes, and, 2) how the task of rostering nursing teams is achieved, both in research (i.e., in the health research and operational research domains) and in practice. Searching questions and methodology were designed to gain a core representative sample of important academic, grey, and guidance texts.

2.1 Scope & Method

The scoping review framework developed by Arksey and O'Malley (2005) was used to guide search strategy development, study screening, and data charting. Potential sources included primary research articles, methodology papers, literature reviews, policy documents, national guidance documents, and professional magazine articles (e.g., editorials, informal surveys/polls) where appropriate. Conference abstracts, dissertations, theses that were not represented by peer-reviewed publications, commentaries or editorials that did not reference peer-reviewed research or general surveys, and study protocols that were not represented by published results were excluded. Searches were first conducted in April 2022 and were updated in May 2023 and in August 2024.

Search questions were developed using the traditional "building blocks" method (Booth, 2008). Synonyms for each concept were then developed by consulting a group of key review papers that explored similar topics and outcomes (Ball *et al.*, 2015; Dall'Ora *et al.*, 2016; Saville *et al.*, 2019; Ejebu, Dall'Ora and Griffiths, 2021; Wynendaele *et al.*, 2021). Topics and outcomes were chosen for their relevance to nursing workforce management: configurations of working hours, scheduling methods, sickness absence (particularly due to anxiety, stress, and depression), job dissatisfaction/turnover, and quality of patient care. While longer-term staff outcomes (e.g., increased risk of chronic disease) are important, this review prioritised outcomes with more immediate operational relevance to scheduling decisions. Search strategies were deployed separately in four literature databases: CINAHL, Medline, PyschINFO, and Scopus. Table 2 and Table 3 provide further details of how searching questions and strategies were constructed. Where appropriate, subject filters/limiters generated by each database were used to narrow search results. In databases hosted on the EBSCO platform, these filters were population- and outcome-specific (e.g., health personnel, care errors). On the Elsevier platform, these limiters were discipline-oriented (e.g., medicine, mathematics, decision sciences).

In addition to systematic searches, targeted searches (carried out on Google Search and Google Scholar) were completed for two specific areas: 1) existing guidance on shift organisation, and 2) problem formulation in Nurse Rostering/Scheduling literature. The first targeted search was completed to ensure that relevant guidance on working hours, shift pattern organisation, and healthcare staff deployment were captured, as they are unlikely to be indexed in academic databases. Given the large body of research in this area, the second targeted search was completed to identify and prioritise seminal OR papers that discuss the history of the Nurse Scheduling/Rostering Problem, how problem formulation is carried out, categories of models/techniques, frequent model objectives and constraints, and applications to practice (in hospital settings).

Table 2. Literature searching questions

Main Question	Supporting Questions
What is the impact/influence of nurses' shift pattern organisation?	What influence does shift organisation have on patients?
	What influence does shift organisation have on nurses?
How is nurse rostering done in practice?	What are the different types of nurse rostering methods?
	How is nurse rostering accomplished in practical settings?
	How is nurse rostering improved with Operational Research (OR) techniques?

Table 3. Search Strategies: Core concepts and alternative terms

Concept	Alternative Terms
Nurses	nurses, healthcare support worker, healthcare assistant, HCSW, HCS, ward managers, nurse manager
Shift Variables	shift work, shift pattern, shift length, day/night shift, shift rotation, rest day, weekly working hours
Rostering/Scheduling	rostering, scheduling, deployment, allocation, work scheduling, personnel staffing, personnel scheduling
Self-Roster	self-roster, self-schedule, flexible scheduling, flexible working, preference scheduling, work time control
E-Roster	e-roster, e-schedule, electronic roster/schedule, decision support system, roster/schedule system, roster/schedule application
Patient Outcomes	safety, error, missed care, care left undone, satisfaction, mortality, quality, performance, nurse-reported outcome, adverse events, falls, ulcers
Nurse Outcomes	burnout, fatigue, stress, wellbeing, mental health/illness, sickness absence, job satisfaction, turnover
Scheduling/Rostering Problems (OR)	rostering/scheduling problem, planning problem

Search results were imported into EndNote (version 20). After the software's rapid duplicate-removal function was used, roughly 12,000 results remained. Following screening by title and abstracts, 532 results were retained. To rapidly identify seminal sources and current research priorities, a successive round of 'stringent' screening was performed. Here, priority was given to: 1) large primary studies and literature reviews that were highly cited and/or published within the last 5-10 years, and 2) studies published in the UK and other countries under the EU Working Time Directive. Following stringent screening, 92 articles were eligible for full-text review and data charting.

For the review's updates, search strategies were re-deployed in the same literature databases and results were limited to articles published from 2021 onwards (first update) and from 2023 onwards (second update); no further limiters were used. The same title/abstract screening rules were used to identify relevant sources. This resulted in the addition of 40 studies (24 in 2023, 16 in 2024), bringing the total number of articles in this scoping literature review to 132. The majority of studies added during review updates were related to the impacts of shift organisation on nurses' wellbeing and performance, while fewer were related to rostering practices with increased work-time control and the nurse scheduling problem in Operational Research (OR). The conclusions of this review did not change with the addition of new studies.

2.2 Results

2.2.1 How does shift organisation impact nurse and patient outcomes?

The majority of search results in this literature review are related to the impact of shift organisation on nurse- and patient-related outcomes. These studies used a variety of methods, however many were cross-sectional surveys of nurses working in different settings. More recently, there has been a growing trend to examine variable relationships with large datasets containing objective administrative data (e.g., hours actually worked linked with rates of sickness absence and care errors) (Härmä, Kecklund and Tucker, 2024). Systematic, scoping, and narrative reviews were also examined; while some of these made moderately confident summaries of select outcomes, many also reported inconclusive and/or mixed results. A summary of findings is described below, organised by the following shift pattern characteristics: shift length; evening, night and weekend shifts; rotating shifts and quick returns; weekly working hours and overtime; compressed workweeks. Taking everything into account, it became apparent that certain shift characteristics demonstrated clearer relationships with outcomes (namely, evening/night/weekend shifts, rotating shifts and quick returns, and overtime), while others remained unclear or were dependent on which specific nurse- or patient-related outcomes were measured (shift length and compressed workweeks).

2.2.1.1 Shift Length

Many studies explored the impact of shift length, with most focusing on the effects of working extended/long shifts. In terms of patient-focused outcomes, an early study found that when nurses worked shifts ≥12 hours, the risk of making an error was significantly increased (Rogers *et al.*, 2004). Other more recent studies also found an increased risk of nurse-reported failing patient safety, quality of care, and 'care left undone' (Stimpfel and Aiken, 2013; Griffiths *et al.*, 2014; Ball *et al.*, 2017) as well as patient dissatisfaction with care (Stimpfel, Sloane and Aiken, 2012) when working ≥12-hour shifts. In contrast to these findings, an experimental study by James *et al.* (2021) found that while measures of nurses' subjective sleepiness, attention, cognitive effectiveness significantly decreased after working three consecutive 12-hour shifts, measures of performance during task simulation did not significantly change. However, it is noted that the instrument used to evaluate performance during simulations was originally developed for student nurses, and thus may have led to inaccurate measurements amongst experienced staff. An analysis of objective working hours found that vital signs observations were more likely to be delayed when health care assistants were working 12-hour shifts (Dall'Ora *et al.*, 2019b). Similarly, recent analyses of administratively recorded safety and patient incident data found that mental health units regularly employing 12-hour nursing shifts had significantly higher instances of disruptive events and physical/verbal assaults against staff. (Beckman *et al.*, 2022; Dall'Ora *et al.*, 2023a).

Qualitative data reveal that nurses themselves may disagree on which shift pattern enables better continuity of care. One study found that nurses uniformly agreed that 12-hour shifts are better for continuity (Haller and Quatrara, 2018), while another cited conflicting beliefs depending on if continuity should be evaluated within a single day or across several days (Baillie and Thomas, 2017). Other studies however were not able to find a significant influence of long shifts on patient outcomes (Stone *et al.*, 2006; Battle and Temblett, 2018).

Reviews evaluating the impact of long shifts on patient outcomes have either found mixed or adverse effects. An early systematic review found both improved and worsened patient outcomes with 12-hour shifts (e.g., more care errors but less care complications and shortened length of stay) (Estabrooks *et al.*, 2009). In an analysis of eighteen studies exploring the association between shift length and various patient outcomes, six studies found increased risk of some adverse events for patients when nurses' shift lengths were longer, however medication errors, falls, ulcers, and near-misses in errors were not significantly related to shift length (Bae and Fabry, 2014). Harris *et al.* (2015) reported that there was a general dearth of evidence exploring the direct connection between shift length and patient outcomes.

In contrast to these inconclusive summaries, Clendon and Gibbons (2015) reported that in six studies representing the majority of their total review sample, higher rates of care errors (e.g., care left undone, medication errors, charting errors, central-line bloodstream infections, poor pain control) were found when nurses worked 12-hour shifts. Similar findings were cited by Dall'Ora *et al.* (2016), where increased rates of errors and decreased quality of care and patient safety were found in multiple large studies. Moreover, a recent systematic review found that working more than 12 hours per day and 40 hours per week resulted in many worsened patient outcomes, including quality of care, errors/near errors, infections, and mortality from pneumonia (Bae, 2021).

For nurse-related outcomes, the direction of results differed when comparing social/work-life balance outcomes and nurses' health outcomes (e.g., sickness absence and fatigue). Perceptions on working 12-hour shifts were found to be 'more positive' in relation to job satisfaction, off-duty time and family life (McGettrick and O'Neill, 2006). In another early study, when compared to 8-hour shifts, nurses working 12-hour shifts were more satisfied with their jobs, were less emotionally exhausted, and more satisfied with their work schedules (Stone *et al.*, 2006). Longer rest periods, reduced commuting time, and better sleep are some of the many benefits of working long shifts – however study authors Ingstad and Haugan (2024) note that the novelty of long shifts in this study's setting (nursing homes) may have influenced responses. Outcomes may also particularly improve if nurses had requested to work longer shifts in the first place, or if measurements were taken immediately post-implementation (Battle and Temblett, 2018; Hong *et al.*, 2021). Haller *et al.* (2020) found that nurses perceived different benefits among 8-hour, 10-hour, and 12-hour shifts, stating that different elements related to work tasks, handoffs, and work-life balance fared better under certain shift systems.

Qualitative evidence showed that nurses perceived 12-hour shifts to be better for overall job satisfaction, time away from work, and reduced commuting time (Haller and Quatrara, 2018). Similarly, in a study of nurses who switched to working 8-hour shifts reported not having enough time to finish their work when compared to previously working 12-hour shifts, with many requesting to leave the unit after the change was enforced (Baillie and Thomas, 2019). When interviewing nurses about different shift systems, the concept of burnout was only mentioned when discussing 12-hour shifts (Haller *et al.*, 2020). Other contextual elements must also be considered when interpreting nurses' perceptions and views. For example, in their evaluation of a hospital quality improvement project, Jabaley *et al.* (2022) found that even though nurses working in outpatient settings claimed many benefits to working 12-hour shifts, nurses clarified that working 12-hour shifts in inpatient settings were more exhausting as a result of unpredictable workloads. In another study (Suter and Kowalski, 2021), many consequences (e.g., exhaustion, poor inter-shift recovery, anxiety about returning to work after long periods away from wards) were reported by nurses after the introduction of 12-hour shifts– but authors note that 12-hour shifts were introduced against nurses' wishes, and that the mandatory nature of the change likely influenced perceptions.

Some larger studies also report negative outcomes. Here, authors found that nurses who worked long shifts were more likely to experience burnout and job dissatisfaction when compared to shorter shifts (Estryn-Béhar and Van der Heijden, 2012; Stimpfel, Sloane and Aiken, 2012; Dall'Ora *et al.*, 2015; Ball *et al.*, 2017; Fond, Lucas and Boyer, 2023). Nurses were also likely to report increased sleepiness and inter-shift fatigue when working long shifts (Geiger-Brown, Trinkoff and Rogers, 2011; Geiger-Brown *et al.*, 2012). Moreover, when analysing administrative records, working long shifts increased rates of sickness absence (Dall'Ora *et al.*, 2019a; Larsen *et al.*, 2020; Rodriguez Santana *et al.*, 2020) and risk of occupational injury (Härmä *et al.*, 2020). Lastly, in a recent cross-sectional study examining the effects of changing nurses' workhours during the early stages of the COVID-19 pandemic, being made to work longer shift lengths (i.e., more than 8 hours) resulted in significantly increased odds of turnover intention when compared to those whose shift lengths did not change (Djupedal *et al.*, 2022).

Five literature reviews examined the relationship between shift length and nurse outcomes, with many providing inconclusive summaries. Estabrooks *et al.* (2009) were unable to summarise studies examining health provider outcomes (e.g., wellbeing, stress and job satisfaction), citing issues in study methodological rigour. Similarly, Merkus *et al.* (2012) reported that evidence related to sickness absence was largely inconclusive for shift length variables, citing significant heterogeneity in reporting of shift characteristics; it is noted that this review was published prior to recent large objective studies exploring this same outcome, as reported above. Harris *et al.* (2015) found that nurses preferred working 12-hour shifts (due to better organisation of home/social life activities), even though other studies in this review also found an increased risk of fatigue and poor sleep quality when nurses worked these shifts. Bae and Fabry (2014) report an association between long working hours and adverse nurse outcomes like fatigue, need for recovery, and intent to leave the job. Dall'Ora *et al.* (2016) found that while some outcomes worsened with the use of 12-hour shifts (e.g., performance, vigilance and monitoring, and fatigue) other outcomes had mixed results (e.g., job satisfaction, burnout and intention to leave). A recent review additionally found that 12-hour shifts (and particularly consecutive 12-hour shifts) impeded recovery from work (Gifkins *et al.*, 2020). Lastly, in a recent discussion paper covering several outcomes (including organisational outcomes like staffing, costs), little evidence was found to support the value propositions associated with long shifts, indicating that original claims of improved costs, nurse productivity and care continuity are questionable (Dall'Ora, Ejebu and Griffiths, 2022).

2.2.1.2 Evening, Night, and Weekend Shifts

Many of the studies examining these shift types looked at nurse- related outcomes (e.g., health, wellbeing) with the majority citing disruptions to rest and social life being potential mechanisms. However, results are interpreted with caution, as these shift types are also likely to be impacted by other workforce organisation variables, like fluctuations in staffing levels and work demands. Estryn-Behar *et al.* (2010) found that amongst nurses who left their workplace, frequently cited reasons for leaving included working too many nights and too many weekends. Similarly, when comparing 8-, 10-, and 12-hour day/night shift patterns, 8-hour and 10-hour night shifts and working less than 6 night shifts total per month were associated with greater risk for dissatisfaction with working time (Estryn-Béhar and Van der Heijden, 2012). In analyses of objective working hour characteristics, an increase in the proportion of evening and night shifts worked resulted in an increase in nurse-reported work-life conflict (Karhula *et al.*, 2018) and risk of occupational injury was significantly increased during evening shifts and workdays following night shifts (Härmä *et al.*, 2020).

Nurses working 12-hour night shifts experience increased sleepiness at the end of their shift when compared to nurses working 12-hour days only (Geiger-Brown *et al.*, 2012) as well as when comparing weekend work with no weekend work (Geiger-Brown, Trinkoff and Rogers, 2011). In a recent survey of nurses about missed care, high chronic fatigue levels and low inter-shift recovery were independently associated with missed care during night shifts (Crincoli *et al.*, 2024). Similarly, nurses working shift patterns with night shifts experience increased fatigue during their free days, as well as needing longer sleep periods when working night shifts (Härmä *et al.*, 2019; Min, Hong and Kim, 2022). In a two-year cohort follow-up study, (Waage *et al.*, 2021) found increased odds of nurses developing shift work disorder (i.e., excessive sleepiness and/or insomnia as a result of circadian misalignment) if the number of night shifts worked in the last year increased by 10 or more when compared to baseline. Moreover, in an experimental study testing the impact of adding a rest day between working two nights shifts and two evening shifts, Kubo *et al.* (2022) found that nurses' levels of exhaustion and distress significantly decreased post-intervention (however, it is noted that this scheduling change was specifically requested by nurses due to difficulties with working a backward-rotating shift pattern).

Furthermore, working more than 2 weekends per month, ≥4 consecutive nights shift, and working ≥50 evening shifts or more than 12 spells of ≥ 5 consecutive night shifts was associated with increased likelihood of sickness absence (Estryn-Béhar and Van der Heijden, 2012; Ropponen *et al.*, 2019; Larsen *et al.*, 2020). Dall'Ora *et al.* (2020) similarly found that when staff worked ≥75% of their shifts at night in the last 7 days, increased rates in long-term sickness absence were recorded, challenging the assumption that working more night shifts aids circadian rhythm adjustments. In contrast however, Peutere *et al.* (2021) found that night work was not significantly associated with sickness absence, irrespective of the exposure window analysed (ranging from 10 to 180 days).

Of the four literature reviews examining these shift types, all found worsened outcomes for nurses and patients. In their review of the “off-shift literature”, de Cordova *et al.* (2012) concluded that patient outcomes like mortality, serious health events, and post-surgery complications were worse during weekends, whereas employee outcomes like fatigue, mental wellbeing, and job satisfaction were worse on night shifts when compared to regular day shifts. Dall'Ora *et al.* (2016) concluded that night work is linked with poorer nurse performance and decreased job satisfaction when compared to day work. Merkus *et al.* (2012) found that for female health care workers specifically, fixed evening shifts were associated with longer sick leave. In their systematic review of qualitative evidence, Weaver *et al.* (2023) concluded that nurses working night shifts often have difficulties with balancing sleep/recovery with home-life, maintaining healthy lifestyles, and fatigue and exhaustion – all of which impacted their performance at work and lives outside of work. Lastly, in a systematic review and meta-analysis by Okechukwu *et al.* (2023), pooled effects for increased odds for depression were found amongst nurses working night shifts.

2.2.1.3 Rotating Shifts, Quick Returns

A small group of studies explored the effects of different types of rotating work. It is suspected that this small number was due to the fact that rotational shiftwork is usually assessed as a controlling variable (if at all), rather than as a unique independent factor with varying parameters. In a qualitative study of nurses’ perceptions of shift length, nurses reported that while 12-hour shifts made them more fatigued when compared to 8-hour shifts, this fatigue was likely more due to working rotating 12-hour shifts specifically (Haller and Quatrara, 2018). Similar results were reported in another qualitative study investigating sleep and fatigue management strategies used by health care staff (including nurses), where participants commented on the challenges of working late-early-late shift combinations (Booker *et al.*, 2024a). Rosenström *et al.* (2021) found that amongst several working patterns derived from historical data, irregular rotation between mornings, evenings and nights was the strongest predictor of sickness absence. Dall'Ora *et al.* (2016) found that job performance, error rates, and acute fatigue worsened when compared to fixed day shifts; this was additionally confirmed by the review by Gifkins *et al.* (2020), where rotating shifts were found to impede recovery from work. In another review of the effects of shift work on nurse injuries, rotating shifts (in addition to long working hours and overtime) increased the risk of needlestick/sharps injuries and other work-related accidents (Imes *et al.*, 2023). Lastly, in a review of organisational interventions that re-organised shift patterns, Bambra *et al.* (2008b) found that interventions changing rotation speed (slow versus fast) and direction (backward versus forward) resulted in the most beneficial effects for workers.

In their book chapter exploring the role of work schedules on occupational health and safety, Geiger-Brown, Lee and Trinkoff (2012) state that the most hazardous aspect of working rotating shifts may be the "quick-return", where workers are given ≤11 hours of rest between shifts. This theory was confirmed by multiple studies in the present review, where frequent quick returns were linked with more sleep problems and increased exhaustion and fatigue, levels of stress, sickness absence, work-life conflict, dissatisfaction with work hours, turnover intentions, and developing shift work disorder (Geiger-Brown, Trinkoff and Rogers, 2011; Flo *et al.*, 2014; Dahlgren *et al.*, 2016; Karhula *et al.*, 2017; Karhula *et al.*, 2018; Ropponen *et al.*, 2019; Larsen *et al.*, 2020; Dahlgren *et al.*, 2021; Waage *et al.*, 2021; Djupedal *et al.*, 2022; Öster *et al.*, 2024) – all of which indicate a clear relationship. Furthermore, in a recent randomised controlled trial of an intervention that reduced the number of quick returns for health care workers, significant effect sizes for improvements in insomnia and daytime sleepiness were found (Djupedal *et al.*, 2024). By prospectively assessing outcomes and using randomisation to minimise confounding, this particular study provides stronger causal evidence for the positive effects of reducing quick returns and helps to address some key limitations of earlier cross-sectional and retrospective research.

As expected, reviews exploring the impact of quick returns were able to confirm many of these conclusions (Vedaa *et al.*, 2016; Min, Min and Hong, 2019; Gifkins *et al.*, 2020). Therefore, one can assume that when ergonomic recommendations are used for these two variables (fast, forward-rotating shifts and fewer quick returns) better outcomes for nurses can be expected. However, in a recent survey of nursing staff about the benefits and drawback of quick returns, Öster *et al.* (2022) found that nurses perceived quick returns as an enabler of continuity of care when compared to other shift combinations, even if this was at the expense of their own recovery. There was a dearth of evidence exploring the direct impact of quick returns on patient outcomes.

2.2.1.4 Weekly Working Hours, Overtime

Across the board, studies examining extended weekly hours and overtime demonstrated adverse outcomes for both nurses and patients. In an early study, Rogers *et al.* (2004) found that when nurses worked overtime or ≥40 hours per week, risk of making care errors was significantly increased, which was concerning as there were over 500 shifts that 393 nurses reported being mandated or 'coerced/guilted' to work overtime during a four week period. Similar findings were found in Griffiths *et al.* (2014), where working overtime was linked with increased reports of care left undone and decreased patient safety and quality of care. Moreover, in a study examining the mediating role of fatigue, working overtime (along with a higher number of patients per nurse) positively correlated with number of care tasks left undone (Min *et al.*, 2021). This same research group also found that previous-day overtime hours and working consecutive overtime days were associated with decreased alertness scores during work, particularly during the morning shift (Min *et al.*, 2022).

Geiger-Brown, Trinkoff and Rogers (2011) found that when nurses were mandated to work overtime, there were increased reports of restless sleep. Similarly, Min, Hong and Kim (2022) found significantly increased acute and chronic fatigue as overtime hours increased. Estryn-Behar *et al.* (2010) found that amongst nurses who left their workplace, "too much overtime work" was a frequently reported reason for leaving. A recent large cross-sectional study similarly found that for nurses working in hospitals specifically, longer weekly working hours increased the odds of them leaving their nursing jobs (Bae, 2023). Working ≥40 (long) and ≥48 hour (very long) workweeks also increased the likelihood of sickness absence when analysing objective administrative records (Ropponen *et al.*, 2019; Larsen *et al.*, 2020).

As expected, literature reviews examining these shift variables reported similar conclusions. The majority of studies reviewed by Bae and Fabry (2014) found worsened outcomes for nurses (e.g., injury, burnout, fatigue, absenteeism, and organisation of home-life) when they worked ≥40 hours and/or voluntary/mandatory overtime. Similarly, Dall'Ora *et al.* (2016) concluded that working overtime was linked with making errors, reporting poor quality of care and patient safety, and increased rates of missed care. Bae (2021) and Bell *et al.* (2023) concluded that working ≥40 hours per week and working overtime resulted in several adverse outcomes for patients, including care errors, medication errors, and infection rates. However, a recent systematic review on the impact of staffing and scheduling on nurse turnover reported mixed results on variables such as mandatory overtime and proportion of overtime hours (Bae, 2024).

2.2.1.5 Compressed Workweeks

Few studies examined the impact of nurses working compressed work weeks (i.e., where total weekly hours are worked in a fewer number of days) in comparison to other systems. Rather, results simply stated that this shift system can potentially represent several parameters due to its connection with long shifts, weekly working hours, quick returns, and rest periods (Geiger-Brown and Lipscomb, 2010; Dahlgren *et al.*, 2016; Dall'Ora *et al.*, 2016; Haller and Quatrara, 2018; Gifkins *et al.*, 2020). One study measuring reaction time, vigilance, and attention scores found that all three significantly decreased after nursing staff worked three 12-hour shifts within 72 hours (when compared to measurements taken after a single 12-hour shifts) (Thompson, 2019). Two literature reviews offered limited and mixed conclusions. In their review of interventions aiming to implement compressed workweeks for shift workers in general, Bambra *et al.* (2008a) concluded that while compressed workweeks did not consistently improve health-related outcomes for workers, they may improve work-life balance outcomes. Inconclusive results were also reported by Dall'Ora *et al.* (2016), as they cited a single study reporting negative patient outcomes when nurses worked compressed working weeks specifically with rotating shifts.

2.2.1.6 Summary

While some shift organisation parameters show clearer relationships with outcomes (e.g., working ≥40 hours per week, working overtime, irregular rotation patterns, and/or too many quick returns usually lead to poor outcomes for both patients and nurses), other parameters demonstrate relationships that are not as straightforward or conclusive, particularly for long shifts and compressed workweeks. For the latter two, this lack of clarity likely arises from certain outcomes (e.g., nurses' work-life balance) faring better than others (e.g., nurses' sickness absence, nurses' burnout, patient safety), as well as from the unmeasured influence of confounding factors like nurses' shift pattern preferences and level of choice and control over working hours (these latter concepts were explored further in the first study of this doctoral research project, detailed in Chapter 4). Nevertheless, in addition to shift types and patterns themselves, another key element of staff deployment is also likely to be at play: the actual process of rostering nurses in practice.

2.2.2 How are nurses' rostered in practice?

Studies related to this topic centred on four themes: traditional rostering practices, participatory rostering practices (including team-based rostering and self-rostering), the use of electronic rostering technology, and exploring the "nurse scheduling problem" in Operational Research (OR) literature. A small group of studies explored the impact of different practices on patient- and nurse-related outcomes, however in general, study authors reported that in addition to the rostering practices themselves, the context in which they were implemented and supported (including intervention goals, support from management, and supporting organisational policy) play an equal role in determining outcomes.

2.2.2.1 Traditional Rostering Practices

In their analysis of nurse rostering practices in 50 hospital wards across the UK, Silvestro and Silvestro (2000) found that a variety of methods for rostering were used. However, wards traditionally used some version of manual 'departmental' rostering, where rosters are planned by a single ward manager. This type of planning includes some key phases: providing opportunity for nurses to submit preferences, planning the roster and reconciling staff preferences with service needs, publishing the roster, documenting changes thereafter (shift swaps, unplanned absences, overtime recording), and finalising the roster for payroll (Drake, 2014b). Overall, this method was popular among managers, as they perceived it to be the quickest method of generating rosters that were balanced, safe, and met ward demands (Silvestro and Silvestro, 2000).

However, several drawbacks are reported. Firstly, reliance on a single individual to create rosters requires this individual to have excellent skills in establishment/deployment planning, conflict resolution, and fairmindedness. Moreover, a considerable number of design parameters must be considered, including staff coverage and skill mix, contracted hours for each employee, annual leave entitlements, study leave entitlements, and preferred shift patterns (particularly those recommended by the HSE) (Burton *et al.*, 2018). Yet, managers are usually provided minimal training on how to design effective rosters despite its critical importance to care delivery and staff management (Silvestro and Silvestro, 2008; Caruso *et al.*, 2022; Booker *et al.*, 2024b). Not involving staff in the rostering process may also lead to little appreciation for the complexity of this task, which can ultimately lead to dissatisfaction and perceived favouritism when requests for alternative work times and arrangements are not accommodated.

In the UK, guidance on generating rosters for shiftworking health care staff traditionally comes from policies set by individual Trusts/hospitals and tacit knowledge owned by managers (Silvestro and Silvestro, 2008; Drake, 2019). However, national guidance has also been published in an effort to decrease unwanted variability. In the guidance document "Good Practice Guide – Rostering", published by the then NHS Improvement (now part of NHS England), several recommendations for ensuring rosters make efficient use of available staff are provided (McIntyre and NHS Improvement, 2016). Here, 'ownership' of the rostering process is shared amongst several roles within an organisation, however it is usually the task of managers to develop rosters and ensure that they are in-line with existing policies. This guidance also provides a set of key performance indicators that can be used to evaluate rosters, e.g., monitoring the use of annual leave, roster approval lead time, percentage of rosters created automatically with software, and number of bank hours requested and worked. Overall, this guide frames the rostering process solely by the needs of the service (by ensuring adequate staffing numbers) rather than staff wellbeing and preferences. This is most pronounced in their guidance on how to manage requests for flexible working hours (which they label ‘working restrictions’), where managers are encouraged to limit requests and the frequency of shift swapping among staff.

More recent guidance from the NHS Staff Council (2021b) offers a completely different approach to accommodating staff preferences for work time (which they label ‘flexible working’). Here, they recommend that employers be more flexible with requests so that staff can have improved work-life balance and job satisfaction – particularly when considering worsening staff shortages and increased spending on external temporary staff. This change in narrative is most apparent with the recent revision of NHS working terms and conditions, where employers are now expected to promote flexible working and NHS employees can now submit more than one flexible working request per year (regardless of reasons) from day-one of employment. Potential requests could include: working fixed patterns, staggered start and finish times, longer shifts and compressed work weeks, and self-rostering (NHS Staff Council, 2021a).

2.2.2.2 Team Rostering, Self-Rostering

In contrast to traditional departmental rostering by managers, participatory methods of rostering enable staff to be more involved in this critical operational task. While rosters must still be approved by managers, these methods enable staff to have better control over their working time as well as more open communication around resolving scheduling conflicts. One of these methods includes team-based rostering, where a select group of nominated staff share responsibility for creating rosters. This lead team is charged with determining the ideal balance among coverage, ward demand, and their colleague’s long-term preferences and requests for working time (Timewise, 2019). Another mode of team-based rostering includes splitting staff into separate teams that each nominate a leader to manage rostering for their particular group. These leaders collect preference information from their own team and then come together to build a satisfactory roster covering all teams (Silvestro and Silvestro, 2000). Both of these options claim that through increased transparency, work-time control, and shared ownership of rostering practices, staff will likely be more satisfied with their work hours and job overall. Moreover, because of increased collegiality, staff may be more willing to make compromises on preferences and requests.

Nevertheless, team-based rostering comes with its own limitations. Amongst wards who used a nominated team-based rostering method, Silvestro and Silvestro (2000) found that while staff felt more empowered and cooperative within their groups, rostering became unmanageable in larger wards: too many teams and leaders resulted in conflict between teams when trying to reconcile preferences, which in-turn resulted in taking focus away from ensuring appropriate ward coverage. Moreover, 're-working' the roster was frequent, leading to wastes in staff time and resources when compared to traditional department rostering. Reporting on the implementation of a team-rostering pilot on seven wards, Timewise (2019) cited overall intervention success (increased preference-honouring and collective responsibility), but this success was a result of exhaustive implementation planning, which included gaining support of senior leadership and management, comprehensive training for roster team leads, and continuous monitoring and improvement of the intervention as needed. At the end of this report, several recommendations are given, citing that successful team-rostering is reliant on thorough planning and guidance at the organisational level.

In contrast to team-based methods, self-rostering involves collective team effort in the creation of rosters. Here, a blank/unassigned roster that contains all shifts necessary to maintain continuity of care is released to the team. Staff then bid for whichever shifts they would like to work (Silvestro and Silvestro, 2000; NHS Staff Council, 2021b). When self-rostering is hosted on accessible software, additional features can include viewing colleagues' shift choices, resolving bidding conflicts, or filling gaps in coverage by altering shift choices (Garde *et al.*, 2012; Albertsen *et al.*, 2014; Turunen *et al.*, 2020; O'Connell *et al.*, 2024). Other software options incorporate ergonomic scheduling rules by displaying colour-coded prompts when staff choose adverse working patterns (Karhula *et al.*, 2020).

Several studies in this review examined the influence of self-rostering and increased work-time control on staff-related outcomes, like changes in wellbeing and hours/shift types worked. Silvestro and Silvestro (2000) found that self-rostering methods were best suited for smaller wards where scheduling complexity is not too high, and when used in these settings, staff preferences were accommodated, deployment of staff was more efficient, and staff morale and retention were improved. Similarly, Pryce, Albertsen and Nielsen (2006) found that when compared to the control group, nurses who chose their shifts as part of an open-rota system reported improved job satisfaction, work hours satisfaction and work-life balance. Garde *et al.* (2012) found that even though caring staff were more likely to choose more varied shift lengths when rostering their own hours (compared to pre-intervention), mental distress, sleep quality, and need for recovery was improved, indicating that the effects of self-rostering were likely not related to the observed changes in working hours. Turunen *et al.* (2020) found a decrease in sickness absence in wards using self-rostering software when compared to wards using traditional scheduling methods. Similarly, Grøtting and Øvergård (2023) found that among different organisational strategies for scheduling, those that allowed for individual adjustments was the only strategy associated with decreased sickness absence.

In contrast, in an analysis of pan-European survey data on working conditions in the health, retail, and hospitality sectors, high work-time control did not result in improved workers' self-rated health, sleep, and wellbeing (Backhaus, 2022). Similarly, in a survey of nearly 900 nursing staff working in the UK and Ireland, Dall'Ora *et al.* (2023b) found that choice over working hours had no mediating effect on burnout or exhaustion. Moreover, while unable to find significant changes in wellbeing outcomes, Nabe-Nielsen *et al.* (2012), Karhula *et al.* (2018) and Karhula *et al.* (2020) found significant changes in working hours, with regularity of hours decreasing, flexibility of hours increasing, and employees choosing to work more 'unsocial' shifts and ≥12-hour shifts. A similar increase in adverse shift configurations (i.e., longer shifts and shortened inter-shift recovery periods) were reported by Turunen *et al.* (2022) in their study of a self-rostering intervention for hospital employees, leading to an increase in number of sickness absence days and number of sickness episodes. However, when this rostering intervention incorporated an evaluation tool that flagged unsafe configurations of working hours, changes to adverse working hours and sickness absence days/episodes were statistically nonsignificant. In a qualitative study of nurse managers who were interviewed about the practicalities of accommodating nurses' shift requests, participants commented on the challenges of reconciling safe working hours policies with nurses' choices of shifts, for example when they chose to work several consecutive shifts to enable longer periods away from work (Epstein *et al.*, 2023). A latent class analysis of the working patterns of 13,540 full-time workers found that those grouped into the 'flexible' type with extended shifts had significantly decreased work-life satisfaction when compared to those grouped into the 'flexible' type with standard hours, suggesting that working time control cannot mitigate all working time-related risks when workers have high workloads as a result of shiftwork (Brauner *et al.*, 2019).

Bailyn, Collins and Song (2007) found that during a pilot self-rostering intervention, nurses perceived better work-time control and that they could provide better care to patients. However, following the trial, the intervention failed as a result of staff not following rostering rules and prioritising their own preferences over ward needs. Other self-rostering interventions were not able to significantly improve sleep quality, work-family conflicts, and work-family facilitation, citing confounding factors like failed intervention implementation, staff reductions, and too much variability in the roster finalisation process (Garde, Nabe-Nielsen and Aust, 2011; Albertsen *et al.*, 2014). Finally, in a systematic review exploring self-rostering interventions, some studies found improved nurse outcomes (e.g., increased satisfaction with scheduling and decreased turnover), however the authors concluded that these results should be interpreted cautiously due to variation in implementation processes (Wynendaele *et al.*, 2021).

2.2.2.3 Electronic Rostering

Electronic-rostering technology in hospitals has gained popularity over recent years with advances in information technology and improved ability to link administrative datasets. When used effectively, managers are able to intelligently plan and deploy staff according to live views of ward demands and patient acuity, staffing levels and skill-mix, and leave and absence records. Other potential benefits include enabling staff to submit of flexible working requests, view their rosters, and request leave through streamlined processes. Moreover, some technologies are capable of automatically generating schedules based on pre-set rostering rules, reducing the time spent on generating rotas resolving conflicts arising from nurses' shift preference requests (Soomro *et al.*, 2018; NHS, 2020; O'Connell *et al.*, 2024).

Use of e-rostering technology intensified in England's NHS following the release of the Carter (2016) review on hospital productivity and performance. In this review, investigators found significant variation in organisational rostering policies, as evidenced by disparity in managing annual leave, shift patterns and flexible working. Moreover, they found variation in the use of e-rostering technology, with some hospitals using it superficially (e.g., simply transferring manual paper rosters to e-rosters) and others only starting to use data integration features. Following this review, the NHS released newer guidance on best practices for e-rostering the health workforce (NHS, 2020). Many resources are provided in this document, including instructions on establishing e-rostering governance and steps for successful implementation of e-roster technology.

Four papers in this literature review specifically examined two key elements related to e-rostering technology: the usefulness of standards/key performance indicators recommended by the Carter Review, as well as critical factors for successful implementation. In their analysis of roster lead time from 77 wards in a single acute trust, Drake (2018) found that when wards were able to publish rosters 4 weeks or 6 weeks ahead of the working period (the Carter Review recommends 6 weeks), temporary staff usage reduced to 18% and 9% respectively. However, when examining this relationship through regression, roster lead time was optimised at 4.3 weeks, with longer lead time resulting in 'negligible' changes in temporary staff use. Another study by this author involved analysing 27 publicly available e-roster policies from hospitals across the UK (Drake, 2019). They found that policies contained significant overlap in introductory language, and while many mentioned the importance of 'fair' and 'safe' rosters, none provided definitions for either term. Rules about breaks, leave requests and roster approval times were similar amongst policies, whereas rules about shift pattern parameters (consecutive days/nights, quick returns, and long-shifts) were not as uniform, or were not present at all.

Soomro *et al.* (2018) conducted qualitative interviews with e-rostering technology end-users (ward managers, nurses), inquiring about their perceptions on factors for successful implementation. Frequent themes included having an effective rostering policy, clear implementation objectives and governance, and strong leadership, amongst many others. In their evaluation of the implementation of the HealthRoster (Allocate) e-rostering software in a single hospital, Hasson *et al.* (2018) found that half of survey participants believed that the e-rostering system did not match with existing hospital policies. One major barrier was related to the submission of flexible working requests on the system, where nurses reported dissatisfaction with restrictiveness. Moreover, after the introduction of e-rostering, long-established working patterns for some staff were suddenly changed, and many of the rosters created with the auto-generate function were not workable in practice – an indication that software algorithms struggled to mimic the rostering practices used in this setting.

2.2.2.4 Summary

In conclusion, traditional, manager-led rostering appears to be the 'default' method of rostering nurses in hospitals, as managers are assumed to be the most knowledgeable in determining the correct balance of staffing needs in relation to ward demands. However, this method allows for little input from nursing teams themselves, which is problematic when attempting to honour their working time preferences. Participatory methods of rostering, such as team-based or self-rostering, allow for more input from nurses and enables shared ownership of the rostering process, but studies in this literature review found that these methods can quickly become inefficient when too much time is spent on resolving scheduling gaps or conflicts. Moreover, when given more work-time control, nurses themselves may choose to work more variable hours and shift types. Some studies in this literature review found that these changes in working hours resulted in improved wellbeing and absence-related outcomes, while others did not. These mixed results likely arise from differences in when outcomes are measured (e.g., outcomes improve when measured immediately post-implementation, but this impact declines on the long-term), or as a result of vaguely worded and/or poorly enforced rostering policies. Furthermore, electronic rostering software is often advertised as an excellent tool for intelligent scheduling (whether manager-led or participatory-based) and therefore uptake is encouraged by national bodies. However, once again, these technologies are likely to only be as successful as their implementation, which in-turn is dependent on compatibility with existing workflows and organisational support.

Separate from the literature examining nurses' shift pattern organisation and rostering practices presented so far, there exists a complementary body of research that examines these topics from an Operational Research (OR) / Management Science perspective. In this research discipline, the main aim is to improve system-level decision making in settings that must account for numerous interrelated factors. Through the use of advanced solving techniques, OR presents as an excellent method candidate for solving complex health care delivery problems – including the designing of improved nurse rosters.

2.2.3 The 'nurse scheduling problem'

Oft-labelled the 'Nurse Scheduling Problem' (NSP), this category of personnel scheduling problems has been studied by OR researchers for over fifty years due to its complexity and opportunity for innovation in solutions. When attempting to solve NSPs, the overall goal is to find the best way to automatically assign nursing staff to shifts across a rostering timeframe. Assignment of shifts is dependent on the overall objective(s) of the model and how model constraints are designed. Some NSPs are manageable enough to be solved optimally, resulting in an exact solution. When problem size grows too large however, heuristics can be applied to quickly eliminate infeasible solutions and/or find those that are 'good enough' (Vanhoucke and Maenhout, 2009) – which is similar to nurse rostering in practice, as effective rotas must be produced quickly (Burke *et al.*, 2004).

Brief searches of literature on the NSP quickly reveal a plethora of studies and techniques. In one earlier seminal paper, Burke *et al.* (2004) provided a state-of-the-art review of NSP problem formulation and solution methods. They additionally provide definitions for common terminology used in the field, summarised in Table 4.

Table 4. Frequent terminology used in NSP literature

Term	Definition
Planning period	The time interval in which nurses must be rostered (typically 4 weeks in length, but can vary).
Shift Type	Periods of duty that are defined by start- and end-times. Most NSPs organise models based on the traditional 3-shift system.
Skill Category	Groups of staff who have particular qualifications or skillsets.
Coverage Constraints	The number of staff needed for every shift and skill category over the entire planning period. Information for this constraint usually comes from some measure of workload.
Preference Constraints	Restrictions that are based on personal requests and preferences for shifts or days. These constraints often conflict with coverage constraints.

Hard vs. Soft Constraints	Hard Constraints – rules that must be satisfied in any solution Soft Constraints – rules that are desirable but not mandatory
Work Regulations	The working hour contracts that nurses have with their employers.

Differences are drawn between scheduling for different time horizons: while long-term planning is more relevant for determining overall staffing levels, "short-term" (or mid-term) planning refers to the daily/weekly/monthly deployment of nursing teams. Rostering approaches can also exist on a spectrum between two opposites: 1) cyclical scheduling, where nurses are assigned to pre-defined shift patterns that fit their needs or where nurses rotate through a standardised roster for fair distribution of all shifts, and 2) preference scheduling, where unique rosters are developed each period that incorporate nurses' changing preferences (Burke *et al.*, 2004).

There are many ways of incorporating model elements, adding more variability in problem formulation in the literature. For example, objectives (i.e., what the model is trying to maximise or minimise) can differ among solutions, e.g.: minimising staff costs, maximising accommodation of preferences, or maximising equity among rosters (Legrain, Bouarab and Lahrichi, 2015; Petrovic, 2019; Özder, Özcan and Eren, 2020). There are also differences in how constraints are organised. For example, when facing staffing shortages, coverage constraints (which historically have been incorporated as hard, inviolable constraints) can be classified as a soft constraint with pre-determined penalties for violations (Maenhout and Vanhoucke, 2010). Nurses' preferences for working time can also be incorporated in different ways, but are usually expressed as a summary of requested days on and off that change between scheduling periods (Vanhoucke and Maenhout, 2009). Lastly, different solution techniques can be employed, either in isolation or as hybrids. In general, these techniques fall into three categories: mathematical programming (e.g., linear/integer programming, column generation), heuristics (e.g., tabu search, genetic algorithms), and constraint programming (Petrovic, 2019; Özder, Özcan and Eren, 2020). Given all of this heterogeneity, researchers frequently test their solutions with widely available NSP generators, complexity indicators, and benchmark instances to aid comparison of models and solutions (Vanhoucke and Maenhout, 2007; Vanhoucke and Maenhout, 2009; Abdalkareem *et al.*, 2021).

Despite the overwhelming number of solutions reported in the literature, papers retrieved by this review highlight an extensive research-to-application gap. Drake (2014a) suggests that this gap is a result of theoretical objectives/constraints being unable to adequately represent the messy (and often political) rules that govern rostering in practical settings. They also suggest that in general, NSP studies focus more on improving computational/solving technique rather than developing models that can be used in practice. This echoed an earlier paper by Kellogg and Walczak (2007), where only 30% of systems mentioned by research articles made it to the implementation phase (and when they did, most were in single-ward settings). In their classification of scheduling software available for commercial use across several industries, Petrovic (2019) commented that in order to bridge the gap between theoretical research and implementation in health settings, researchers must be willing to engage with roster creators to decipher ideal model formulation. Two studies who did engage with schedulers both noted the complicated nature of creating rosters in practice, and that this resulted in more careful consideration of objectives and constraints (Legrain, Bouarab and Lahrichi, 2015; Böðvarsdóttir *et al.*, 2022). Newer studies of nurse scheduling models demonstrate more practical model formulation, like combining algorithmic solving and manager expertise (and specifically, allowing managers to decide which constraints can be violated) (Gradišar *et al.*, 2023), using historical information to determine if nurses' shift preferences were accommodated or rejected in previous planning cycles (Lin *et al.*, 2014), minimising fatigue-inducing schedules by allocating fixed break times, (Amindoust, Asadpour and Shirmohammadi, 2021), assigning rest time according to previous shift type and length (Ceschia *et al.*, 2023), or changing constraint classification and penalty values based on shift type (e.g., different cut-offs for number of consecutive day shifts versus consecutive night shifts) (Nurmi, Kyngäs and Kyngäs, 2022).

2.3 Overall Summary & Evidence Gaps

This literature review offered a broad overview of elements related to nurses' shift pattern organisation and the task of nurse rostering in theory and in practice. When taking these summaries into consideration, four gaps and opportunities for research were identified.

First, as there is no uniform mechanism for recording nurses' working hours in the UK, our current knowledge and characterisation of their shift patterns largely comes from self-reported sources in cross-sectional research (see section 1.1.2 for an in-depth discussion of this topic). However, more recent studies of NHS nursing staff have begun to use hospital datasets to analyse objective working hours – a trend that has also been observed internationally (Härmä, Kecklund and Tucker, 2024). Future shift work research would considerably benefit from using objective data to clarify the hours actually worked by nurses when analysing relationships with outcomes. This work can be further enhanced by using newer frameworks for identifying work patterns from register-based data (Härmä et al., 2015).

Second, findings from this review indicated that when nurses had more control over their working hours, they are likely to choose a wider variety of shift lengths and types to suit their personal needs. Moreover, there has been a distinct change in the narrative of relevant policy/guidance from various NHS-linked organisations (e.g., the National Quality Board, NHS

Employers, NHS Staff Council), where emphasis on deploying nurses solely according to the 'needs of the service' is now increasingly tempered with a need to understand how shift patterns impact nurses' performance and wellbeing, as well as a strong push for employers to offer flexible working options to better incorporate working time preferences during rostering. As such, more evidence is needed to understand nurses' needs and what factors (both in- and outside of work) drive nurses' shift preferences, particularly beyond ad hoc requests for days on/off. This knowledge is critical for identifying systematic and operational strategies for addressing nurses' needs during roster development.

Third, in reviewing evidence on the influence of shift pattern variables, certain shift characteristics demonstrated more predictable relationships with improved/worsened outcomes (e.g., increased number of quick returns likely result in worsened outcomes across the board), while others showed varied relationships depending on the outcomes measured (e.g., working long shifts resulted in better work-life balance for nurses from having more days off, but also resulted in worsened nurse burnout and patient safety). This latter group of studies also tended to focus on separate comparisons of shift characteristics (e.g., day vs. night shifts, 8- vs. 12-hour shifts) rather than analysing patterns of work, which should also consider rest periods, weekly working hours, and overtime. To further disentangle our understanding of these relationships, future research should aim to find which shift patterns (i.e., patterns that combine multiple variables and parameters) lead to worsened outcomes.

Lastly, despite many potential methods for rostering nurses (e.g., manual and manager-led rostering, participatory methods such as team- and self-rostering, and newer e-rostering technology) examination of rostering policies from Trusts across England reveal that definitions of the most 'ideal' roster either still largely focused on service demand (and staff wellbeing/choice is not mentioned), or, they use vague language that provides little to no guidance on how to actually create 'ideal' rosters. Parallel to this, there is a clear evidence-to-practice gap in the OR literature regarding the Nurse Scheduling Problem (NSP). Studies in this review found that many models do not capture the full complexity of creating rosters in practice: in reality, the divide between hard and soft constraints is less clear, and parameters assumed to be fixed actually vary (e.g., shift types, staffing requirements) depending on different circumstances and settings. As such, future nurse scheduling models should account for more 'practical' elements. This could include modelling nurses' general preferences (e.g., reducing adverse/difficult shift patterns, improving roster consistency and fairness), using real-world scheduling data to determine realistic fluctuations in coverage, or incorporating objective outcome data important to nurses and managers (e.g., sickness absence) when generating and evaluating solutions.

Chapter 3 Project Methodology

This chapter begins with the theoretical underpinnings that guided this doctoral research. Pragmatism is introduced as the main philosophical paradigm, and an overview of its core tenets is provided. Following this, a conceptual framework that integrates three key existing models around shift work is presented, highlighting the mediating role of fatigue between nurses' working hours and their health and wellbeing. Finally, an overview of the three research studies completed is provided, including how they each address the main research questions as well as details on data collection and analysis.

3.1 Guiding Theory

When designing research studies, choosing an appropriate philosophical paradigm ensures that the aims, objectives, and methods for data collection/analysis are aligned with one another and with the phenomena under investigation. For this doctoral research, Pragmatism was chosen as a guiding philosophy due to its emphasis on finding solutions for practical problems. In contrast to other paradigms that primarily rely on abstract theory or empirical observation, Pragmatism asserts that 'reality' is fundamentally tied to the experiences of individuals when interacting with their environments. Therefore, the value of any concept or idea is found in its tangible effects or consequences when applied to real-world scenarios (Morgan, 2014). This emphasis on practicality aligns well with research fields requiring dynamic approaches to understanding complex phenomena. Pragmatism's flexible approach to epistemological inquiry encourages use of the most appropriate tools and techniques to investigate specific questions, often necessitating a combination of quantitative and qualitative methods with varying levels of data integration. In essence, deliberation over research methods is guided by each one's ability to address questions effectively rather than by adherence to some methodological doctrine.

Pragmatism is a popular choice in the field of health care services research, where often the goal is to find ways of improving operational efficiency in different care environments and contexts. Some recent examples include: developing recommendations for integrating nursing education, practice and research into mutual feedback loops (Dolan, Nowell and McCaffrey, 2022), designing research that is meaningfully coproduced with patients (Allemang, Sitter and Dimitropoulos, 2022) and evaluating public health interventions aimed at addressing 'wicked' problems such as obesity (Crane *et al.*, 2019). These examples also demonstrate the value of using mixed/multiple methods of data collection and analysis in order to capture a more comprehensive understanding of complex issues. When applying this reasoning to research on the effects of shift work on nurse wellbeing specifically, different options for studies/methods arise. For example, quantitative methods might be used to characterise and measure exposure and the impact of intense shift work on measures of nurse wellbeing, while qualitative methods could provide insight into nurses' values, experiences, and perceptions of working different configurations of shifts. After comparing and contrasting key results from each of these phases, integrated knowledge can then be used to inform the design of an intervention that optimises the organisation of shift patterns and team rotas. Given the multifaceted nature of this project's topic, the knowledge gaps identified in the Literature Review (Chapter 2), as well as the overall aim of *optimising* nurses' shift patterns, this integrated approach was ultimately the methodology chosen for this doctoral research.

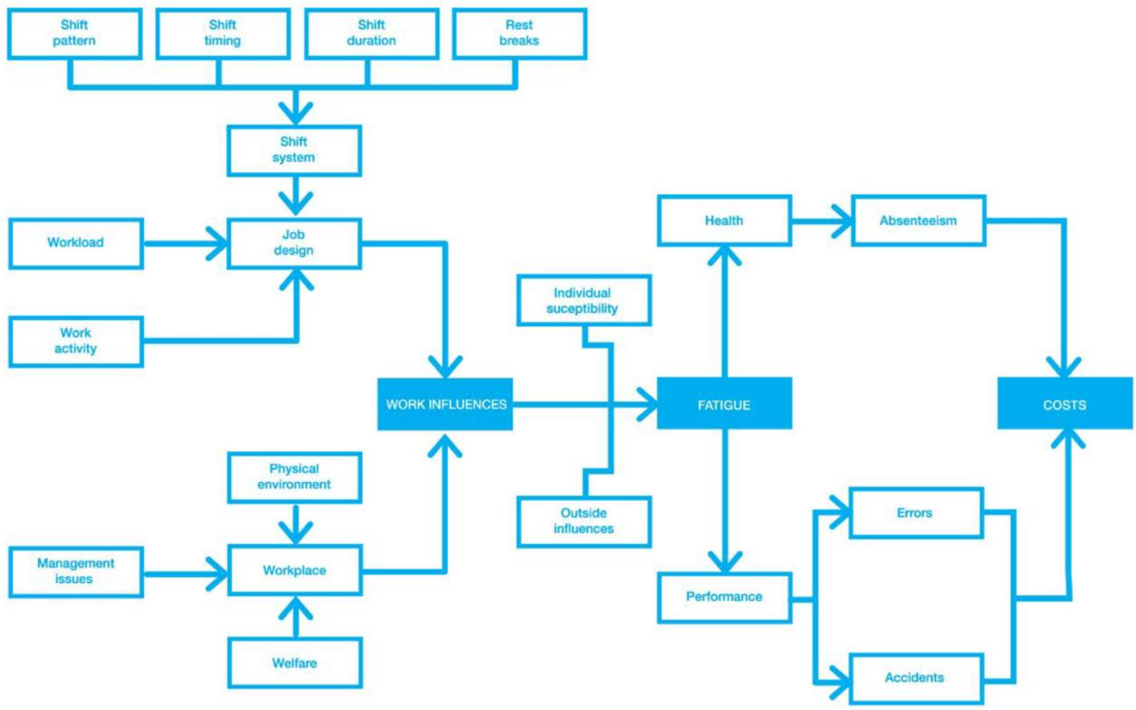
While Pragmatism offers a useful 'outcome-oriented' framework, it is not without its limitations. Pragmatisms' inherent versatility can present challenges in replicability as a result of non-transparent study design and execution. In striving to be adaptable and responsive to practical needs, unrestricted flexibility can also weaken the applicability of findings in contexts that differ too greatly from the original setting. To mitigate this risk, methodological choices and limitations must be clearly justified and documented. For this research, such details can be found in the present chapter, within each study chapter (chapters 4, 5, and 6), as well as in Chapter 7 (Strengths and Limitations).

Lastly, Pragmatism's strong emphasis on practical outcomes can come at the expense of theoretical depth. Addressing this risk therefore involves reviewing and incorporating existing relevant frameworks into the research design and ensuring that findings are derived within this broader context. Therefore, to ground this doctoral project in existing knowledge around shift patterns and the organisation of working hours, three frameworks/models were identified and assessed. Two of these were identified during the literature review: the first visualises how job design (including shift work) can lead to impacts on workers' performance and organisational costs (Health and Safety Executive (HSE), 2006) while the second provides strategies for accurately characterising working time (Härmä *et al.*, 2015). The third was identified as a seminal theory of the antecedents of job-related stress, leading to worker burnout (Demerouti *et al.*, 2001). Following a brief description of each theory/model, an integrated conceptual framework, which guided research objectives, methods, and interpretation of results, is presented.

3.1.1 "The Causes and Consequences of Fatigue"

In the guidance document titled "Managing Shiftwork: Health and Safety Guidance", the Health and Safety Executive (HSE) provide an overview of how UK employers can assess risk and improve working environments for shift workers across all industries. Many regulations within this document highlight the mediating role of worker fatigue and how it can negatively impact workers' wellbeing and performance. A visual model of the causes and consequences of fatigue, originally designed by shift work research experts Folkard et al (2003), is presented in Figure 1. Here, "shift system" (including shift pattern, shift timing, shift duration, and rest periods) is listed as an important element of "job design", alongside "work activity" and "workload". As a result of poorly designed jobs, this flowchart demonstrates how increased fatigue can in turn result in poorer worker health, increased absenteeism, impaired performance, and increased rates of errors/accidents – all of which lead to additional costs.

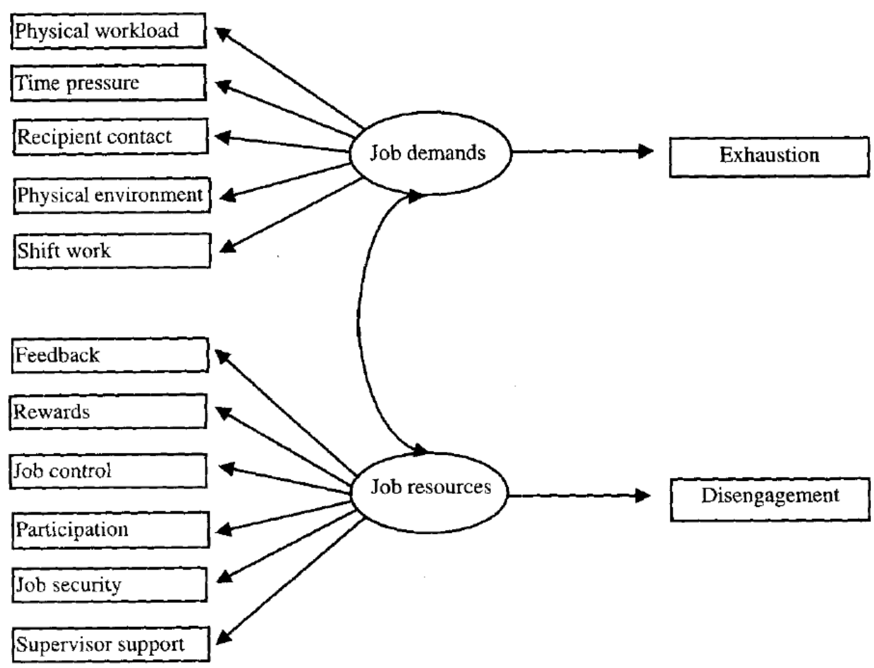
Figure 1. The causes and consequences of fatigue (Folkard et al, 2003; HSE 2006)



3.1.2 "The Job Demands-Resources Model of Burnout"

This popular model of occupational stress (Figure 2) posits that an imbalance between one's job demands (aspects of a job that contribute to physiological and psychological costs, e.g., workload, time pressures) and the job resources one has to meet those demands (aspects of a job that stimulate personal growth and autonomy over one's work, e.g., manager support, rewards) will result in higher worker burnout. Moreover, an excess in job demands is thought to be most predictive of worker exhaustion, whereas a lack of job resources is most predictive of disengagement from work. In this model, "shift work" is listed as an exemplary job demand, specifically in the context of unfavourable working hours that interfere with workers' health, family and social life. Moreover, in their review of studies using this model in nursing research, McVicar (2016) found that over the years, there appears to be an increase in the potential burden of "shift work" as a job demand in this population.

Figure 2. The job demands-resources model of burnout (Demerouti et al., 2001)



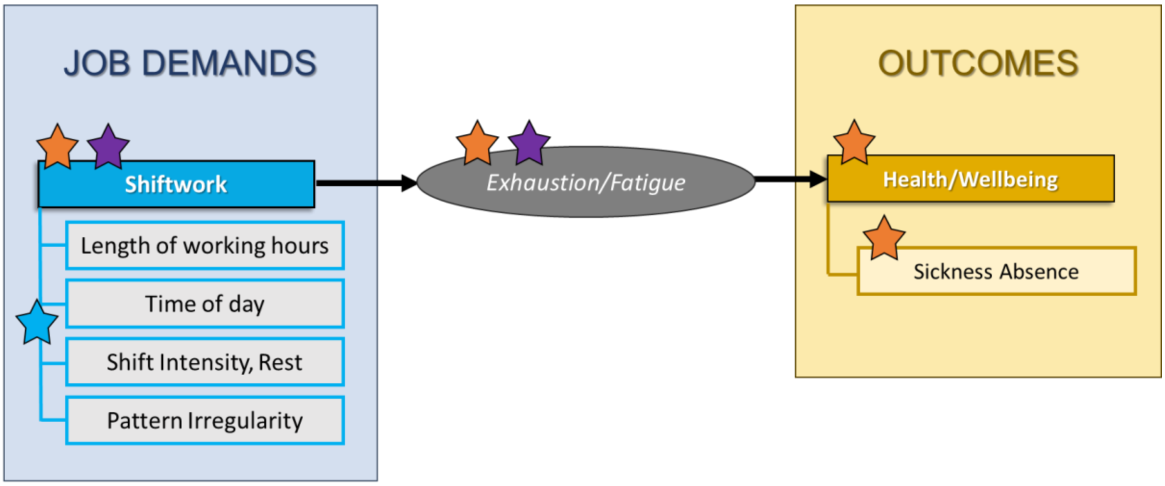
3.1.3 "Characterising Four Dimensions of Working Time Patterns"

With the recent increased use of register-based data (i.e., from electronic rosters or payroll records) in observational research around shift work, Härmä and colleagues developed an analysis framework to help researchers discern working time patterns (and assessments of exposure to shift work) from large, employer-sourced datasets. This framework was originally derived from the assessment of 14.5 million shifts worked by nurses and physicians in 2008-2013 in Finland. Dimensions of raw data included start and end times for each daily shift and instances of sickness absence days, which were in turn linked with demographic information (age, gender, role, working hours contract, etc.). In this framework, 29 shift variables were derived and categorised into the following groups: "length of working hours" (including daily, weekly, and annual hours), "time of the day" (the proportion of morning, evening, and night shifts worked), "shift intensity" (including consecutive shifts and recovery periods), and "social aspects of working hours" (including distribution of days off, irregularity of working hours, and worktime control). As such, this framework was chosen as a method of ensuring that the influence of "shift work", as described in the first two models, is more accurate, detailed and multi-dimensional.

3.1.4 Integrated framework

Considering the above theories and focusing on the elements most relevant to nurses' shift patterns, a conceptual framework was developed and is presented in Figure 3. The sections highlighted in boxes represent the elements that this research focused on, with each colour-coded star referring to how the elements relate to the original theories. Overall, this model demonstrates the theorised downstream effects of using ‘adverse’ configurations of shifts when creating nurses’ rosters, i.e., those that have a higher risk of negatively impacting wellbeing.

Figure 3. Integrated conceptual framework



Harma et al (2015) – Epidemiological Exposure Assessment of Working Patterns
HSE/Folkard et al (2006) – Causes and Consequences of Fatigue
Demerouti et al (2001) – Job Demands-Resources Model of Burnout

3.1.4.1 The Role of Fatigue

In this conceptual framework, work-induced fatigue plays an important role as a theoretical mediator between shift work organisation and wellbeing-related outcomes. Work fatigue is defined as a state of physical, mental, and/or emotional exhaustion that results from prolonged exposure to work demands (Frone and Tidwell, 2015). This type of fatigue can result in reduced alertness, impaired cognitive function, and a general decline in overall energy levels that cannot be alleviated through sleep alone. In addition to providing an impact framework and harm mitigation strategies around shift work, the HSE identify worker fatigue as an occupational hazard that must be managed at an organisational level and emphasise that a “planned and systematic approach to assessing and managing the risks of shift work (in relation to fatigue) can improve the health and safety of workers” (HSE, 2019).

Fatigue is prevalent in nursing due to high work demands and continuous monitoring of patients for extended periods of time. When nurses are working non-standard schedules however, this fatigue can be exacerbated by poorly organised shift patterns (Peršolja, 2023), including having to work long hours, excessive night work, lengthy spells of consecutive working days, or frequent/irregular shift rotation. Nurses may also develop symptoms of burnout as a result of building fatigue levels (Gustavsson, Hallsten and Rudman, 2010), ultimately leading to reduced overall health and job satisfaction (Dall'Ora *et al.*, 2020). Therefore, recognising the role of fatigue as a conduit for poor worker health is essential for developing strategies for optimising shift patterns.

While this thesis did not directly measure nurses' work fatigue, it did inform the development of research questions and outcomes. For example, the conceptual framework includes sickness-related absenteeism as a key outcome of interest in this thesis, as it is useful for typifying worker wellbeing (Wikman, Marklund and Alexanderson, 2005) and is known to be influenced by both worker fatigue and adverse shift work configurations (Dall'Ora *et al.*, 2019a; Sagherian *et al.*, 2019; Dall'Ora *et al.*, 2020). Furthermore, each shift pattern variable studied in this research was categorised into distinct shift pattern 'profiles' to strengthen strategies for analysis and interpretation, two of which were inspired by fatigue as an adverse mediator: "Intense Shifts" and "Inadequate Rest" (see section 4.5.1 for more details regarding these profiles).

3.2 Research Questions, Setting, & Phases

3.2.1 Overall Aim, Questions, & Objectives

The aim of this programme of research was to explore strategies for optimising shift patterns for nurses working in acute hospital wards. Given the evidence gaps found in the literature, the methods-focused ethos of Pragmatism, and the conceptual framework that ties shift pattern configurations with impacts to nurses' health and wellbeing, the main research questions and objectives were:

1. What factors should be considered when creating optimised shift patterns for nurses?
    a. Using survey data, determine and understand what nurses identify as important when it comes to the scheduling of their working hours (Study 1).
    b. Using nurses' historical e-roster data, determine which shift pattern variables influence risk of sickness absence (Study 2).
2. How can these factors be balanced so that nurses' preferences and wellbeing are both prioritised?
    a. Using results derived from Study 1 and 2, develop a mathematical optimisation model that assigns shifts across a fictional nurse roster in ways that accommodate both preferences and wellbeing (Study 3).

3.2.1.1 Population & Setting

This thesis focuses on registered nurses working in acute adult hospital wards. Acute wards, as defined by the National Institute for Health and Care Excellence (NICE), are hospital settings that provide overnight care for adult patients experiencing a variety of serious health conditions (excluding intensive care, high dependency, maternity, mental health, day care, and acute admission or assessment units) (National Quality Board, 2018). Within these wards, a multidisciplinary team (i.e., including medical, allied health, and nursing staff) delivers patient care through close monitoring, specialised support, and rapid intervention (e.g., particularly in response to patient deterioration). Nurses represent the largest segment of the workforce in acute wards, encompassing various roles. These include registered nurses, who have completed a university-level nursing degree; healthcare assistants or support workers, who provide basic care such as hygiene and feeding; and nursing associates, who hold a two-year diploma and serve as a bridge between registered nurses and support staff. As professionals with specialised clinical expertise, registered nurses take a leading role in planning and implementing care for their assigned patients. As such, workforce planning must be carefully designed to ensure optimised nurse staffing and allocation - especially in acute wards, where the demands of round-the-clock care require effective shift planning.

3.2.2 Research Phases

This section provides general details for each of the three studies conducted as part of this doctoral research. Further and specific methodological details can be found in each study chapter.

3.2.2.1 **Qualitative Phase:** The important factors nurses consider when choosing shift patterns: a cross-sectional study (Study 1)

The first study involved the analysis of cross-sectional survey responses collected from nearly 900 nurses working across the United Kingdom and Ireland in June-October of 2021. This survey was created as part of a larger shift patterns research project funded by the National Institute for Health and Care Research (NIHR) Applied Research Collaboration (ARC) Wessex (one of 15 nationally-funded research centres that investigates issues currently faced by the health and social care systems) and led by Dr. Chiara Dall'Ora, Associate Professor in Health Workforce research at the University of Southampton. Approval for this study was obtained from the University of Southampton's office for Ethics and Research Governance (approval IDs 65122.A2 and 57489.A2). This survey asked several questions related to nurses' typical working hours (including typical shift length and pattern, timing of shifts, within-shift and between-shift rest periods, weekly working hours, and overtime) and their experiences and beliefs around shift patterns. To capture a greater breadth of opinions and perceptions, survey respondents could indicate their views regardless of the shift types they actually worked.

For this thesis, a thematic analysis of nurses' open-ended responses around the factors they prioritise when choosing their shift patterns was completed. Themes constructed from nurses' shift preferences and values were created and contrasted with responses from other survey items, including: comparisons of worked versus preferred shift patterns, nurses' satisfaction and choice over shift patterns, and nurses' views on aspects related to work and life. In the context of this thesis and its overall aim, this study served as an important exploratory step, as engaging with nurses themselves increases the likelihood that any subsequent changes/improvements to shift patterns are rooted in what they value. As such, the results of this study informed the choice and prioritisation of variables investigated in each successive study.

3.2.2.2 **Quantitative Phase:** Associations between adverse working hours and nurses' sickness absence: a longitudinal analysis of e-roster data (Study 2)

This study involved the secondary analysis of registered nurses' historical shift and sickness absence data, as recorded by electronic staff rostering systems from all acute inpatient wards in two NHS hospital Trusts in England. Data was collected as part of another larger NIHR-funded research project that was led by Professor Peter Griffiths, Chair in Health Services Research at the University of Southampton, which had the overall aim of exploring the staff-, patient-, and cost-related consequences of different staffing configurations in acute hospitals. Approval for the parent study was obtained from the University of Southampton's office for Ethics and Research Governance (approval ID 52957) and the NHS Health Research Authority (approval ID NIHR128056). University approval for secondary analysis as part of this doctoral research was also sought and obtained (approval ID 70459). The sub-dataset used included approximately 1.4 million worked shifts and 20,000 sickness absence episodes recorded for all registered nurses working between April 2015 and September 2020.

From this data, a series of variables were derived that correspond with different shift types and patterns, i.e. the shift configurations worked in the 7 and 28 days prior to each worked shift and sickness absence episode. Exposure variables included: long working hours, excessive night work, high number of consecutive working days, inadequate recovery time, and frequent shift rotation. Logistic mixed regression models were used to estimate the relationships of these variables with sickness absence, in terms of the change in odds (odds ratio) of a shift being cancelled due to the start of a sickness absence episode.

The results of these regression models strengthened findings from the first study by providing objective information on how different configurations of shifts impacted a key dimension of staff wellness. Statistically significant predictors of sickness absence were used to inform how each shift variable was configured in the mathematical optimisation model developed for Study 3, specifically in terms of the penalty coefficient weight assigned to each model constraint. The dataset created for this study also provided practical knowledge on how competing rostering priorities were reconciled in practice, which was key for formulating the optimisation model's fixed parameters.

3.2.2.3 **Optimisation Phase:** Mixed-integer programming solutions for wellbeing- and preference-based scheduling of nurses in inpatient wards (Study 3)

The final study involved the formulation of a mathematical optimisation model that generates nurse rotas with optimised shift patterns. In this model, shifts were automatically assigned according to the overall objective of minimising the solution's penalty value, which in itself was based on the cumulative assignment of adverse shift types and patterns. Model resources and requirements included the planning horizon (28 days), set of available full-time nurses with respective working hours limitations, staffing blocks (i.e., segments of the 24-hour ward day that require a certain number of nurses) and shift types. Each of these parameters were derived from frequent configurations and patterns uncovered from the Study 2 dataset, including per-hour estimations of RN staffing levels, as well as frequent shift lengths, start/end times, and handover periods used in practice.

The model's overall objective function was to minimise the summative penalty cost of the model. The primary decision variables were the shift assignments the model chose, i.e. the shift type t assigned to nurse i on day d. Each shift assignment was restricted by a series of constraints that were categorised into one of three shift pattern 'profiles' developed from Study 1: Intense Shifts (shift configurations that contribute to exhaustion/fatigue), Inadequate Rest (shift configurations that prevent meaningful recovery), and Social Disruption (shift configurations that are harmful to social routines and nurses' personal priorities). These constraints had varying permission levels - i.e., allowed with a small, medium, or large penalty, (or forbidden altogether) - as advised by the results of the literature review, Study 1, and Study 2. Auxiliary decision variables were used to represent penalties incurred when an adverse configuration was assigned. Experiments were conducted to test the model's ability in handling varied staffing configurations and shift preference profiles, as well as to compare changes in computational time, objective function value(s), penalties incurred, and shift types used.

Chapter 4 | Study 1: The important factors nurses consider when choosing shift patterns: a cross-sectional study

This chapter features the first study that was completed, which aimed to gain a deeper understanding of what is important to nurses when thinking about shift patterns. Given the dearth in knowledge around the factors that lead nurses to prefer certain shift types or patterns over others, this study provides essential information around what nurses want from their rotas, all of which was critical to the design of successive studies in this doctoral thesis. The results of this study have been published in the Journal of Clinical Nursing (Emmanuel *et al.*, 2024) and the article is included in Appendix A.2 for reference.

4.1 Introduction

Nurses' shift patterns are characterised by various aspects including shift length, timing and rotation, total/distribution of weekly working hours, and recovery periods – all of which should be organised in ways that protect nurse wellbeing. In Europe and the United Kingdom, official guidance and regulations offer shift pattern design strategies to reduce harm, e.g., capping weekly working hours, limiting consecutive working days, and ensuring a minimum of 11 hours of rest between shifts (Health and Safety Executive (HSE), 2006). Complimentary to this guidance exists a well-established body of evidence highlighting the impacts of shift work and night work on employee physical health, mental health, and social wellbeing (Grzywacz, 2016; Arlinghaus *et al.*, 2019; Moreno *et al.*, 2019), as well as on their performance and safety while at work (Folkard and Tucker, 2003; Wagstaff and Sigstad Lie, 2011; Dall'Ora *et al.*, 2016). Given all these elements, the task of organising shifts into rosters is often challenging, especially with competing priorities like maintaining service delivery and managing staffing numbers and skill mix.

Some nursing roles may offer more autonomy over when and how long to work, as well as pay premiums when working during unsocial hours (e.g., night shifts and weekend shifts) (NHS Staff Council, 2020; NHS Employers, 2022). As a result, nurses themselves may prefer to work certain shift configurations or modified weekly working hours to suit their personal needs in and outside of the workplace. A popular example includes nurses who prefer to work long shifts (i.e., shifts lasting 12 hours or more), as it is thought to enable better patient care continuity and more days off from work when compared to working short shifts (i.e., shifts lasting 8 hours or less) (Ball *et* *al.*, 2015). Nonetheless, research has also shown that working long shifts can lead to harmful outcomes for patients as well as increased burnout and job dissatisfaction for nurses (Dall'Ora, Ejebu and Griffiths, 2022). The conflict between these viewpoints stresses a need for closer examination of the relationships between different shift configurations and nurses' choices over working time.

A recent literature review of studies exploring nurses' views and preferences around shift patterns (Ejebu, Dall'Ora and Griffiths, 2021) highlighted that nurses had varied opinions about the benefits and drawbacks of different shift types, for both themselves and for patients. Views also differed according to personal characteristics and attributes (e.g., age, having childcare responsibilities) rather than shift types alone. This review concluded that the factors that lead nurses to prefer certain shifts are not well understood, as there are likely many work- and life-related priorities that are considered when expressing shift preferences. Understanding these mechanisms is critical for successfully operationalising nurses' preferences in the rostering process, which is a key target for employers wanting to promote flexible working practices as a means of attracting and retaining nurses.

Therefore, the aim of this study was to gain a deeper understanding of what is important to nurses when thinking about their shift patterns and the organisation of their working time.

4.2 Method

4.2.1 Participants

This study analysed responses from an anonymous cross-sectional survey distributed to nursing staff across the United Kingdom and Ireland. Full details regarding survey development and distribution are reported elsewhere (Dall'Ora *et al.*, 2023b). Respondents eligible for survey participation included all nursing staff working in the following roles: registered nurse (i.e., those who completed a nursing degree at the university level), health care assistant or support worker (those with varied and/or informal training who assist with hygiene, feeding, and other elements of basic care), and nursing associate (those who completed a formal two-year diploma and help bridge the gap between registered nurses and assistants/support workers). Nurses working in roles that did not involve care provision (e.g., managerial or academic positions) were not eligible for participation.

4.2.2 Survey Details

The survey was developed in consultation with a diverse group of stakeholders to ensure questions were relevant to the target population, including registered nurses, health care assistants, and nursing union leads. Variables related to characterising shift patterns were selected from a key literature review summarising the impact of shift work on workers' performance and wellbeing (Dall'Ora *et al.*, 2016).

Shift work was defined as any work scheduled outside of standard daytime hours on weekdays (i.e., before 7:30 AM and after 6:00 PM) or working on weekends. Shift length was defined as 'long' (11 or more hours), 'short' (fewer than 9 hours) or 'medium' (between 9 and 11 hours). After accounting for unpaid break time, shifts of 11 hours or more were compatible with a two-shift '12-hour' system, whereas shifts of less than 9 hours were compatible with a three-shift '8-hour' system with some overlap between shifts. Rotating shifts were defined as day and night shifts worked within the same rota.

Descriptive data included respondents' demographics (gender, role, age, geographical location, childcare responsibilities) and distribution of usual shift characteristics (length, pattern). Nurses were asked to rate their satisfaction with their worked pattern, to rate the level of choice they have over their shifts, and to indicate their ideal shift length and pattern. To understand perceptions about working different shifts, nurses were asked to indicate if they agreed, disagreed, or did not believe that working short/long/rotating shifts influenced 14 aspects of work and personal life (e.g., having enough breaks during shifts, enough days off to recover from work). For example, when considering "ability to provide good patient care", nurses were asked to indicate if they agreed, disagreed, or did not believe that working short/long/rotating shifts influenced the aspect in question. Data for the aspects 'enough breaks during shift' and 'healthy diet' when working rotating shifts were not collected in the online survey and are therefore not included in comparisons.

Qualitative data were collected from a single, open-ended question located at the end of the survey asking, "If you could choose your shift patterns, what would be the most important factor in that choice". No limits on response length were imposed.

4.2.3 Data Collection & Analysis

Responses were collected between June and October of 2021. The survey was launched through two routes: (1) to a targeted nursing staff population in two large National Health Service (NHS) trusts in the South of England, and (2) through open invitation via social media (Twitter/X), nursing union membership contact lists, and select nursing journals. With the use of open-ended recruitment channels, a target sample size could not be estimated in advance. However, examination of resulting confidence intervals provide an alternative estimate for the precision achieved. E.g., the proportion of nurses satisfied with their current working pattern was estimated with a margin of error of less than +/- 4 % based on the binomial exact 95% confidence interval (Newcombe, 1998).

For the present study, descriptive data were summarised to understand respondents' demographics and common shift characteristics. To aid direct comparison of nurses' satisfaction with different worked shift patterns, responses were dichotomised to "satisfied" vs. "not satisfied" (i.e., *'neither satisfied nor dissatisfied'*, '*moderately dissatisfied*', and '*very dissatisfied'* responses were grouped to "not satisfied"). Comparisons of ideal versus worked shift length and shift pattern were analysed with crosstabulation and Cohen's Kappa to determine if and which nurses' shift preferences were being realised. Percentages of agreement for aspects related to work and life were calculated to compare differences across the three shift types. As there was little missing data for the variables of interest (ranging from 0.3% to 10.3% missing, with most falling below 8.0%), pairwise deletion was used to minimise loss of data from partially completed surveys (Newman, 2014). Quantitative data were analysed using SPSS version 28.

Qualitative data were analysed through thematic analysis (Braun and Clarke, 2012). Open-ended responses were extracted from the response dataset and imported into a separate spreadsheet. All responses were read-through and general observations about data and potential categories/themes were recorded. Responses were then re-read to identify codes, or the 'essential' elements contained within each response. Codes were then grouped into categories and overarching themes that captured descriptive information within responses and latent connections between responses. The full dataset was analysed inductively so that codes, categories, and themes could be constructed directly from nurses' responses. Codes and categories were also quantified, however resulting frequencies were interpreted as a rough measure of what respondents were willing or able to discuss, and not as a direct measure of significance (Vaismoradi, Turunen and Bondas, 2013). To check analysis validity, categories and themes were repeatedly compared with nurses' original responses as well as against patterns uncovered from quantitative data where possible.

4.3 Results

4.3.1 Description of Participants

After removal of non-eligible responses (e.g., non-nursing staff, working outside UK and Ireland) a total of 873 valid responses remained; 790 responses (90.5%) were collected through the open call and 83 responses (9.5%) were collected from the targeted Trust population. Registered nurses made up the majority of respondents (n=658, 75.3%) while 188 (21.5%) were health care assistants/support workers and 25 (2.8%) were nursing associates. Respondents were 42 years old on average (range 20-70 years old) and 752 (86.1%) identified as female. Most nurses worked for the NHS (92.2%), worked in hospital inpatient units (66.9%), and reported 'acute adult care' as their primary area of practice (38.3%). Among the 372 (42.6%) respondents who cited having childcare responsibilities, 183 (49.2%) had primary responsibility and 150 (40.3%) shared responsibilities more or less equally with their spouse/partner.

Most nurses reported usually working long shifts (≥11 hours; N=575, 66.4%) while 227 (26.2%) worked short shifts (≤9 hours) and 64 (7.4%) worked medium shifts (9.1-10.9 hours). Just over half of nurses (N=449, 52%) usually worked night shifts as part of a rotating schedule. Table 5 provides details on the respondents' 'usual' shift configurations distributed by shift length category. Among the nurses who normally worked long shifts, 287 (50.2%) worked ≥4 days per week, 172 (32.1%) worked ≥48 hours per week, and 98 (17.2%) worked ≥4 days in a row.

Table 5. 'Usual' shift pattern characteristics distributed by shift length category

	All shift lengths N (col %)	Short Shifts (≤9 hrs) N (row %)	Medium Shifts (9.1-10.9 hrs) N (row %)	Long Shifts (≥11 hrs) N (row %)
Shift Pattern (Main Job)				
No Shift Work (traditional hours)	90 (10.4)	81 (90.0)	5 (5.6)	4 (4.4)
Day Shifts only (inc. evening)	273 (31.6)	89 (32.6)	39 (14.3)	145 (53.1)
Rotating Shifts (inc. night)	449 (52.0)	52 (11.6)	13 (2.9)	384 (85.5)
Night Shifts only	51 (5.9)	3 (5.9)	7 (13.7)	41 (80.4)
Total	863 (100.0)	225 (26.1)	64 (7.4)	574 (66.5)
Weekly Working Hours (All Jobs)				
37.5 hours or less (part-time)	184 (22.3)	69 (37.5)	22 (12.0)	93 (50.5)
Between 37.5 and 48 hours	411 (49.9)	102 (24.8)	38 (9.2)	271 (65.9)
48 hours or greater	229 (27.8)	27 (11.8)	30 (13.1)	172 (75.1)
Total	824 (100.0)	198 (24.0)	90 (10.9)	536 (65.0)
Days worked per week (All Jobs)				
≤ 2 days	60 (6.9)	9 (15.0)	4 (6.7)	47 (78.3)
3 days	278 (32.3)	28 (10.1)	12 (4.3)	238 (85.6)
4 days	278 (32.3)	40 (14.4)	33 (11.9)	205 (73.7)
5 days	189 (22.0)	123 (65.1)	9 (4.8)	57 (30.2)
≥ 6 days	56 (6.5)	26 (46.4)	5 (8.9)	25 (44.6)
Total	861 (100.0)	226 (26.2)	63 (7.3)	572 (66.4)
Days worked in a row (All Jobs)				
≤ 2 days	336 (39.0)	23 (6.8)	12 (3.6)	301 (89.6)
3 days	234 (27.2)	38 (16.2)	23 (9.8)	173 (73.9)
4 days	102 (11.8)	27 (26.5)	16 (15.7)	59 (57.8)
5 days	135 (15.7)	102 (75.6)	9 (6.7)	24 (17.8)
≥ 6 days	54 (6.3)	35 (64.8)	4 (7.4)	15 (27.8)
Total	861 (100.0)	225 (26.1)	64 (7.4)	572 (66.4)
Rest days per week (All Jobs)				
1-2 days	339 (40.6)	151 (44.5)	21 (6.2)	167 (49.3)
3-4 days	445 (53.4)	53 (11.9)	35 (7.9)	357 (80.2)
5-6 days	50 (6.0)	10 (20.0)	4 (8.0)	36 (72.0)
Total	834 (100.0)	214 (25.7)	60 (7.2)	560 (67.1)

4.3.2 Nurses' satisfaction, choice, and preference over shifts

The distribution of nurses' satisfaction over their shift patterns was varied: 10.7% were very dissatisfied, 18.3% were moderately dissatisfied, 19.2% were neither satisfied nor dissatisfied, 33.5% were moderately satisfied, and 18.3% were very satisfied. When dichotomised, half of nurses (N=449, 51.8%) reported being satisfied with their shift patterns overall, with the highest proportion of nurses satisfied when working day shifts (including evening/late shifts) and the lowest proportion when working rotating shifts (60.9% vs. 44.1% respectively). Regarding choice, 59.1% of nurses reported having little or no choice over their shifts and 68.5% reported that their shifts were mostly or completely determined by their employer. To determine which nurses are having their preferences met, crosstabulations of worked versus ideal shift pattern and shift length were performed (Table 6). There was only moderate agreement between worked and preferred shift pattern (Cohen's κ= 0.393, 95% CI 0.34-0.44, $p<0.001$) (Sim and Wright, 2005). Eighty-nine percent of nurses working day shifts and 86% working permanent night shifts were working their preferred shift pattern, however only 44% working rotating shifts preferred this pattern. Similarly, there was only moderate agreement between worked and preferred shift length (Cohen's κ= 0.321, 95% CI 0.27-0.37, $p<0.001$). Seventy-eight percent of nurses working short shifts were working the shift length they preferred, but only 56% working long shifts preferred this length. When stratified by age, level of agreement differed for some groups (when compared to the total): more older nurses reported working their ideal shift pattern (age 50-59, Cohen's κ= 0.547, 95% CI 0.44-0.66, $p<0.001$) and fewer younger nurses reported working their ideal shift length (age 20-29, Cohen's κ= 0.196, 95% CI 0.08-0.31, $p<0.001$.)

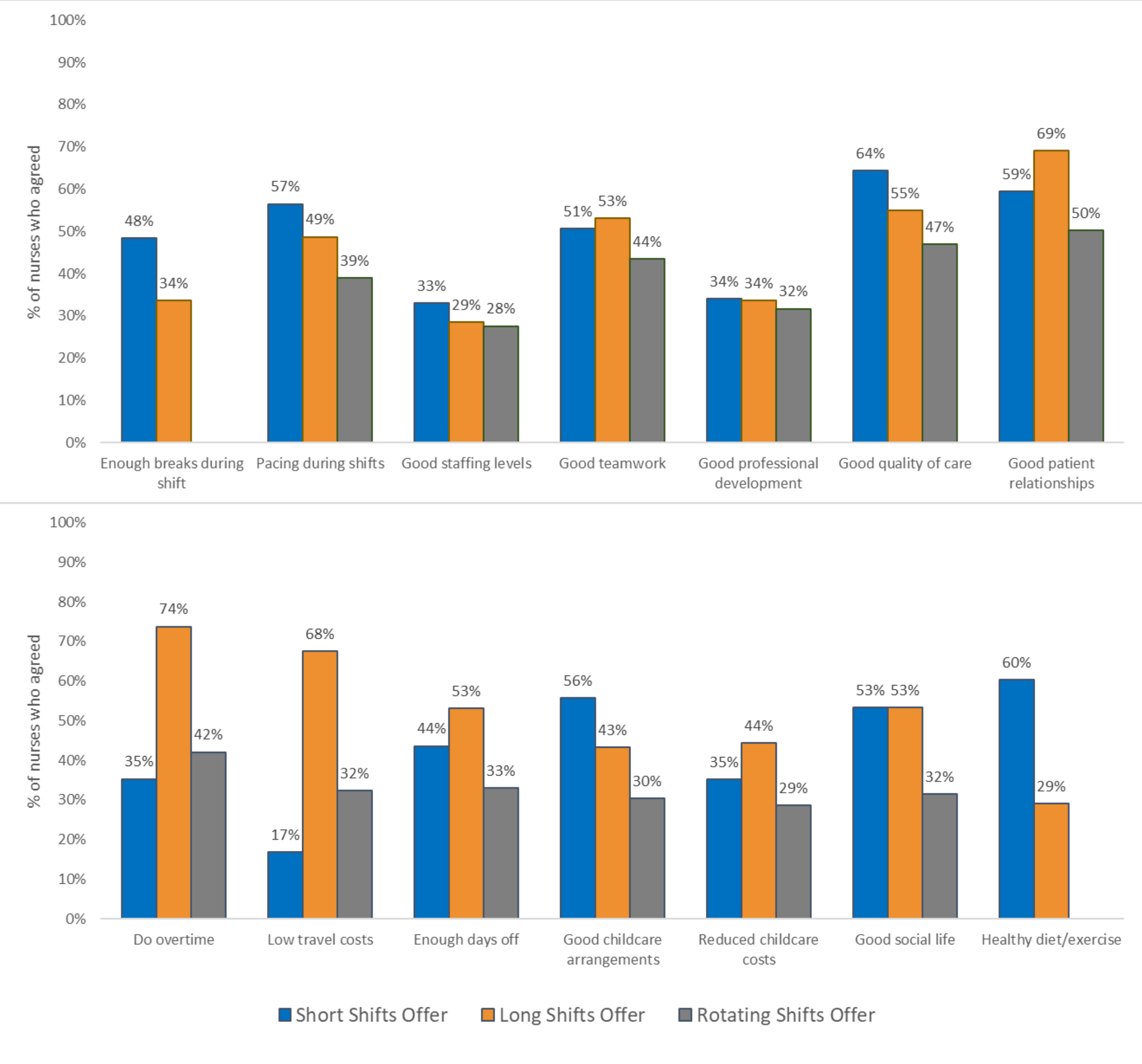
Table 6. Crosstabulation of worked vs. preferred shift pattern/ideal shift length

	Preferred Shift Pattern			
	Day Shifts only (inc. evening) N (row %)	Rotating Shifts (inc. night) N (row %)	Permanent Night Shifts N (row %)	Total N (Column %)
Worked Shift Pattern				
Day Shifts only (inc. evening)	242 (89.6)	25 (9.3)	3 (1.1)	270 (35.4)
Rotating Shifts (inc. night)	209 (47.2)	194 (43.8)	40 (9.0)	443 (58.1)
Permanent Night Shifts	5 (10.0)	2 (4.0)	43 (86.0)	50 (6.6)
Total	456 (59.8)	221 (29.0)	86 (11.3)	763 (100.0)
	Ideal Shift Length			
	Short (≤9 hours) N (row %)	Medium (9.1-10.9 hours) N (row %)	Long (≥11 hours) N (row %)	Total N (Column %)
Worked Shift Length				
Short (≤9 hours)	168 (77.8)	21 (9.7)	27 (12.5)	216 (26.0)
Medium (9.1-10.9 hours)	35 (57.4)	16 (26.2)	10 (16.4)	61 (7.3)
Long (≥11 hours)	166 (29.9)	77 (13.9)	312 (56.2)	555 (66.7)
Total	369 (44.4)	114 (13.7)	349 (41.9)	832 (100.0)

4.3.3 Nurses' perceptions when working different shifts

Distributions of nurses' responses when asked about the influence of working short, long, and rotating shifts on various aspects of work and life outside of work were calculated. Direct comparisons of the proportions of nurses who agreed with each statement are illustrated in Figure 4.

Figure 4. Nurses' beliefs on aspects of work and life outside work

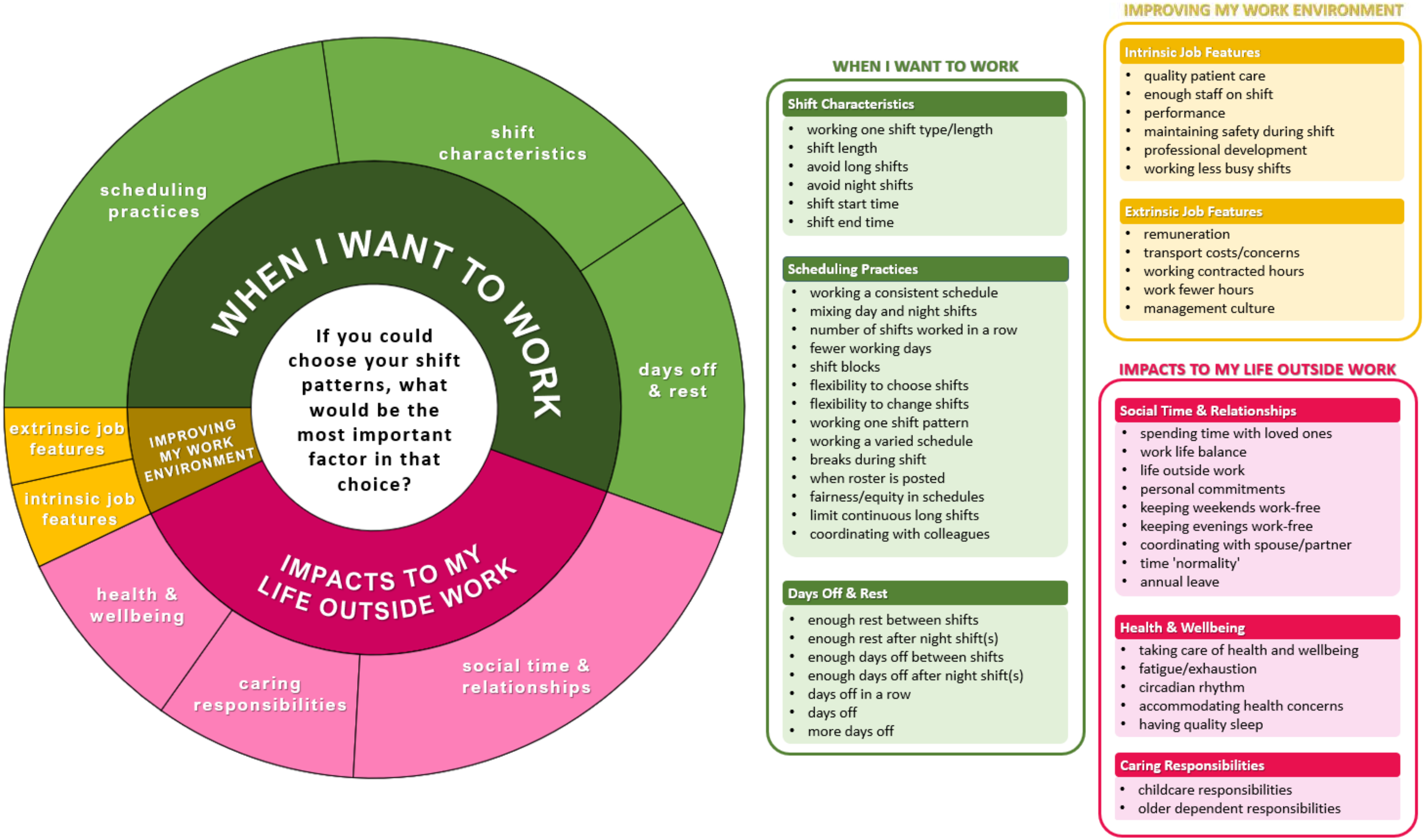


Proportions of agreement for most items generally fell in the low-middle range, indicating that there was no shift type that clearly provided more advantages for nurses. This was particularly true for aspects related to nurses' lives outside of work, like having enough days off for recovery, efficient childcare costs/arrangements, and having a good social life. Some exceptions were noted, including 'low travel costs' and 'better ability to do paid overtime' when working long shifts and 'healthy diet/exercise' when working short shifts. For items related to patient care, a higher proportion of nurses agreed that long shifts offer good patient relationships, whereas a higher proportion agreed that short shifts offer good quality of care. For other work-related aspects, higher proportions agreed that working short shifts offer enough breaks and the ability to pace oneself during shifts. Aspects in relation to working rotating shifts usually had the lowest proportion of agreement and were considerably lower (when compared to short or long shifts) for items like ‘pacing during shifts’, ‘enough days off’, ‘good childcare arrangements’, and ‘good social life’.

4.3.4 Qualitative Themes & Categories – What factors are important to nurses when choosing shifts?

A total of 778 valid responses were collected when nurses were asked “If you could choose your shift patterns, what would be the most important factor in that choice?”. Responses usually contained three types of information: the factors themselves, why these factors were important, and what would help/hinder attaining that factor (i.e., their preferences). Many nurses described more than one factor, resulting in most responses having multiple codes assigned. Thematic analysis resulted in the generation of 54 unique codes organised into eight categories, which were then grouped into three themes: ‘***When I want to work’***, ‘***Impacts to my life outside work’***, and ***‘Improving my work environment’***. Themes, categories, and codes are described in the following sections and are illustrated in Figure **5**; segments of this diagram represent code frequency (i.e., the total number of times a code was assigned across all responses, divided by category (outer ring) and theme (inner ring)), with larger segments indicating higher frequency.

Figure 5. Qualitative themes, categories, and codes



4.3.4.1 Theme 1: 'When I want to work'

This theme contains three categories (*shift characteristics, scheduling practices*, and *days off & rest*) and had a code frequency of N=614 (55.4%). Different working time preferences were identified, including individual shift pattern characteristics (e.g., shift length, shift timing and rotation speed, patterns of days off) as well as what should be done during the scheduling process to ensure rotas are fair and safe. Some nurses stated their specific preferences without providing additional context (e.g., "*Monday long day. Tuesday to Friday days off. Saturday & Sunday long day. Following week have the weekend off*..." (participant 192)), but in responses that included more information, pathways between factors and resulting shift preferences varied or even contrasted. For example, when citing health and wellbeing, one nurse stated that they'd prefer to work "*only nights, for regular body rhythm, physically and mentally*..." (pt. 172), whereas another nurse stated their preference for "*straight days because this suits my health better*..." (pt. 276). A summary of nurses' shift preferences is described in the following paragraphs.

Shift Characteristics. Many nurses preferred to only work during the day, while others shared their willingness to work night shifts. Some disliked how night shifts were assigned and shared how they would prefer these shifts to be organised – some preferred to work all night shifts in one continuous stretch, while others preferred to work evenly spaced-out night shifts. Nurses also commented on shift start time and end time. While some preferred shifts that started earlier in the day (e.g., 7:00 AM), others wanted to avoid early shift start times particularly if they were coming off of nightwork. Comments about shift end time centred on wanting to finish shifts on time (i.e., avoid working longer than scheduled) rather than wanting to finish at a particular time of the day. When nurses mentioned shift length, many wanted to work shorter shifts, to avoid working long shifts, or to have the flexibility to choose which shift length to work. Reasons for preferring short shifts centred around wanting to not feel exhausted or fatigued (e.g., "*Working 8-9 hour shifts maximum where I can practice safely and effectively, without mental and physical exhaustion*" (pt. 582). Preferring long shifts was also prevalent, most frequently to enable shorter workweeks and more days off (e.g., "*long shifts therefore maximising number of rest days in between*" (pt. 732). However, working too many long shifts in a row (e.g., more than 2-3 in a row) made this shift length less desirable.

Respondents also voiced preferences for patterns of work. Nurses wanted to avoid working day and night shifts within the same week, or work earlies/days immediately after working nights (e.g., "*Not rotating from nights to days then back to nights in a short space of time*" (pt. 305)). Preferences for number of shifts worked in a row depended on whether days off or personal wellbeing was prioritised: some preferred to work all shifts together so that rest days were also successive, whereas others preferred to limit consecutive shifts so that they could avoid exhaustion (e.g., "*All shifts back to back, so days off feel more beneficial*..." (pt. 168) versus "*...not working consecutive shifts so that I am exhausted by the time I get a day off*" (pt. 417)).

Scheduling Practices. Beyond the specifics of when to work, many nurses described long-term preferences for their rotas, like needing more consistency and predictability. Consistency could be achieved in different ways, like when shifts were worked in recognisable blocks (e.g., "*know what I am doing each week, either set days or set nights, so I can predict what I am working*..." (pt. 580)) or when nurses could predict which days of the week they would be working (e.g., "*set days in and off e.g. 4 on 4 off*" (pt. 240). Nurses specifically disliked working rotas with no discernible order (e.g., "*...at the moment it seems random or dictated purely by staffing needs*" (pt. 782). Alongside rota consistency, appropriate lead time for roster publishing was important, (e.g., a minimum of 6 to 8 weeks, "*Late rota completion is hugely disappointing and makes life outside work harder to organize*" (pt. 692)). However some respondents warned that finalising rosters too far in advance impedes one's ability to plan around unforeseen conflicts.

Flexibility in the scheduling process was represented by nurses' desire to have more choice over their shifts from the start (e.g., "*Allowing people to choose what is right for them*" (pt. 520)). For some, flexibility was needed to recover from or change difficult shift patterns (e.g., "*Having the freedom to give myself more days to recover between weekly shifts* (pt. 518)", "*Being able to choose patterns where you have enough days to rest and reset between shifts*" (pt. 647)). Honouring these flexible requests must also be done equitably, particularly when it comes to undesirable shifts (e.g., *"...treating everyone's rota equally and not favouring others*" (pt. 375). Flexibility was also mentioned by one nurse who valued coordinating coverage with colleagues (e.g., "*Opportunity to liaise with colleagues and negotiate when is good for them and myself to work*" (pt. 976)).

Days Off & Rest. Rather than discussing the arrangement of their working time, nearly 200 nurses wrote about how their days off should be organised. Having appropriately arranged days off was needed to make this period meaningful and worthwhile (e.g., "*...have 2–3 days off to actually feel like I'm resting*" (pt. 715)). For some nurses, days off were specifically needed to recover after work (e.g., "*Having enough time off to recover emotionally and physically between shifts*" (pt. 696), but for others, enough rest was needed in order to prepare for the next series of shifts (e.g., "*To have my days off to myself to re energise myself for my next shift*" (pt. 523)). Most commonly, a single day's rest in between ending a night shift and starting early/day shift was problematic (e.g., "*Enough rest time between day and night shifts. I often have only 24 hours between finishing a night shift to going to days and find it really hard*" (pt. 628)). The rest period given between shifts within a single stretch was also important for some (e.g., "*Having at least*

11 hours between shifts, we sometimes finish shifts at 9:30pm and start the next day at 7am" (pt. 949)).

In summary, nurses provided rich information on the shifts they preferred. Preferences were diverse, ranging from very specific (e.g., the exact days and times one would like to work) to more general (e.g., wanting to avoid working too many shifts in a row). Nurses also described the scheduling practices that they believed could improve their experiences on the long-term – working less difficult shift configurations from the start, improved roster consistency and predictability, and having more flexibility to work the hours that they can. These concepts were also identified as enablers for organising one's personal life outside of work, as discussed in the next theme.

4.3.4.2 Theme 2: 'Impacts to my life outside work'

This theme explored the first subset of factors that led nurses to have the preferences described in the first theme. Many of these factors related to nurses' personal lives (code frequency of N=415, 37.5%), signifying that shift preferences were largely determined by how those shifts might impact priorities outside of work. These priorities were organised into three categories: social time & relationships, caring responsibilities, and health & wellbeing. Reasons for having shift preferences were presented as non-negotiable (e.g., *"I consider my children before choosing a shift"* (pt. 199), *"...I suffer from migraines, so I am unable to work long days and do Monday-Friday..."* (pt. 685)) or as desirable if possible (e.g., *"I would like to sleep. After night shifts, I cannot stabilise my sleep..."* (pt. 507), *"I would want to come home earlier on shorter days to rest, see family, exercise..."* (pt. 768)), indicating that some reasons were prioritised higher than others.

Social Time & Relationships. Of the 58 nurses who mentioned 'work-life balance', 41 nurses simply cited the term itself without any additional context. When more information was provided, work-life balance was related to activities at home (e.g., "*Work life balance, having days off to manage home life and family*" (pt. 373)). Nurses also wanted time for other personal commitments and activities, like hobbies, housework, shopping and appointments, exercise, and social time with friends. While some individual shift types supported these priorities, above all, rota consistency and flexibility were repeatedly mentioned as enablers for work-life balance and organising personal commitments (e.g., "*Having one day off the same each week so that I could structure activities at home around that day*" (pt. 88), "*Consistency in having same 8 shifts to have a decent personal life outside work*" (pt. 502), "*Choose what suits my personal life*" (pt. 274), "*What works for me and gives me work life balance*" (pt. 501)).

Nurses specified that the mere fact of having days off from work did not necessarily result in having quality family time – especially when they felt exhausted as a result of work (e.g., "*Time off with family where I'm not exhausted*" (pt. 393), "*Quality time with my children and family without being permanently drained, exhausted, and sad*" (pt. 138)). Coordinating schedules with a spouse/partner was also important, particularly if they also worked shifts and conflicts were frequent. Many nurses wanted to protect specific times/days that they believed to be more conducive to social activities and relationships. For these 'normal' social hours – such as evenings and weekends – nurses wanted to minimise the shifts that disturbed these periods and thus preferred working day shifts on weekdays (e.g., "*Ensuring enough social time - i.e. weekend/evenings*" (pt. 783), "*Increased time with my family so less night shifts or weekends*" (pt. 344), "*It would be early shifts to feel like you have more time with family*" (pt. 936)). One nurse also specifically expressed feelings of guilt when working shifts that disturb family time *("…as little disruption as possible to my children's routines at home, also not working on important days like Christmas and bank holidays because I feel guilty for not spending them with my family*" (pt. 62)).

Caring Responsibilities. Over 100 nurses stated that caring responsibilities was the most important factor. Some mentioned needing enough time to care for older dependents (i.e., elderly parents), however, this factor overwhelmingly focused on the task of childcare. Arranging childcare was described as difficult and costly, particularly when reconciling assigned shifts with the operational hours of daycare facilities and schools. Depending on each nurses' individual situation, shift preferences varied (e.g., "*Ability to care for my kids and reducing the stress of trying to sort out childcare as it's very difficult to do so on long days/nights*" (pt. 872), "*I would prefer to work longer shifts […] I wouldn't have to pay as much childcare costs for my daughter to go to nursery which would create a lot less stress from my life*" (pt. 950), "*Child care is one thing I struggle with, it's easier when [they're] in school, but the cost of after school care is very expensive and it all stops at 5! So easier to do night shifts…*" (pt. 442). Nurses mentioned that having predictable working hours helped with this task, once again highlighting the importance of consistency (e.g., "*That the pattern could stay the same each week so it would be easier for childcare needs. Many nurseries like set days and when our rota is changing from week to week this can be difficult*" (pt. 911)).

Health & Wellbeing. For those who mentioned specific long-term health conditions (e.g., chronic pain, migraines), late starts/finishes, long shifts, or having too many working days in a row exacerbated illness symptoms. In general however, rather than connecting health/wellbeing concerns with performance or productivity at work, more nurses focused on their rest days and lives outside of work. As discussed in the first theme, rest days are frequently used to recover from working shifts. For some nurses, recovery explicitly meant having to look after one's own wellbeing (e.g., "*Allowing enough blocked days off to recover mentally and physically from work and look after my health…*" (pt. 391), "*Enough time for self-care*" (pt. 618). Similarly, some nurses wanted to have enough time to live healthier lifestyles overall (e.g., "*Having time to recover from work, spend time with family & have a healthy lifestyle*" (pt. 888)).

In addition to impacts on general health, many nurses mentioned feeling excessive tiredness, exhaustion and/or fatigue as a result of shift work (particularly when working many long shifts in a row, rotating shifts within short periods of time, and overtime). These symptoms spilled over into life outside work and impacted one's ability to engage in social activities (e.g., "*Not feeling tired and being home with family*" (pt. 263), "*Personal life, childcare and family. Long days leave me exhausted on my days off*" (pt. 236)). Nurses also cited disruption to sleep cycles and wanted to work shifts that established a better routine for their 'body clocks' (e.g., "*Consistent, regular hours so your body clock can get into a routine*" (pt. 106), *"…not mixing days and nights in a week […] this does not observe HSE best practice guidelines and messes with the body clock and sleep patterns. It should not be allowed to happen*" (pt. 471)).

In this theme, nurses described many factors that influence their shift preferences. Overall, the organisation of working time impacted rest periods in problematic ways, often resulting in nurses not having enough time and energy to engage in activities outside of work. Resulting shift preferences aimed to minimise disruption to life outside work, for example, reducing the number of working days, having sufficient time off for rest and recovery, fewer evening/weekend shifts to protect social time, or preferring night shifts to ensure availability during days for childcare. The high code frequency of this theme suggests that many preferences for working time depended on nurses' priorities outside of work. In contrast, the third and final theme reviews the smaller number of responses related to nurses' experiences at work.

4.3.4.3 Theme 3: 'Improving my work environment'

This theme explored the second subset of factors influencing nurses' shift preferences, containing two categories (*intrinsic job features, extrinsic job features*) and a code frequency of N=79 (7.1%). Here, nurses described the performance- and administrative-related factors they prioritised (e.g., "*Workload and staffing levels*" (pt. 811), "*Better rates of pay*" (pt. 179), "*A shift where I feel I have accomplished the care I have wanted to give for my patients*" (pt. 258)). Overall, responses centred around nurses' desire to have their working environment, as well as their ability to fulfil duties at work, improved.

Intrinsic Job Features. Using terms such as 'care continuity', 'care mistakes', 'patient safety' and 'time spent with patients', some nurses stated that being able to provide high quality patient care was an important factor. When it came to their resulting preferences, nurses had different opinions on the shift lengths that enabled better patient care. Long shifts (and reduced number of handovers) were seen as beneficial by some (e.g., "*Patient continuity, reduced handovers less likely to miss information...*" (pt. 816)). However, several more called out the risks of working long shifts (or more than 8 hours at a time), particularly in terms of their own productivity (e.g., "*Not 12 hours. More mistakes & patients deserve a nurse not pacing themselves!*" (pt. 630), "*...patient safety should be the main concern and long shifts are not conducive to good patient care. Short shifts are far more productive and safe*." (pt. 710)). Nurses also identified staffing levels as an important factor, and adequate staffing was needed so that nurses could manage their workloads and take their designated breaks during shifts (e.g., "*To not have so much pressure on the shift, with the right amount of staff on and to take my break when needed*" (pt. 938)). Having down-time for continuous learning was also identified (e.g., "*Days off and nights as they are a time I can do my e-learning and not rush about all shift*" (pt. 795)).

Extrinsic Job Features. Remuneration was important, with nurses wanting the best arrangements of shifts to optimise working hours and take-home pay. Some nurses preferred to work shifts that had pay premiums or to work additional shifts on their days off to supplement basic pay (e.g., "*Shift that pays best so I can reduce my total hours*" (pt. 601), "*The ability to work extra shifts between. I can't live on my basic pay*" (pt. 357)). While pay was important, other nurses were careful to balance this priority with spending time with family during normal social hours (e.g., "*To have enough time with family however being well paid"* (pt. 370), "*Working weekends brings in extra income but does not allow for spending time with family and friends*" (pt. 573)). Commuting costs and concerns were mentioned by a few, and for one nurse, this meant preferring to work fewer shifts per week to minimise travel time ("*Long days as I travel 1 hour each way...means less shifts/week if I prefer*" (pt. 559). Lastly, perceived support from management was mentioned, highlighting nurses' need for supervisors who were flexible and respectful of their time (e.g., "*I would like to be able to leave early, if possible, without management making me feel like I am 'committing fraud' given that I don't get breaks or claim for TOIL*" (pt. 925)).

In summary, this theme highlighted the importance of organising nurses' working conditions in ways that benefit them and enable them to do their jobs efficiently. Some shift preferences were mentioned, however nurses prioritised other important work organisation elements, like having adequate numbers of staff and having enough time/opportunity to take breaks and complete training. While all responses were collected under the context of understanding shift pattern preferences, responses in this theme highlighted some complementary intrinsic and extrinsic job features that warrant consideration when examining nurses' perceptions of work and working time.

4.4 Discussion

This research addresses one of the core research gaps/opportunities identified in section 2.3 by examining multiple facets of the topic of nurses' shift preferences: what shifts nurses usually work and how this compared with ideal/preferred shifts, nurses views on aspects related to work and life when working different shifts, and the important factors nurses consider when expressing their preferences.

The proportions of nurses who were satisfied with their shift patterns were lower when they worked long shifts and rotating shifts. This mirrors previous findings, where nurses working these configurations were more likely to be dissatisfied with their job overall and more likely to have intentions of leaving their job (Lu *et al.*, 2012; Dall'Ora *et al.*, 2015; Ferri *et al.*, 2016). Mismatching between preferred and worked shifts may partially explain or moderate this dissatisfaction, as there was a greater disconnect between ideal and actual work hours when nurses worked long shifts and rotating shifts. However, many nurses in this study preferred and were satisfied with what they usually worked, suggesting that for some, preferences and wishes are realised. Responses on aspects of work and life demonstrated some perceived benefits when working certain shifts – greater proportions of nurses agreed that long shifts offer good patient relationships, the ability to do overtime, and low travel costs, and that short shifts offer good quality of patient care and a healthy diet/exercise pattern – echoing previous research (Richardson *et al.*, 2007; Nicholls *et al.*, 2017; Dall'Ora, Ejebu and Griffiths, 2022). Rotating shifts did not offer clear advantages for any of the domains addressed. This was also reflected in nurses' qualitative responses, where the poor arrangement of shift start/end time and rest time when working rotating shifts were mentioned as difficult in many contexts. Many of the other factors identified as important in qualitative responses - like having good staffing levels, having enough days off for rest and recovery, efficient childcare organisation, having a good social life, and having a healthy lifestyle - had low proportions of agreement regardless of shift type. This finding complements previous research exploring the influence of different shift configurations, as the mere fact of working short, long, or rotating shifts is unlikely to influence views or preferences alone. Rather, the organisation of shift types and weekly working hours in relation to one another and over the long-term likely play more important roles (Dall'Ora *et al.*, 2016).

Focusing on what nurses considered important when choosing shift patterns, a great number of factors were related to their priorities outside of work. Similarly, a considerable number of nurses wrote about how they prefer their days off to be arranged, signifying the importance of having work schedules that support a good work-life balance. Work-life balance is traditionally framed by the conflict arising between work and family roles and responsibilities, including childcare (Greenhaus and Beutell, 1985; Netemeyer, Boles and McMurrian, 1996). Over one-hundred nurses in this study cited childcare responsibilities as an important factor. This high code frequency was attributed to two possible explanations: arranging childcare is important for nurses and takes clear precedence when choosing shifts, and/or, given traditional interpretations of work-life balance, nurses feel that childcare is one of the few reasons accepted as valid when expressing shift preferences in practice. Evidence of the latter has been found elsewhere, particularly amongst hospitals evaluating rostering processes/policies, where an inherent ‘hierarchy of preferences’ (with childcare taking top priority) was flagged as an obstacle to remove (Harris *et al.*, 2010; NHS Employers, 2020). In contrast, contemporary definitions approach work-life balance more holistically, making room for more priorities, including rest, social time, and leisure (Kalliath and Brough, 2008; Pichler, 2009) – all of which were also found in nurses’ qualitative responses.

Certain configurations of shift patterns and working time, including long weekly working hours, unpredictable shifts, and shifts worked during social hours and nights have been identified as potential stressors on work-life balance (Albertsen *et al.*, 2008; Arlinghaus and Nachreiner, 2016; Grzywacz, 2016; Arlinghaus *et al.*, 2019). Some shift configurations may be actively chosen by nurses to enable work-life balance, like long shifts or compressed working weeks (Dall’Ora, Ejebu and Griffiths, 2022). However, consequences can appear on the long-term, such as increased fatigue and longer time needed for recovery - which nurses identified in this study as disruptive to their priorities in and outside of work. With increasing numbers of nurses in the UK citing work-life balance as the reason for leaving their current role (NHS Digital, 2022), finding feasible ways of improving work-life balance for nurses, especially when considering the design of their work schedules, remains an important area of inquiry. However, as work-life balance may not always be explicitly defined, researchers and ward managers should take care to understand what factors nurses have in mind when stating this concept, as different priorities attributed to the work-life balance ‘umbrella’ (e.g., childcare responsibilities versus rest and recovery) will likely result in conflicting shift preferences.

Incorporation of nurses’ varied individual preferences is undoubtedly difficult from a scheduling perspective, both in terms of safeguarding ward coverage and ensuring fair consideration of requests. To avoid the difficult and time-consuming task of reconciling these elements in practice, ward coverage is likely to be prioritised and limited (or no) choice over working time may be offered to nurses, as demonstrated in this study. As an alternative to this challenging status quo, more ‘universal’ scheduling practices could be applied that still support nurses’ individual needs and preferences. In their qualitative responses, nurses mentioned three concepts that could work in this sense: reducing the use of adverse shift patterns, improving consistency in personal rotas, and increasing flexibility and control over working time.

Although relevant guidance urges employers to avoid the use of adverse or non-ergonomic shift patterns (e.g., excessive weekly working hours or inadequate rest periods between shifts) (Health and Safety Executive (HSE), 2006), this may not be prioritised in settings that are resource constrained. With the worsening health workforce crisis in the UK, nurses report having to work longer hours and more challenging schedules to ensure some level of minimum ward coverage (Royal College of Nursing, 2021b; Nursing & Midwifery Council, 2022). Evidence of this was also present in the current study, as nurses mentioned many difficulties with working non-ergonomic shift patterns. Furthermore, among the nurses who usually worked long shifts, notable proportions also worked at least 4 days per week, more than 4 days in a row, and more than 48 hours per week – all exceeding guidance. Being made to work difficult shift patterns poses negative implications for rates of sickness absence, job satisfaction, and retention, likely as a result of increased burnout, disrupted recovery, and poor work-life balance (Jacobsen and Fjeldbraaten, 2018; Dall'Ora *et al.*, 2020; Gifkins *et al.*, 2020).

To support ward managers in creating rosters that are safer for nurses, modern rostering technology could be used to develop ergonomic rotas while also balancing ward coverage, staffing numbers, and patient demand. Previous research has demonstrated benefits for health care workers when embedding ergonomic shift work recommendations in rostering software, particularly in terms of reducing adverse working patterns, sleep difficulties, and occupational injury (Karhula *et al.*, 2021; Härmä *et al.*, 2022; Shiri and Härmä, 2023), but outcomes related to work-life balance are less understood. Moreover, nurses may still prefer to work more difficult shift patterns when given the choice (Karhula *et al.*, 2018; Karhula *et al.*, 2020), but in these cases, risk could still be mitigated thereafter (e.g., if a nurse prefers to work long shifts only, limit the number of long shifts that are worked in a row).

Rota consistency and predictability were also identified as enablers of better experiences in- and outside of work. Even if individual preferences differed, the need for consistency frequently united responses and was defined by nurses as working the same shift types or start times, having the same working days and days off each week, or having a more predictable shift pattern rotation. In the UK, the issue of working unpredictable shift patterns has been recently prioritised by the NHS Long Term Plan (NHS, 2019) as well as the Royal College of Nursing (Royal College of Nursing, 2020), however solutions have yet to be identified. Having rosters published in reasonable timeframes facilitates nurses' ability to manage personal commitments (Carter, 2016; Drake, 2018), however if planned shifts have no discernible pattern or sense of consistency, nurses may still find it difficult to plan and engage in their lives outside of work. Moreover, in a recent analysis of pan-European survey data on working conditions, high levels of employer-enforced work-time variability (i.e., variable weekly working hours, working days per week, and daily start/end times) resulted in poorer self-rated health, wellbeing, and sleep for workers. Authors also found that high work-time variability (and low work-time control) was a more frequent feature of the health sector when compared to the retail or hospitality sectors (Backhaus, 2022).

Nurses also wanted more flexibility around their shift patterns. These findings align with nurses' definitions of 'flexible working' in other studies, where flexibility centres more on choice and control rather than short-notice rota changes or increased variability in work tasks (Atkinson and Hall, 2011; Beckers *et al.*, 2012; Nabe-Nielsen *et al.*, 2012). Recent NHS guidance (NHS Staff Council, 2021b;a) has encouraged employers to adopt flexible working policies to give nurses more control over their working time and reduce barriers to requesting alternative arrangements, which could include working fixed patterns, staggered start/finish times, and compressed or elongated workhours. This guidance also emphasises that these arrangements should be accessible to everyone, and not only for those with caring responsibilities. Previous research exploring the objective working hours of health care staff with high worktime control showed that these workers chose greater variability in shift types (i.e., more evening and weekend shifts) and length when compared to those with intermediate or low worktime control, but did not necessarily compromise ergonomic recommendations for shift patterns (Garde *et al.*, 2012; Karhula *et al.*, 2019).

Other flexible worktime interventions, like self/team-scheduling (where employees schedule their rota themselves, given pre-established rules) or participatory-scheduling (where coverage needs, guidance on working time arrangements, and employees' preferences are combined through formal processes) are gaining popularity in some settings. Previous research exploring the success of such interventions has shown mixed results (Beckers *et al.*, 2012; Wynendaele *et al.*, 2021). Employer and management concerns on implementation and feasibility of such policies and interventions can also hinder uptake and success. Nevertheless, given that nurses in this study mentioned flexibility in the context of choosing shift patterns that are more predictable or less adverse, many flexible working requests could theoretically be addressed by safeguarding ergonomic guidelines and predictable working patterns.

4.4.1 Limitations

Although extensive piloting and cognitive testing was undertaken to develop the survey, test-retest reliability was not tested and therefore the stability of expressed preferences and opinions over time cannot be inferred. Second, respondents were prompted to be brief in their qualitative response (i.e., "...what would be the *most* important factor") and therefore some context related to shift choice/preference was likely to have been missed. Nonetheless, many respondents still provided multiple and related elements in their responses despite this prompt.

Third, given that the survey was anonymous and was in-part distributed online, the ability to track respondents submitting more than one response was not possible. However, with the survey's length, the required level of engagement, and the absence of participation incentives/rewards, it was estimated that the likelihood of the submission of multiple responses was low. Lastly, the survey did not explicitly capture the views and experiences of managers and schedulers. Future research should explore the scheduling process from their point of view, particularly when it comes to managing nurses' shift preferences alongside operational needs, workforce shortages, and the recent increased demand to support employee work-life balance.

4.5 Conclusions

In summary, nurses consider and value a variety of factors when thinking about their shift pattern preferences. Many of these factors were related to nurses' priorities outside of work, such as looking after their personal health & wellbeing, protecting social time & relationships, and managing caring responsibilities. These findings contribute to the growing body of research on the importance of nurses' wellbeing in and outside of the workplace by highlighting the need to organise shift patterns in ways that protect and promote a good work-life balance. Working short, long, or rotating shifts did not offer clear advantages in terms of fulfilling nurses' priorities when compared to one another, and therefore, assumptions about relevant outcomes when working specific shift types (e.g., 'long shifts are great for work-life balance') should be questioned. Nurses also described three general scheduling practices that would support their individual priorities and shift preferences: using ergonomic shift pattern recommendations when establishing rosters, ensuring shift patterns are consistent and predictable, and facilitating more flexibility and control over working time. These concepts have previously shown benefits for workers in healthcare settings and could be feasibly implemented with existing guidance and modern rostering technology.

4.5.1 Incorporating Findings

Table 7 demonstrates how the results of this study informed the choice of independent variables for each successive study in this doctoral thesis. First, nurses' examples of what they preferred or disliked when it comes to their shift patterns were selected, particularly in terms of how they impacted each thematic category: days off and rest, social time and relationships, caring responsibilities, health and wellbeing, and certain intrinsic/extrinsic job features. These shift types and patterns were then organised according to this thesis' Conceptual Framework (i.e., prioritising nurse health/wellbeing, the mediating role of fatigue, categorising working time exposures) and were further grouped into three shift pattern 'profiles':

1. **Intense Shifts**, i.e. shift configurations that cause considerable build-up of physical and mental fatigue, including long shifts (shifts lasting ≥12 hours), night shifts (shifts occurring during the night period and ending before 08:00), and extended periods of consecutive working days (≥ 3 shifts worked consecutively, i.e. fewer than 24 hours between each shift).
2. **Inadequate Rest**, i.e. shift configurations that result in not having enough time away from work for rest and relaxation, particularly as a result of inconsistency and disruption to circadian rhythms (including night-to-day and day-to-night rotations occurring within a 7-day period), quick returns (≤11 hours between shifts), and short returns (≤48 hours between a night-to-day shift rotation).
3. **Social Disruption**, i.e. shift configurations that are harmful to social routines and nurses' personal priorities, including having too many working days, too much weekend work, and too many shifts occurring during social hours (e.g., night shifts).

Table 7. Identifying nurses' general preferences

Study 1		***Conceptual Framework***	
Findings: Nurses' General Preferences	*Decision*: Variable(s), Goals	Working Time Exposure Category	Shift Pattern Profile
Not working too many long shifts to prevent exhaustion	Limit the number of **long shifts** assigned	Length of Working Hours	**Intense Shifts**
	Avoid assignment of shifts that result in **long working weeks** (>48 hours per calendar week)		
Willingness to do night work if organised and distributed fairly	Evenly distribute and limit **night shifts** among all nurses in a team	Time of Day	
Avoid shift configurations that disturb periods of day/week that are usually reserved for social activities (late evenings, nights)			
Avoid shift configurations that result in feeling too tired/exhausted, particularly in terms of not being able to have quality rest, relaxation, or recreation	Limit the number of **long work spells** assigned, i.e. spells of working 6 or more consecutive days	Shift Intensity (consecutive working days)	
	Limit the number of **intense work spells** assigned, i.e. spells of working 3 or more consecutive long days and/or nights		
Preferring to have at least 11 hours of rest between consecutive shifts	Limit the number of short recovery periods (<11 hours rest, i.e., **quick returns**) between any two shifts	Shift Intensity (short inter-shift recovery)	**Inadequate Rest**
Preferring to have more than 24 hours between finishing a	Limit the number of short recovery periods (<48 hours,		

night shift and starting a day shift	i.e. **short returns**) between ending a night shift and starting a day shift		
Dislike of working both day and night shifts within short periods of time (e.g., a week)	Minimise the number of **shift rotations** occurring within a 7-day period	Shift Rotations	
Avoid shift assignments that excessively disturb circadian rhythms and sleeping patterns			
Maximising consistency to make childcare arrangements and other personal priorities easier to organise and manage			
Avoid starting a day shift shortly after completing a night shift	Avoid assignment of shifts resulting in backward rotation (night-to-day) within a 7-day period		
Willingness to do weekend work if organised well and distributed fairly	Evenly distribute and limit **weekend work** among all nurses in a team	Social Aspects	**Social Disruption**
Avoid shift configurations that disturb periods of day/week that are usually reserved for social activities (weekends)			
Fewer working days enable more days away from work, less commuting time, and better ability to work extra shifts	Limit the number of **working days** where possible		

Chapter 5 | Study 2: Associations between adverse working hours and nurses' sickness absence: a longitudinal analysis of e-roster data

This chapter features the second study that was completed, which explored how certain configurations of shifts impacted a key dimension of nurse wellness: sickness absence. In contrast to previous research using cross-sectional and self-reported outcomes, this longitudinal analysis of objective roster data offers a deeper understanding of the working time exposures that are associated with poor nurse wellbeing. Furthermore, the results of this study informed the formulation and magnitude of penalties/costs assigned in the scheduling optimisation model developed in the final phase of this thesis.

5.1 Introduction

When facing issues with recruitment and retention of qualified nursing staff, health systems must protect the wellbeing of their workforce by ensuring working hours and environments are healthy and safe. One useful outcome for monitoring is staff sickness absence, as documented by historical rosters and/or payroll records. Unlike subjective measures of workforce wellbeing (e.g., employee pulse surveys, self-reported job satisfaction), administrative records of shifts cancelled due to sickness absence offer a more objective representation of staff wellness: when calling in sick, one can assume that staff are not able to work because they are not well. Furthermore, significant upticks or differences in rates of sickness absence between different working environment exposures can provide clues as to where targeted improvement strategies are needed.

Recent national data on sickness absence rates among nurses working in England's NHS show some concerning trends in this regard (NHS Digital, 2024). These data reveal higher levels of sickness when compared to those prior to the start of the COVID-19 pandemic, as well as when compared to other health professions and the public sector overall. The most commonly recorded reasons for sickness absence (when measured by percentage of FTE days lost due to sickness) were related to anxiety, stress, depression, and other psychiatric illness (25%) (NHS Digital, 2024). Furthermore, 46% of registered nurses responding to the NHS Staff Survey (2023) reported feeling unwell as a result of work-related stress specifically over the last 12 months. Although preventing all sickness absence is not possible, any potential harmful contribution of nurses' working environments should be minimised.

Previous research analysing administrative records of shifts and sickness absence have shown increased rates when nursing staff are working certain configurations, including long shifts (i.e., shifts lasting 12 hours or more), night shifts, long weeks (i.e., >48 working hours per week), and quick returns (i.e., less than 11 hours of inter-shift recovery time) (Dall'Ora *et al.*, 2019a; Ropponen *et al.*, 2019; Dall'Ora *et al.*, 2020; Larsen *et al.*, 2020; Santana *et al.*, 2020). However, there is a gap in understanding the effects of more complex shift configurations, particularly those that occur over multiple days. The present study builds on this previous research by analysing shift pattern variables identified by NHS nurses as particularly difficult or adverse in Study 1, e.g. working several long and/or night shifts consecutively, having fewer than 48 hours rest between ending a night shift and starting a day shift, and frequent shift rotations within short periods of time.

5.2 Method

This was a retrospective longitudinal analysis of historical shift and sickness absence data, as recorded by electronic staff rostering systems from all adult acute inpatient wards in two NHS hospital Trusts in England. Original data were collected and anonymised as part of a larger project exploring the staff-, patient-, and cost-related consequences of different health care staffing configurations (Griffiths *et al.*, 2023). In this larger parent study, the 24-hour ward day was split into two periods labelled ‘day’ (07:00 to 18:59) and ‘night’ (19:00 to 06:59), with each study day beginning at 07:00. Nursing staff were categorised by administrative pay bands, with those in bands 2-4 classified as nursing assistants (i.e., health care support workers and nursing associates) and those in band 5 (or above) classified as registered nurses. Unique identifiers were used to link shifts and sickness episodes to the same nurse across the study period, and therefore all variables and analyses were calculated at the shift-per-nurse level. Demographic information for staff (e.g., age, year join/left hospital, number of years in current role) were not available due to data governance restrictions from participating Trusts. Shifts that were cancelled due to sickness were aggregated into episodes, starting on the first day that a nurse was absent from work and finishing on the day they returned for at least one shift.

For the present study, the roster records of all registered nurses (i.e., band level 5 or above) scheduled to work on wards between April 2015 and September 2020 were analysed. From these data, a series of shift pattern variables were created to account for the following configurations: long working hours, night work, spells of consecutive working days, inadequate recovery time, and shift rotations. Specifically, this included:

- Proportion of shifts worked as long shifts (shifts lasting 12 hours or more)
- Proportion of shifts worked during the night (shifts that finish at 08:00 or earlier)

- Number of spells of consecutive shifts, including 'long' spells (working ≥ 6 consecutive shifts) and 'intense' spells (working ≥3 consecutive long or night shifts)
- Number of inadequate rest periods, including 'quick' returns (having ≤11.5 hours of rest between any consecutive shifts) and 'short' returns (having ≤48 hours between a night-to-day shift rotation)
- Number of shift rotations occurring within a 7-day period (including night-to-day and day-to-night rotations)

The following control variables were also considered to account for working time-related factors that may influence sickness absence independently of shift work: total number of working hours, total number of hours worked as bank (i.e., when working shifts that cover temporary shortfalls in settings that are different to one's "home" role or ward), and the number of previous sickness absence episodes. Part-time status was also controlled and was defined as working fewer than a median of 0.75 FTE hours per week in the previous quarter (i.e., median of ≤26 hours per week in the previous 13 weeks) (Van Bastelaer, Lemaître and Marianna, 1997). Each predictor and control variable was defined by an exposure period, i.e. the counts and proportions of each characteristic worked in rolling windows of 7 and 28 days prior to each worked shift and sickness absence episode. Sickness episodes that were preceded by zero working hours in the previous 28 days were removed. Creation of these variables was completed with the *pandas* (McKinney, 2022) and *datetime* python packages in Spyder (version 5.5.1), and the full code used to create the dataset for the present study can be found in Appendix B.1.

This analysis was structured as a case-control design, with sickness absence episodes treated as cases and worked shifts as controls. Random intercept logistic mixed models were used to estimate the association between shift pattern predictors and sickness absence. Given the hierarchical nature of the data, intraclass correlation coefficients (ICC) were calculated to determine the presence of significant clustering behaviour in the outcome; clustering was detected on the nurse-level and was therefore included as random effects in all models. The influence of shift pattern variables on nurses' sickness absence were tested via: 1) univariable models, which examined each shift pattern variable separately without accounting for controls, 2) uni-predictor models, which tested how each shift pattern variable behaved when controls were held constant, and 3) full multivariable models, which included all shift pattern variables and control variables. To test for multicollinearity between predictors, variance inflation factors (VIF) were calculated, where VIF values <5 indicated low multicollinearity (James *et al.*, 2013). Regression models with the smallest Akaike information criterion (AIC) and Bayesian information criterion (BIC) values were interpreted. Modelling was undertaken using the *lme4* package in R (version 4.4.0) (Bates *et al.*, 2015), and the full code is included in Appendix B.3.

5.3 Results

5.3.1 Descriptive Statistics

The final dataset contained 1,367,497 worked shifts and 19,876 sickness absence episodes from 7,515 registered nurses across 95 wards. The majority of shifts were from nurses working full-time (3789 nurses working 821,681 shifts (60%)), and sickness episodes lasted a median of 4 days long (IQR 2-8 days). Table 8 provides an overall and yearly snapshot of the shift pattern variables regularly worked by full-time nurses specifically. The number of records available for full-time nurses varied across study years: 76,881 records in 2015 (76,033 shifts and 848 sickness episodes), 154,589 records in 2016 (152,644 shifts and 1945 sickness episodes), 155,485 records in 2017 (153,571 shifts and 1914 sickness episodes), 155,099 records in 2018 (153,099 shifts and 1961 sickness episodes), 167,216 records in 2019 (165,476 shifts and 1740 sickness episodes), and 121,586 records in 2020 (120,819 shifts and 767 sickness episodes).

Statistics demonstrate a fairly stable pattern over the 5-year study period. In general, full-time nurses worked on average 12.5 hours per shift (including breaks), 37.5 hours per week and 137.5 hours per month. A typical week involved working three long shifts, one of which was a night shift. A typical month included one intense consecutive spell, four quick returns, and three shift rotations. Long consecutive spells of work and short returns were rare across the dataset, however, a slight increase in counts for the latter is noted from 2019 onwards. Similar increases are seen for the number of intense spells (mean of 0.8 in 2015 versus 1.0 in 2020) and quick returns (mean of 3.6 in 2015 versus 4.1 in 2020) in 28-day lookback windows, indicating that shift configurations became slightly more adverse over time.

Table 8. Shift pattern configurations worked by full-time nurses

	Overall		2015		2016		2017		2018		2019		2020	
7-day lookback	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median
Tot working hours	34.3 (5.0)	37.5	33.9 (4.8)	37.5	33.9 (4.7)	37.5	34.1 (4.5)	37.5	33.9 (4.9)	37.5	34.6 (5.3)	37.5	35.0 (5.6)	37.5
N shifts	2.9 (0.5)	3.0	2.9 (0.5)	3.0	2.9 (0.5)	3.0	2.9 (0.4)	3.0	2.9 (0.5)	3.0	2.9 (0.5)	3.0	2.9 (0.5)	3.0
Avg shift length	12.0 (1.1)	12.5	12.0 (1.1)	12.5	12.0 (1.1)	12.5	12.0 (1.1)	12.5	12.0 (1.1)	12.5	12.0 (1.0)	12.5	12.1 (1.0)	12.5
N long shifts	2.5 (0.7)	3.0	2.4 (0.8)	3.0	2.4 (0.7)	3.0	2.5 (0.7)	3.0	2.4 (0.7)	3.0	2.5 (0.8)	3.0	2.5 (0.8)	3.0
Prop long shifts	0.9 (0.2)	1.0	0.9 (0.3)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0
N night shifts	1.0 (0.8)	1.0	1.0 (0.7)	1.0	1.0 (0.7)	1.0	1.0 (0.7)	1.0	1.0 (0.8)	1.0	1.0 (0.8)	1.0	1.1 (0.8)	1.0
Prop night shifts	0.3 (0.3)	0.3	0.3 (0.2)	0.3	0.3 (0.2)	0.3	0.3 (0.2)	0.3	0.3 (0.3)	0.3	0.4 (0.3)	0.3	0.4 (0.3)	0.3
N long spells	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.0 (0.0)	0.0
N intense spells	0.1 (0.1)	0.0	0.1 (0.1)	0.0	0.1 (0.1)	0.0	0.1 (0.1)	0.0	0.1 (0.1)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0
N quick returns	0.9 (0.4)	1.0	0.9 (0.4)	1.0	0.9 (0.4)	1.0	0.9 (0.4)	1.0	0.9 (0.4)	1.0	1.0 (0.4)	1.0	1.0 (0.5)	1.0
N short returns	0.2 (0.2)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0	0.2 (0.2)	0.0
N shift rotations	0.7 (0.4)	1.0	0.7 (0.4)	1.0	0.7 (0.4)	1.0	0.7 (0.4)	1.0	0.7 (0.4)	1.0	0.7 (0.4)	1.0	0.7 (0.5)	1.0
28-day lookback	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median
Tot working hours	133.1 (18.1)	137.5	130.7 (17.2)	137.5	131.5 (16.9)	137.5	132.7 (16.4)	137.5	131.3 (17.4)	137.5	134.7 (18.2)	137.5	137.1 (20.8)	137.5
N shifts	11.3 (1.7)	11.0	11.1 (1.7)	11.0	11.2 (1.6)	11.0	11.3 (1.6)	11.0	11.1 (1.7)	11.0	11.4 (1.7)	11.5	11.5 (1.8)	12.0
Avg shift length	12.1 (1.1)	12.5	12.1 (1.2)	12.5	12.1 (1.1)	12.5	12.1 (1.1)	12.5	12.1 (1.1)	12.5	12.1 (1.1)	12.5	12.2 (1.0)	12.5
N long shifts	9.6 (2.8)	10.5	9.3 (2.9)	10.0	9.4 (2.7)	10.0	9.6 (2.7)	10.5	9.4 (2.8)	10.0	9.7 (2.8)	11.0	10.0 (2.9)	11.0
Prop long shifts	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0	0.9 (0.2)	1.0
N night shifts	4.1 (2.9)	4.0	3.9 (2.7)	4.0	4.0 (2.7)	4.0	4.0 (2.8)	4.0	3.9 (2.8)	4.0	4.2 (3.1)	4.0	4.3 (3.2)	4.0
Prop night shifts	0.4 (0.2)	0.4	0.4 (0.2)	0.4	0.4 (0.2)	0.4	0.4 (0.2)	0.4	0.4 (0.2)	0.4	0.4 (0.3)	0.4	0.4 (0.3)	0.4
N long spells	0.0 (0.1)	0.0	0.0 (0.1)	0.0	0.0 (0.1)	0.0	0.0 (0.1)	0.0	0.0 (0.1)	0.0	0.0 (0.1)	0.0	0.0 (0.1)	0.0
N intense spells	0.9 (0.7)	1.0	0.8 (0.7)	1.0	0.8 (0.7)	1.0	0.8 (0.7)	1.0	0.8 (0.7)	1.0	0.9 (0.7)	1.0	1.0 (0.8)	1.0
N quick returns	3.9 (1.6)	4.0	3.6 (1.6)	4.0	3.8 (1.5)	4.0	3.9 (1.5)	4.0	3.8 (1.6)	4.0	4.0 (1.7)	4.0	4.1 (1.8)	4.0
N short returns	0.6 (0.6)	0.0	0.6 (0.6)	0.0	0.6 (0.5)	1.0	0.6 (0.5)	0.0	0.6 (0.5)	0.0	0.7 (0.6)	1.0	0.7 (0.6)	0.0
N shift rotations	2.6 (1.6)	3.0	2.6 (1.5)	3.0	2.6 (1.5)	3.0	2.6 (1.6)	3.0	2.5 (1.5)	3.0	2.5 (1.6)	3.0	2.6 (1.7)	3.0

5.3.2 Univariable & Uni-predictor Models

Exploring both univariable and uni-predictor associations enabled a more comprehensive analysis of relationships: univariable models provided information on baseline associations between each exposure variable and sickness absence, while uni-predictor models isolated independent effects while also adjusting for controls (i.e., part-time status, number of bank hours, number of sickness episodes, total hours); these results are found in Table 9.

Table 9. Shift pattern configurations and odds of sickness– univariable models

7-day lookback	Univariable		Uni-predictor†	
	OR (95% CI)	Sig	OR (95% CI)	Sig
N long shifts	0.88 (0.87-0.90)	***	1.01 (0.97-1.04)	n.s.
Prop long shifts	0.80 (0.75-0.85)	***	0.83 (0.78-0.89)	***
N night shifts	0.95 (0.94-0.97)	***	1.06 (1.04-1.08)	***
Prop night shifts	1.06 (1.01-1.11)	*	1.13 (1.07-1.18)	***
N long spells	0.05 (0.01-0.38)	**	0.12 (0.02-0.83)	*
N intense spells	1.01 (0.96-1.06)	n.s.	1.31 (1.24-1.38)	***
N quick returns	0.97 (0.95-0.99)	**	1.25 (1.22-1.29)	***
N short returns	0.94 (0.90-0.98)	**	1.05 (1.00-1.11)	*
N shift rotations	0.94 (0.92-0.96)	***	1.03 (1.01-1.06)	*
28-day lookback	**Univariable**		**Uni-predictor†**	
	OR (95% CI)	**Sig**	**OR (95% CI)**	**Sig**
N long shifts	0.99 (0.98-0.99)	***	1.03 (1.02-1.04)	***
Prop long shifts	1.11 (1.02-1.20)	*	1.16 (1.06-1.26)	***
N night shifts	0.98 (0.98-0.99)	***	1.01 (1.00-1.02)	*
Prop night shifts	0.98 (0.91-1.05)	n.s.	1.10 (1.02-1.18)	*
N long spells	0.69 (0.59-0.81)	***	0.94 (0.80-1.11)	n.s.
N intense spells	0.95 (0.93-0.97)	***	1.01 (0.98-1.03)	n.s.
N quick returns	0.98 (0.97-0.99)	***	1.03 (1.02-1.05)	***
N short returns	0.96 (0.94-0.98)	***	1.00 (0.97-1.02)	n.s.
N shift rotations	1.00 (0.99-1.01)	n.s.	1.02 (1.01-1.03)	**

* significant at p<0.05, ** significant at p<0.01, *** significant at p<0.001

† each shift pattern variable tested with the following control variables held constant: : total working hours, total hours worked as bank, number of previous sickness episodes, and part-time status

When accounting for control variables, some shift configurations exhibited a change in direction of effects (e.g., number of night shifts in the previous 7 days), while others gained or lost statistical significance (e.g., number of intense spells in the previous 7 days, number of short returns in the previous 28 days). In 7-day uni-predictor models, the largest odds of sickness were found for number of intense spells (OR=1.31, 95% CI 1.24=1.38, p<0.001) and number of quick returns (OR=1.25, 95% CI 1.22-1.29, p<0.001). In 28-day uni-predictor models, the largest odds of sickness were found for the proportion of long shifts (OR=1.16, 95% CI 1.06-1.26, p<0.001) and the proportion of night shifts (OR=1.10, 95% CI 1.02-1.18, p<0.05).

5.3.3 Multivariable Models

Two multivariable models were examined, the results of which are included in Table 10:

- Model A: associations between all shift pattern variables (measured as counts, except for long shifts and night shifts, where proportions were used) and odds of sickness absence across 7-day lookback windows
- Model B: associations between all shift pattern variables (measured as counts, except for long shifts and night shifts, where proportions were used) and odds of sickness absence across 28-day lookback windows

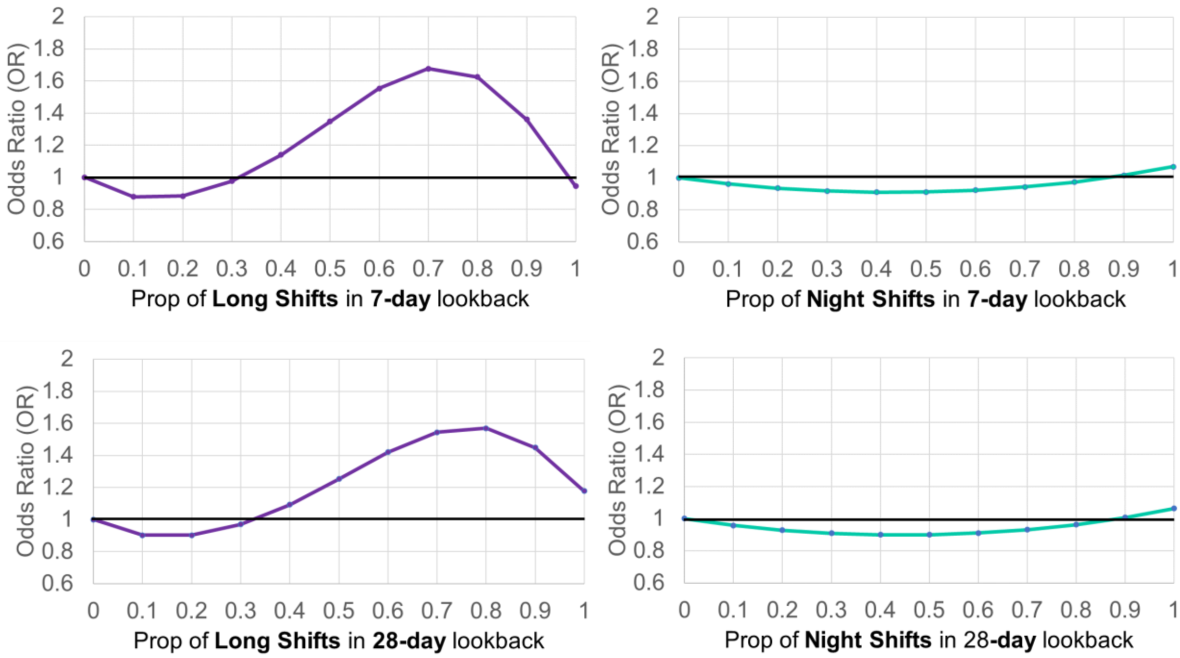
Proportions were used for long shifts and night shifts to enable consistent comparison of exposure effects across lookback windows with varied total working hours. Polynomial terms were also introduced for these variables to accommodate nonlinear effects after exploratory analyses revealed changes in directions of effects when comparing categories of proportions (i.e., 0.0., 0.01-0.25, 0.26-0.50, 0.51-0.75, 0.76-0.99, 1.0) on odds of sickness. Three options for including nonlinear terms were compared to determine which combinations resulted in the best model fit, i.e., using : 1) quadratic terms for both proportion of long/night shifts, 2) cubic terms for both proportion of long/night shifts, and 3) cubic terms for proportion of long shifts and quadratic terms for proportion of night shifts. Option 3 resulted in the lowest AIC and BIC values and was therefore selected for interpretation (Table 10). Nonlinear curves for the proportion of long shifts and proportion of night shifts were then plotted using 0.1 proportion intervals and are illustrated in Figure 6. The specific plotting values for these graphs can be found in Appendix B.4.

Table 10. Shift pattern configurations and odds of sickness – multivariable models

Variables	Model A: 7-day Lookback		Model B: 28-day Lookback	
	OR (95% CI)	Sig	OR (95% CI)	Sig
Part-time status	1.00 (0.96-1.04)	n.s.	0.99 (0.95-1.03)	n.s.
Total hours	0.98 (0.97-0.98)	***	0.99 (0.99-0.99)	***
Total bank hours	0.94(0.94-0.95)	***	0.98 (0.98-0.98)	***
Number of sickness episodes	0.56 (0.50-0.63)	***	0.64 (0.61-0.68)	***
Proportion of long shifts	(refer to Figure 6)	***	(refer to Figure 6)	***
Proportion of night shifts	(refer to Figure 6)	***	(refer to Figure 6)	***
Number of long spells	0.09 (0.01-0.66)	*	0.98 (0.83-1.16)	n.s.
Number of intense spells	1.24 (1.16-1.32)	***	0.99 (0.96-1.02)	n.s.
Number of quick returns	1.23 (1.19-1.27)	***	1.04 (1.02-1.05)	***
Number of short returns	1.05 (0.99-1.11)	n.s.	0.97 (0.94-1.00)	n.s.
Number of shift rotations	1.09 (1.04-1.13)	***	1.04 (1.02-1.06)	***
AIC	145645		159245	
BIC	145849		159438	

* significant at p<0.05, ** significant at p<0.01, *** significant at p<0.001

Figure 6. Cubic and quadratic curves for proportion of long shifts and night shifts



In Model A (7-day), multiple predictors significantly increased the odds of sickness absence. For every intense spell of work, quick return, and shift rotation, there was a 24%, 23% and 9% respective increase in the odds of sickness. Working long consecutive spells of work significantly and considerably decreased odds of sickness (OR=0.09, 95% CI 0.01-0.66, $p<0.05$), however this shift configuration was very rare with only 1937 cases across the whole dataset. In Model B (28-day), only quick returns (OR=1.04, 95% CI 1.02-1.05, $p<0.001$) and shift rotations (OR=1.04, 95% CI 1.02-1.06, $p<0.001$) retained statistical significance. Controlling variables consistently slightly reduced odds of sickness, however a large decrease in odds was observed for previous sickness in the lookback window.

All terms for proportion of long shifts (linear, quadratic, cubic) and proportion of night shifts (linear, quadratic) returned as statistically significant ($p<0.001$). In both 7-day and 28-day models, working approximately >30% of shifts as long increased odds for sickness (relative to working no long shifts), with the highest odds occurring around the 80% mark (7-day OR 1.63; 28-day OR=1.57). Working approximately >90% of shifts as night also slightly increased odds for sickness (relative to working no night shifts), with the highest odds occurring at the 100% mark (7-day OR 1.07; 28-day OR=1.06).

5.4 Discussion

The purpose of this observational study was to gain a more comprehensive understanding of how adverse shift configurations contribute to sickness absence rates among registered nurses.

This was achieved by analysing 1.4 million historical shift and sickness absence records collected from acute inpatient wards in two NHS hospital Trusts between 2015 and 2020. Compared to previous research on the impact of shift work on sickness absence and other indicators of workforce wellbeing, this analysis explored the relationships of more complex patterns of work, such as extended spells of consecutive working days and inadequate inter-shift recovery. This study therefore fills two of the core research gaps/opportunities identified in section 2.3: 1) the need for longitudinal research using data-driven analysis frameworks, and 2) understanding the effects of shift patterns comprised of multiple variables and parameters (versus exclusively single variables e.g., day or night work, short or long shifts).

Nurses working high proportions of long shifts and night shifts had increased risk of sickness (relative to working no long or no night shifts), with the highest odds observed when over 80% of shifts were long (≥12 hours) or when working all night shifts in 7-day and 28-day lookback windows. These findings mirror those of previous studies conducted within England. For example, in an analysis of 601,282 shift records from a large acute hospital, when 75% or more of shifts were worked as long shifts or night shifts in the past 7 days, the odds of sickness absence were increased when compared to working no long shifts (24% increase in odds) or day shifts only (12 % increase in odds) (Dall'Ora *et al.*, 2019a; Dall'Ora *et al.*, 2020). Similarly, in a study that examined the pre-versus-post change in sickness absence rates in a large mental health hospital, an increase in the percentage of sickness hours per week (ranging from 0.73%-0.98%, amounting to the equivalent of 1 shift per ward per week) was found following the implementation of long shifts (Santana *et al.*, 2020).

However, the nonlinear effects observed in the present study provide new and nuanced understanding of these relationships. Although high proportions of long shifts led to increased odds for sickness (relative to working no long shifts), the magnitude of these odds quickly diminished when proportions were greater than 80% in both 7-day and 28-day models and ultimately led to a decrease in odds at the 100% mark in 7-day lookback windows. This first appears as counterintuitive given the demanding and fatiguing nature of extended shifts, as evidenced by a substantial body of literature. One possible explanation for this observation is that nurses who work most or all long shifts benefit from an element of consistency (i.e., always working the same shift length), and therefore are able to establish routines and coping mechanisms accordingly. Rota consistency was identified by nurses in Study 1 of this doctoral research (Chapter 4) as one of the key scheduling practices that is supportive of their personal priorities in and outside of work, and the benefits of having some consistency may lessen the impact of long working hours. Self-selection similar to the ‘healthy worker effect’ (Ritonja *et al.*, 2019) may also help explain this result, as individuals who can work demanding shifts and schedules continue to do so, while those more susceptible to sickness change their working patterns (or switch to standard schedules completely), thus skewing data and relationships toward the appearance of healthier outcomes.

Significant nonlinear effects were also observed for the proportion of night shifts worked in the previous 7 and 28 days, where a slight increase in the odds for sickness only resulted from working 100% night shifts (relative to working no night shifts) - a feature of permanent night schedules. While existing guidance around night work advises against permanent night work, an oft-assumed benefit of this shift pattern is the avoidance of routine disruption that arises from rotating shiftwork. The results of this study contributes to the body of research that challenges this belief, as any benefits derived from consistency in this sense is likely overshadowed by the harmful effects of nightwork in general (e.g., inability to reconcile work routines with personal/social routines, sustained metabolic dysregulation), thus leading to higher rates of sickness. The reduced odds of sickness observed for proportions below 100% may be partially due to a reluctance to call in sick when scheduled to work night shifts, caused by concerns about leaving wards understaffed or forfeiting pay premiums that are often associated with working unsocial hours (NHS Employers, 2024).

Another high-demand shift configuration – intense spells of consecutive work (i.e., working more than 3 long shifts or night shifts consecutively) significantly increased odds for sickness in 7-day lookback windows. This finding complements previous research on the consequences of working many consecutive shifts: increased sickness absence rates when health care workers are working ≥ 4 or 5 consecutive night shifts, as well as consequences to other outcomes such as cognition, performance, occupational injury rates, and sleepiness when nurses are working consecutive long shifts (Hopcia *et al.*, 2012; Hirsch Allen *et al.*, 2014; James *et al.*, 2021). However, results from qualitative research are often mixed, with some nurses preferring consecutive shifts to enable longer periods of uninterrupted time off, while others name the challenges of excessive consecutive shifts that impede one's ability to engage in life outside of work as a result of exhaustion or fatigue (as found in Study 1) (Ejebu, Dall'Ora and Griffiths, 2021; Emmanuel *et al.*, 2024).

The negative effects of working consecutive shifts did not persist when examining long spells of continuous work (i.e., working more than 6 consecutive long or night shifts) as this variable significantly and considerably decreased odds for sickness in multivariable models. This configuration was rare across the dataset (<0.1% of all lookback windows), which may indicate that when a long spell was worked, it was done so out of choice. Previous research suggests that choice and autonomy may influence the relationship between the demands of shift work and staff wellness outcomes (Demerouti *et al.*, 2001; Dall'Ora *et al.*, 2023b), particularly for sickness absence as nurses may less likely to call in sick for shifts they chose or requested.

Other variables tested in the present model that reflected some element of choice, namely the total number of bank hours and the number of sickness episodes in the lookback window, also significantly decreased odds of sickness. For this latter variable however, "choice" does not necessarily reflect freedom in selecting shifts but rather could represent choosing to not call in sick to avoid triggering absence monitoring policies. For example, some NHS Trusts make use of the controversial Bradford scoring tool (Taylor, 2005), which penalises recurrent and short absences and thereby discourages employees from taking frequent sick leave, even when genuinely necessary.

Lastly, shift configurations involving inadequate rest periods, namely quick returns and shift rotations, also significantly increased the odds of sickness in both 7-day and 28-day lookback windows. Of note, these findings were observed even though both variables were defined broadly to capture all relevant cases in the study population (i.e., including both day-to-night and night-to-day changes; defining quick returns as fewer than 11.5 hours of rest between shifts to account for the pervasive use of long shifts). Similar findings have been found in previous register-based sickness absence studies (Larsen *et al.*, 2020; Rosenström *et al.*, 2021), as well as in other research exploring outcomes such as stress, exhaustion and fatigue (Min, Min and Hong, 2019). Nevertheless, short returns – which represent a special case of inadequate rest (<48 hours) between a night-to-day shift rotation – did not return significant results in the models. Having limited rest time between ending a night shift and starting a day shift was frequently identified as a problematic work/rest day configuration by nurses in Study 1 (section 4.3.4); therefore, while this shift pattern may negatively impact overall wellbeing and work-life balance in some ways, it does not seem to directly influence sickness as recorded through official mechanisms.

5.4.1 Limitations

The absence of demographic information in the underlying dataset (e.g., age, years in current role) restricted the ability to control for variables that may also impact odds of sickness absence. However, these confounding effects were at least partially controlled for by accounting for outcome clustering at the individual/nurse level. Second, overtime work (as defined by the NHS, i.e., working in excess of 37.5 hours per calendar week when averaged over a reference period) (NHS Employers, 2024) is another shift variable previously shown to impact staff wellbeing, particularly when worked in excess of a working week with long and/or night shifts (Health and Safety Executive (HSE), 2006). However, this variable could not be reliably assessed, as elements of overtime work (e.g., extra hours worked at the end of a planned shift versus additional shifts that are worked in excess of the full-time limit) were recorded inconsistently. This limitation was in part mitigated by the inclusion of total working hours as a controlling variable, which also effectively captured extra work time that may not have been formally recorded as overtime.

5.5 Conclusions

This study of historical shift records provides detailed insight into the link between working hours and sickness absence among registered nurses working in acute adult hospital wards. Over the 5-year study period, changes in shift patterns were detected, with notable increases in harmful configurations such as lengthy spells of consecutive working days and inadequate inter-shift recovery. These configurations were also associated with higher odds of sickness, with number of quick returns and number of shift rotations demonstrating effects in both 7-day and 28-day lookback windows. High proportions of long shifts and night shifts also significantly increased sickness absence, though these relationships were nonlinear and were likely influenced by other factors such as adaptability to adverse working conditions and discretion used when taking sick leave. These findings are valuable for the development of shift planning policies and scheduling technologies that prioritise safe and effective nurse rosters.

5.5.1 Incorporating Findings

A holistic and contextual approach was used to incorporate findings from Studies 1 and 2 to ultimately inform the shift optimisation model developed in the final phase of this doctoral research (Chapter 6). Although the studies differed in objectives and data sources, each provided valuable implications for improved shift planning. Study 1 explored preferred shift patterns for a healthy work-life balance whereas Study 2 examined patterns specifically linked with increased odds of sickness absence. Furthermore, in Study 1 the majority of survey respondents reported working 37.5-48 hours per week across all sources of employment. In slight contrast, Study 2’s payroll data showed a median of 37.5 hours, however these data do not capture secondary employment or unofficial working time (e.g., overtime). In essence, even though each study addressed distinct aspects of nurse wellbeing and sample populations, integration was still possible given general convergence on findings. Lastly, this holistic approach also ensured that study results did not override one another; e.g., nonsignificant relationships in Study 2 did not result in the exclusion of key variables identified in Study 1.

In general, this process involved using the relationships uncovered in Study 2 to inform how the adverse shift pattern variables identified in Study 1 (section 4.5.1) should be constrained in the scheduling model developed in Study 3. To enable the model to make decisions on shift assignments, penalties were introduced to allow trade-offs based on relative intensity. Assignment of penalties involved the following considerations:

1. **Penalty Magnitude**: Varying degrees of ‘cost’ could be assigned,
    a. **Neutral** (1): There is no additional penalty
    b. **Small** (5): There is a small penalty associated, applied to adverse shift assignments that can be used if necessary to solve the model (i.e., find a feasible roster solution in a reasonable timeframe)
    c. **Moderate** (25): There is a moderate penalty associated, applied to adverse shift assignments that should not be used on principle but may be used if necessary
    d. **Large** (125): There is a large penalty value associated; applied to adverse shift assignments that should be avoided but are not outright forbidden
2. **Single-Day versus Multi-Day Configurations**: Penalty magnitude was assigned with further consideration of the shift pattern length (in days). Multi-day shift assignments (those that occur over multiple days, e.g., intense consecutive spells) were assigned a higher penalty category whereas single-day assignments (e.g., a single long shift) were assigned a lower category to avoid unnecessary penalisation.
3. **Thresholds versus Outset**: Model constraints additionally considered how/when penalties should begin to accumulate. Generally, single-day adverse shift assignments incurred penalties only after exceeding a specified threshold, while multi-day assignments were penalised from the outset. Thresholds were designed to accommodate each pattern’s unavoidable role within 24-hour scheduling (e.g., night shifts, weekend shifts) while also ensuring equitable distribution among each nurse in generated rosters.

For example, the formulation of the constraint for assignment of long shifts evolved in the following manner. In Study 1, nurses expressed a preference to limit long shifts in order to avoid feelings of fatigue and exhaustion; consequently, long shifts were identified as an ‘adverse’ shift pattern configuration that should be minimised (via penalisation) where possible. Study 2 revealed that the proportion of long shifts significantly increased the odds of sickness absence; this led to the decision to penalise long shifts above a certain threshold by a "large" value. However, given that long shifts are a single-day shift configuration that is a necessary feature of shift work in this context, unnecessary penalisation should be avoided; therefore, penalty magnitude was reduced by one level. Thus, the final decision for the optimisation model was to apply a "moderate" penalty to the assignment of long shifts in excess of a set threshold.

The development process for all variable constraints is detailed in Table 11.

Table 11. Integrating nurses' general preferences and results of multilevel models

Adverse Shift Pattern Profile	***Study 1***		***Study 2***		***Other Considerations***	***Final Decision for Optimisation Model (Study 3)***
	Findings: Nurses' General Preferences	***First Decision***: Chosen Variable(s)	*Findings*: Multilevel Models (7-day, 28-day)	***Second Decision***: Penalising adverse shift patterns	*Single Day vs. Multi Day Threshold vs. Outset*	
Intense Shifts	Not working too many long shifts to prevent exhaustion	Limit the number of **long shifts** assigned Avoid assignment of shifts that result in **long working weeks** (>48 hours per calendar week)	In 7-day and 28-day models, working high proportions of long shifts increased odds of sickness	Penalise assignment of long shifts by 'large' value Avoid assignment of ≥ 48 working hours per calendar week	Long shifts are a single-day variable, therefore reduce penalty magnitude. Constraint formulation should penalise after threshold is reached.	Penalise assignment of long shifts above threshold (e.g., >8) by 'moderate' value Forbid assignment of ≥ 48 working hours per calendar week
	Willingness to do night work if organised and distributed fairly Avoid shift configurations that disturb periods that are usually reserved for social activities (late evenings, nights)	Evenly distribute and limit **night shifts** among all nurses in a team	In 7-day and 28-day models, working 100% of shifts as night increased odds of sickness	Penalise assignment of night shifts by 'large' value	Night shifts are a single-day variable, therefore reduce penalty magnitude. Constraint formulation should penalise after threshold is reached.	Penalise assignment of night shifts above dynamic threshold (i.e., based on number of night shifts to be assigned) by 'moderate' value
	Avoid shift configurations that result in feeling too tired/exhausted, particularly in terms of not being able to have quality rest,	Limit the number of **long work spells** assigned, i.e. spells of working 6 or more consecutive days	In 7-day and 28-day models, number of long work spells decreased odds of sickness, however this configuration was rare in the study dataset	Penalise assignment of long work spells by 'small' value	Long spells are a multi-day variable, therefore increase penalty magnitude. Constraint formulation should penalise from the outset.	Penalise assignment of every long work spell by 'moderate' value

	relaxation, or recreation	Limit the number of **intense work spells** assigned, i.e. spells of working 3 or more consecutive long days and/or night	In 7-day model, number of intense work spells greatly increased odds of sickness	Penalise assignment of intense work spells by 'large' value	Intense spells are a multi-day variable, therefore penalty magnitude should be increased, however this has already been assigned the largest option. Constraint formulation should penalise from the outset.	Penalise assignment of every intense work spell by 'large' value
Inadequate Rest	Preferring to have at least 11 hours of rest between consecutive shifts	Limit the number of short recovery periods (<11 hours rest, i.e., **quick returns**) between any two shifts	In 7-day and 28-day models, number of quick returns greatly increased odds of sickness	Penalise assignment of quick returns by 'large' value	Quick returns are a multi-day variable, therefore penalty magnitude should be increased, however this has already been assigned the largest option. Constraint formulation should penalise from the outset.	Penalise assignment of every quick return by 'large' value
	Preferring to have more than 24 hours between finishing a night shift and starting a day shift	Limit the number of short recovery periods (<48 hours, i.e. **short returns**) between ending a night shift and starting a day shift	In 7-day and 28-day models, number of short returns did not significantly impact odds of sickness	Penalise assignment of short returns by 'small' value	Short returns are a multi-day variable, therefore increase penalty magnitude. Constraint formulation should penalise from the outset.	Penalise assignment of every short return by 'moderate' value
	Dislike of working both day and night shifts within short periods of time (e.g., a week) Avoid shift assignments that excessively disturb circadian rhythms and sleeping patterns	Minimise the number of **shift rotations** occurring within a 7-day period	In 7-day and 28-day models, number of shift rotations moderately increased risk of sickness	Penalise assignment of day-to-night rotations by 'neutral' value Penalise assignment of night-to-day rotations by 'small' value	Shift rotations are a multi-day variable, therefore penalty magnitude should be increased, however rotations are a necessary feature of shift work and should not be over-penalised; magnitudes are unchanged. Constraint formulation should penalise from the outset.	Penalise assignment of every day-to-night rotation by 'neutral' value Penalise assignment of every night-to-day rotation by 'small' value

	Maximising consistency to make childcare arrangements and other personal priorities easier to organise and manage					
	Avoid starting a day shift shortly after completing a night shift	Minimise assignment of shifts resulting in backward rotation (night-to-day) within a 7-day period				
Social Disruption	Willingness to do weekend work if organised well and distributed fairly	Evenly distribute and limit **weekend work** among all nurses in a team	n/a	n/a	Weekend shifts are a single-day variable. Constraint formulation should penalise after threshold is reached.	Penalise assignment of weekend shifts above threshold (>4) by 'neutral' value
	Avoid shift configurations that disturb periods of day/week that are usually reserved for social activities (weekends)					
	Fewer working days enable more days away from work, less commuting time, and better ability to work extra shifts	Limit the number of **working days** where possible		n/a	n/a	(alternative constraint): Minimise number of shifts assigned to each nurse

Chapter 6 | Study 3: Mixed-integer programming solutions for wellbeing- and preference-based scheduling of nurses in acute wards

This chapter features the third and final study that was completed, which used the results of Study 1 and 2 to formulate a mathematical optimisation model that generates nurse rotas according to the overall objective of minimising the solution's 'cost' value, i.e., the total number of penalties incurred, based on the assignment of adverse shift patterns. In contrast to traditional studies on the Nurse Scheduling Problem (NSP) that test novel solution techniques, this study aimed to create a new model formulation that incorporates practical elements and produces shift patterns optimised for nurses' working time preferences and wellbeing. For a review of frequently used terminology in scheduling problems, please refer to Table 4 in section 2.2.3, as well as the *Definitions & Acronyms* section of this thesis (page 12).

6.1 Introduction

While there is an abundance of research exploring the various staff- and patient-related consequences of poorly organised shift work, this knowledge does not necessarily translate to clear/actionable rostering policies and procedures that achieve improved outcomes (Drake, 2019). Bridging this gap is important, as the generation of effective and efficient nursing rosters is critical for delivering high-quality patient care in acute care wards. Several priorities must be considered during this process, including achieving staffing level targets, adhering to legal and contractual working time regulations, and mitigating the risks of shift work and night work (Burton *et al.*, 2018).

Monthly rosters are traditionally created manually by managers who rely on tacit knowledge, professional judgement, and guidance from any relevant organisational policies. However, manager-led rostering processes present a number of drawbacks, namely singular ownership and excessive time spent over the rostering process (i.e., planning the roster with staff requests and service needs in mind, publishing the roster, and reconciling inevitable changes thereafter) (Silvestro and Silvestro, 2008; Booker *et al.*, 2024b). In contrast, self-rostering methods transfer the responsibility of shift planning to nurses themselves, which has previously demonstrated improvements to wellbeing outcomes such as team morale, job satisfaction, and work-life balance. Nonetheless, due to issues related to implementation failures and inequitable bidding dynamics, this method of rostering often falls short of fulfilling its original aims (Wynendaele *et* *al.*, 2021). Furthermore, while newer rostering technologies claim to ease scheduling challenges through ward/staff data integration and auto-roster generation, use of these features has thus far been limited in NHS settings (Carter, 2016).

In the field of operational research (OR), the Nurse Scheduling Problem (NSP) has been extensively studied and a range of formulations, solving techniques, and solutions are reported in the literature. However, a significant research-to-application gap remains due to the inherent challenges of modelling real-world rostering (Kellogg and Walczak, 2007; Drake, 2014a; Petrovic, 2019). These studies also often rely on the use of benchmark instances (i.e., standardised problem sets), such as those described by Burke and Curtois (2014) that contain fixed parameters for staffing complement size, shift lengths, and time horizons (e.g., weekly, monthly, or quarterly schedules). Specific scheduling objectives also vary, with many focused on minimising staffing costs or maximising staff wishes for days on or off. While standardised instances with fixed parameters are useful for evaluating the success of new solving algorithms, these instances prevent the generation of new/improved shift types and patterns, thus limiting their utility in this doctoral research.

Therefore, the aim of this study was to address these gaps by developing a new mathematical model for nurse scheduling with objectives, parameters, and constraints designed to capture aspects of rostering in practice, including nurses' shift/scheduling preferences and minimising the use of adverse working hours configurations.

6.2 Methods

6.2.1 Narrative summary

This novel nurse scheduling model integrated findings from Studies 1 and 2. Specifically, key variables for nurse-centred scheduling identified in Study 1 were translated into model objectives, parameters, and constraints in accordance with the variable relationships uncovered in Study 2 (as discussed in section 5.5.1). As distinct aspects of nurse wellbeing were examined in each study, findings were holistically considered, with variables from Study 1 retained even when variable relationships were nonsignificant in Study 2. Additionally, decisions around shift assignments accounted for if they occurred over a single day or multiple days.

The model's parameters were also informed by a descriptive analysis of historical shift data from Study 2, including the frequency of individual shift types as well as fluctuations in staffing levels over the 24-hour ward day. In contrast to traditional NSP models that typically enforce fixed nurse numbers for predefined number of shifts, this model was designed to flexibly assign the most appropriate shift type to meet fixed time "blocks" of coverage while also adhering to a series of mathematical constraints that guided shift assignments.

To evaluate the model's solving capacity, new benchmark instances were developed for three experimental stages, testing its robustness across three common scheduling scenarios: 1) the "Baseline" test, which produced an initial solution for a fictional team of 24 nurses with varying hourly contracts, 2) the "FTE" tests, which produced solutions for 20 randomly generated wards with diverse staffing requirements and team sizes, and 3) the "Preference Profile" tests, which produced solutions that used unique penalty 'profiles' tailored to nurses' more specific scheduling needs.

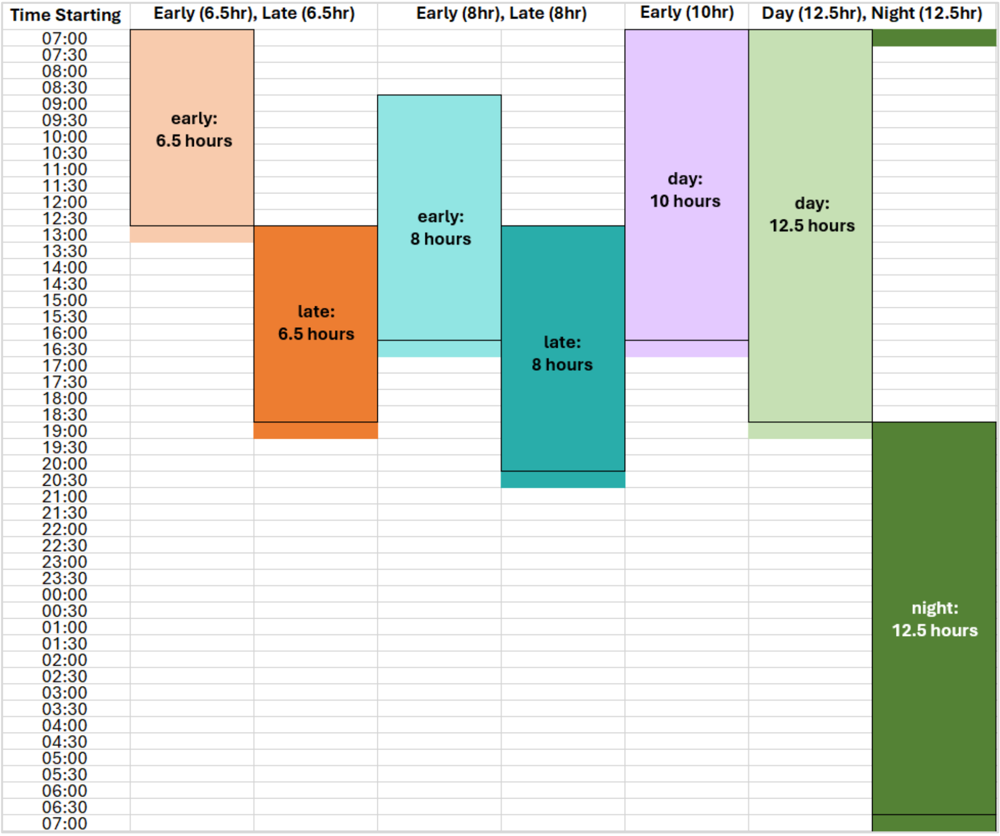
The following sections present a detailed account of the model's development process.

6.2.2 Structuring the 24-hour ward-day

To improve problem formulation in-line with the aims of this doctoral research, incorporation of the operational realities of nurse scheduling in NHS acute care wards was prioritised. To accomplish this, a descriptive analysis of staffing numbers and shift types was undertaken using the dataset from Study 2, which was comprised of electronic staff rostering records from registered nurses working in acute inpatient wards of two NHS hospital Trusts in England between 2015 and 2020.

Across all worked shifts, pairs of shift start times and end times were counted and categorised into day shifts and night shifts, as well as into short (≤8 hours), medium (between 8.1 and 10.9 hours), and long (≥ 11 hours) shifts. For each category, the most frequent pairs were evaluated for their potential usefulness; popular shifts were retained (e.g., 12.5 hour night shifts starting at 19:00 and ending at 07:30 the following morning) whereas unique shifts were chosen for their potential to generate innovative patterns (e.g., 10 hour day shifts starting at 07:00 and ending at 17:00). Figure 7 visualises the final shift types chosen for inclusion in the optimisation model. As standard, 30-minute handover periods were placed at the end of each shift. Of note, the selection of these shift types eliminated the possibility of assignment of quick returns, as all possible consecutive shift combinations resulted in ≥11.5 hours of rest.

Figure 7. Shift types derived from historical dataset



Next, a representative view of coverage was derived from a cross-section of all 95 study wards on a typical operational day (i.e., a weekday outside of influenza season). This 24-hour snapshot was divided into 30-minute intervals and staffing numbers were calculated by totalling the number of nurses present in a specific ward and time interval. For example, a nurse scheduled to work 07:00-15:00 in Ward X was added to the total nurse number for all intervals they were present (first interval 07:00, last interval 15:00). An example of how totals were calculated per ward is illustrated in Figure 8 below. Shift start/end time were also re-examined to determine how many nurses usually worked each shift type over the ward-day.

Figure 8. Nurse numbers across a 24-hour day in ward ID 90420

Start	End	N	hrs	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00
07:30:00	20:00:00	4	12.5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
07:30:00	17:30:00	1	10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
07:30:00	14:00:00	1	6.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19:30:00	08:00:00	3	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			TOT	6	6	6	6	6	6	6	6	6	6	6	6	6	6

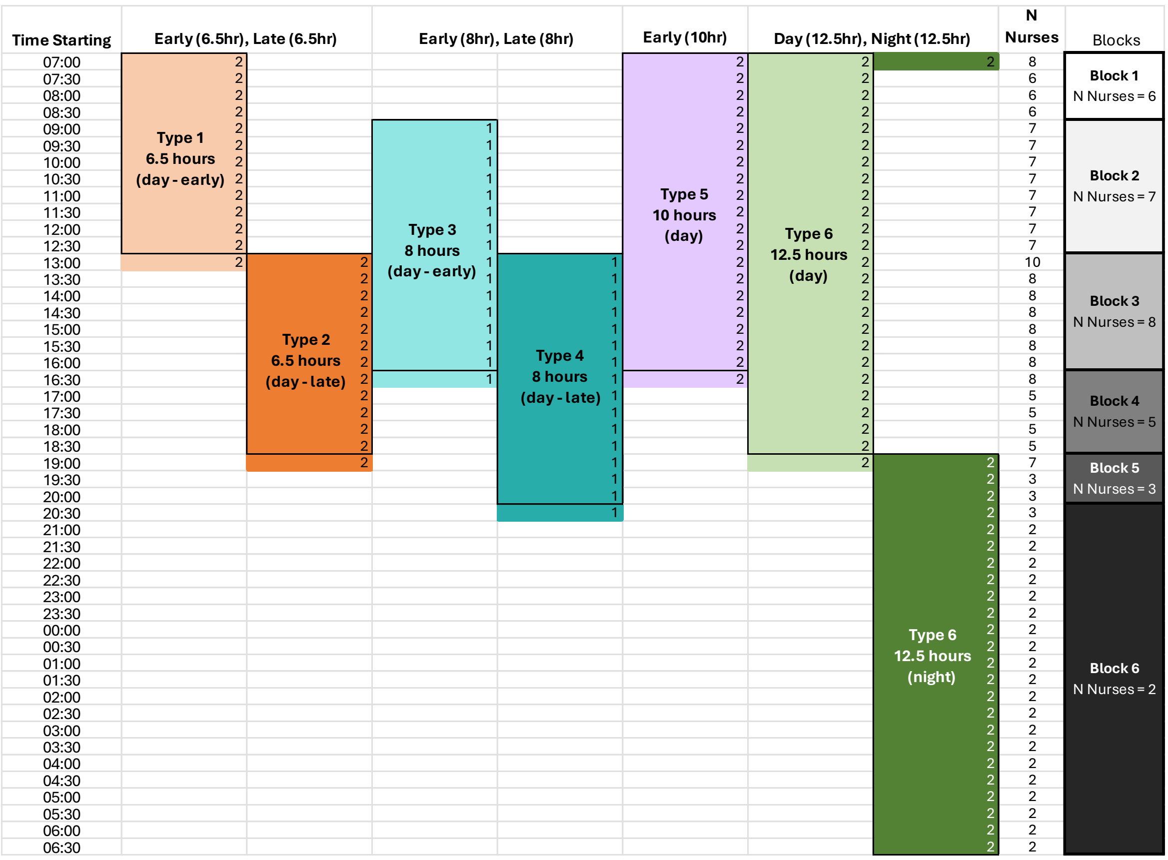
14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	...	07:30	08:00
4	4	4	4	4	4	4	4	4	4	4	4	0	0	0	0		0	0
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0		0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0
0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3		3	3
5	5	5	5	5	5	5	4	4	4	7	7	3	3	3	3		3	3

This breakdown was generated for all available wards in the dataset; several patterns emerged. Nurse numbers showed the greatest variation during the day, primarily due to a greater number of available shift lengths and start times. In contrast, nurse numbers remained stable throughout the night; occasionally these numbers matched daytime staffing levels, but more frequently staffing levels at night were 25%-50% of daytime numbers. Major shift handovers occurred twice daily, usually between 06:00–07:30 and 18:00–19:30, reflecting the popularity of long shifts in these wards, particularly during nights.

Lastly, staffing 'blocks' were created by chronologically overlapping shift types and segmenting at each point where a new shift started or ended. Staffing counts for each block were estimated by summing the number of nurses working a shift that covered that block in the data, excluding handovers. Therefore, rather than assigning nurses to fixed shift types each with their own minimum staffing level (a common feature of NSP benchmark instances), the optimisation model was designed to flexibly assign the most appropriate shift type that would satisfy shift assignment constraints and also maintain minimum staffing levels in each block.

Incorporating all of the above information, the structure of the 24-hour ward day used in the optimisation model was finalised and is shown in Figure 9. In this figure, the number of nurses present for each 30-minute period of the day was calculated by totalling the number of nurses working shifts that covered that 30-minute period. For example, staffing block 1 required a minimum of six nurses as a result of two nurses working an 6.5-hour early shift, two nurses working a 10-hour shift, and two nurses working a 12.5-hour shift.

Figure 9. 24-hour ward day for optimisation model



6.2.3 Optimisation model

This model was formulated as a mixed integer linear optimisation problem. Such formulations are useful for cases where some variables require discrete values (e.g., number of shifts) while others can take any positive value (e.g., number of hours). A planning horizon of 28 days was chosen, with Day 1 starting on a Monday. To ensure shift assignments were distributed evenly throughout the month, each nurse's schedule was cyclically wrapped around to include Day 1, Day 2, and so on where necessary (e.g., a consecutive working spell starting on day 28 would also include days 1 and 2, etc.). The following sections provide details on the sets, parameters, decision variables, and constraints included in the model.

6.2.3.1 Sets & parameters

I	Set of nurses
D	Set of days in the planning horizon, $D = \{1,2,\dots,28\}$
$\widetilde{\mathrm{D}}_{\mathrm{d}_1}^{\mathrm{d}_2}$	Set of consecutive days between day d_1 and d_2 (inclusive) that wrap around the planning period. $\widetilde{\mathrm{D}}_{\mathrm{d}_1}^{\mathrm{d}_2} = \{\omega\,(\mathrm{d}_1 + \mathrm{j}) \mid \mathrm{j} = 0,1,\dots,\mathrm{d}_2 - \mathrm{d}_1\}$ where $\omega(\mathrm{d})$ is a wrap-around function = $\begin{cases} \mathrm{d} \text{ if } \mathrm{d}(\mathrm{mod}\ \lvert\mathrm{D}\rvert) = 0, \\ (\mathrm{mod}\ \lvert\mathrm{D}\rvert) \text{ otherwise} \end{cases}$
$\mathrm{E} \subseteq \mathrm{D}$	Subset of weekend days, $E = \{6,7,13,14,20,21,27,28\}$
$\mathrm{W}_k \subseteq \mathrm{D}$	Subset of calendar weeks, $k = \{1,2,3,4\}$ and • $W_1 = \{1,2,3,4,5,6,7\}$ • $W_2 = \{8,9,10,11,12,13,14\}$ • $W_3 = \{15,16,17,18,19,20,21\}$ • $W_4 = \{22,23,24,25,26,27,28\}$
T	Set of shift types, $T = \{1,2,\dots,7\}$, as defined in Figure 9
$\mathrm{T}_{\mathrm{long}} \subseteq \mathrm{T}$	Subset of long shift types, $\mathrm{T}_{\mathrm{long}} = \{6,7\}$
$\mathrm{T}_{day} \subseteq \mathrm{T}$	Subset of day shift types, $\mathrm{T}_{day} = \{1,2,3,4,5,6\}$
$\mathrm{T}_{\mathrm{night}} \subseteq \mathrm{T}$	Subset of night shift types, $\mathrm{T}_{\mathrm{night}} = \{7\}$
B	Set of staffing blocks, $\mathrm{B} = \{1,2,\dots,6\}$, as defined in Figure 9
T_b	Shift types that cover staffing block b, $\mathrm{b} \in \mathrm{B}$
N_{b}	Number of nurses required for staffing block b, $\mathrm{b} \in \mathrm{B}$
C_{i}	Fraction of contracted hours (between 0 and 1) for nurse i, $\mathrm{i} \in \mathrm{I}$
H_{t}	Length of shift type t in hours, $\mathrm{t} \in \mathrm{T}$
$\mathrm{H}_{\mathrm{max\_week}}$	Maximum hours per nurse per week (48 hours)
$\mathrm{H}_{\mathrm{FTE}}$	Monthly total hours corresponding with full-time employment (150 hours)
A	Set of penalty coefficients, where • α_1 = penalty assigned to long shift deviations, δ_i^1 • α_2 = penalty assigned to night shift deviations, δ_i^2 • α_3 = penalty assigned to intense spell deviations, δ_i^3 • α_4 = penalty assigned to long spell deviations, δ_i^4 • α_5 = penalty assigned to night-to-day rotation deviations, δ_i^5

- α_6 = penalty assigned to short return deviations, δ_i^6
- α_7 = penalty assigned to day-to-night deviations, δ_i^7
- α_8 = penalty assigned to weekend shift deviations, δ_i^8
- α_9 = penalty assigned to any overtime assigned, δ_i^9
- α_{10} = penalty assigned to sum of all shifts assigned, δ_i^{10}

L_1 Maximum number of long shifts assigned per nurse. In this study's experiments, this parameter was set to 8.

L_2 Maximum number of night shifts assigned per nurse. In this study's experiments, this parameter was defined by multiplying the coverage requirement at night with the number of planning days (28), and dividing this product by the size of the nursing team (i.e., to ensure night shifts were distributed equitably).

L_8 Maximum number of weekend shifts assigned per nurse. In this study's experiments, this parameter was set to 4.

S_3 Maximum number of consecutive days worked before an intense spell is incurred. In this study's experiments, this parameter was set to 3.

S_4 Maximum number of consecutive days worked before a long spell is incurred. In this study's experiments, this parameter was set to 6.

6.2.3.2 Decision variables

$x_{idt} \in \{0,1\}, \quad \forall i \in I, d \in D, t \in T$	1 if nurse i works shift type t on day d, 0 otherwise
$\delta_i^1 \in \mathbb{N}, \quad \forall i \in I$	Number of long shifts assigned to nurse i exceeding L_1
$\delta_i^2 \in \mathbb{N}, \quad \forall i \in I$	Number of night shifts assigned to nurse i exceeding L_2
$\delta_{id}^3 \in \{0,1\}, \quad \forall i \in I, d \in D$	1 if nurse i works an intense spell starting on day d, 0 otherwise
$\delta_{id}^4 \in \{0,1\}, \quad \forall i \in I, d \in D$	1 if nurse i works a long spell starting on day d, 0 otherwise
$\delta_{id}^5 \in \{0,1\}, \quad \forall i \in I, d \in D$	1 if nurse i works a night-to-day rotation starting on day d, 0 otherwise
$\delta_{id}^6 \in \{0,1\}, \quad \forall i \in I, d \in D$	1 if nurse i works a short return starting on day d, 0 otherwise
$\delta_{id}^7 \in \{0,1\}, \quad \forall i \in I, d \in D$	1 if nurse i works a day-to-night rotation starting on day d, 0 otherwise
$\delta_i^8 \in \mathbb{N}, \quad \forall i \in I$	Number of weekend shifts assigned to nurse i exceeding L_8

6.2.3.3 Constraints

Number of shifts per day; each nurse is assigned at most one shift per day.

$$\sum_{t \in T} x_{idt} \leq 1, \quad \forall i \in I, \forall d \in D \tag{1}$$

Number of working hours per month; each nurse is assigned their contracted hours. Although an equality constraint would ideally ensure no overtime, it is too restrictive and makes finding feasible solutions challenging. Instead, an inequality is used and the model penalises overtime thereafter.

$$\sum_{d \in D} \sum_{t \in T} H_t \cdot x_{idt} \geq C_i \cdot H_{FTE}, \quad \forall i \in I \tag{2}$$

Number of working hours per calendar week; each nurse is assigned a maximum of H_{max_week} per calendar week.

$$\sum_{d \in W_k} \sum_{t \in T} H_t \cdot x_{idt} \leq H_{max\_week}, \quad \forall i \in I,\ k \in \{1,2,3,4\} \tag{3}$$

Forbidden shift combinations; day shifts cannot consecutively follow a night shift.

$$x_{idt} + \sum_{t \in T_{day}} x_{i(\omega(d+1))t} \leq 1, \qquad \forall i \in I, d \in D, t \in T_{night} \tag{4}$$

Number of weekend shifts; each nurse is assigned a maximum of L_8 weekend shifts per month, with each weekend shift above this limit counted and penalised.

$$\sum_{d \in E} \sum_{t \in T} x_{idt} \leq L_8 + \delta_i^8, \quad \forall i \in I \tag{5}$$

Number of long shifts; each nurse is assigned a maximum of L_1 long shifts per month, with each long shift above this limit counted and penalised.

$$\sum_{d \in D} \sum_{t \in T_{long}} x_{idt} \leq L_1 + \delta_i^1, \quad \forall i \in I \tag{6}$$

Number of night shifts; each nurse is assigned a maximum number of L_2 night shifts per month, with each night shift above this limit counted and penalised.

$$\sum_{d \in D} \sum_{t \in T_{night}} x_{idt} \leq L_2 + \delta_i^2, \quad \forall i \in I \tag{7}$$

Assignment of intense spells; any intense spell (i.e., working S_3 or more consecutive long or night shifts) assigned is counted and penalised.

$$\sum_{d' \in \tilde{D}_d^{d+2}} \sum_{t \in T_{long}} x_{id't} \leq S_3 + \delta_i^3, \quad \forall i \in I, \forall d \in D \tag{8}$$

Assignment of long spells; any long spell (i.e., working S_4 or more consecutive shifts) is counted and penalised.

$$\sum_{d' \in \tilde{D}_d^{d+5}} \sum_{t \in T_{long}} x_{id't} \leq S_4 + \delta_i^4, \quad \forall i \in I, \forall d \in D \tag{9}$$

Assignment of night-to-day rotations; any night-to-day rotation assigned to each nurse is counted and penalised. Rotations are only counted if occurring in a 7-day period.

$$x_{id7} + \sum_{t \in T_{day}} x_{i(\omega(d+\kappa))t} \leq 1 + \delta_{id}^5 + \sum_{t' \in T} \sum_{d' \in \tilde{D}_{d+1}^{d+\kappa-1}} x_{id't'}, \qquad \forall i \in I, \forall d \in D, \kappa = \{2, \dots, 6\} \tag{10}$$

The summation on the right-hand side was used to deactivate the constraint in cases where the rotation sequence was interrupted by another worked shift on an intervening day (κ).

Assignment of short returns; any short return (a special case of NTD rotation) assigned to each nurse is counted and penalised.

$$x_{id7} + \sum_{t \in T_{day}} x_{i(\omega(d+2))t} \leq 1 + \delta_{id}^6 + \sum_{t \in T} x_{i(\omega(d+1))t}, \quad \forall i \in I, \forall d \in D \tag{11}$$

Assignment of day-to-night rotations; any DTN rotation assigned to each nurse is counted and penalised, split into two constraints that account for rotations on $\omega(d+1)$ (12a) or on any day afterwards $\omega(d+\kappa)$ (12b), up to the 7th day.

$$\sum_{t \in T_{day}} x_{idt} + x_{i(\omega(d+1))7} \leq 1 + \delta^7_{id}, \quad \forall i \in I, \forall d \in D \tag{12a}$$

$$\sum_{t \in T_{day}} x_{idt} + x_{i(\omega(d+\kappa))7} \leq 1 + \delta^7_{id} + \sum_{t' \in T} \sum_{d' \in \widetilde{D}^{d+\kappa-1}_{d+1}} x_{id't'}, \quad \forall i \in I, \forall d \in D, \kappa = \{2, \ldots, 6\} \tag{12b}$$

The summation on the right-hand side of 12b was used to deactivate the constraint in cases where the rotation sequence was interrupted by another worked shift on an intervening day (κ).

Staffing blocks (i.e., cover requirements); the number of nurses assigned to each staffing block on each day must be at least the minimum number of nurses needed for that particular block.

$$\sum_{i \in I} \sum_{t \in T_b} x_{idt} \geq N_b, \quad \forall d \in D, \forall b \in B \tag{13}$$

6.2.3.4 Objective Function

$$\min\left(\alpha_1 \cdot \sum_{i \in I} \delta^1_i + \alpha_2 \cdot \sum_{i \in I} \delta^2_i + \alpha_3 \cdot \sum_{i \in I} \sum_{d \in D} \delta^3_{id} + \alpha_4 \cdot \sum_{i \in I} \sum_{d \in D} \delta^4_{id} + \alpha_5 \cdot \sum_{i \in I} \sum_{d \in D} \delta^5_{id} + \alpha_6 \cdot \sum_{i \in I} \sum_{d \in D} \delta^6_{id} + \alpha_7 \cdot \sum_{i \in I} \sum_{d \in D} \delta^7_{id} + \alpha_8 \cdot \sum_{i \in I} \delta^8_i + \alpha_9 \cdot \sum_{i \in I} \left(\left(\sum_{d \in D} \sum_{t \in T} (H_t \cdot x_{idt}) \right) - c_i \cdot H_{FTE} \right) \right)$$

This objective function achieved two goals: 1) minimising all penalties incurred from assignment of adverse shift configurations, and 2) minimising the hours assigned across the planning horizon to avoid overstaffing of blocks and overtime for nurses. Incorporation of separate decision variables with unique penalties for each adverse shift configuration provided the model with greater solving flexibility via a system of prioritisation for satisfying constraints.

6.2.4 Instance generation (data)

To test the solving capacity of the optimisation model, a series of new ward instances were created. The first instance (*ward_prime*) was designed to represent a typical NHS acute ward and was manually derived through the descriptive analysis of historical roster data, as described in section 6.2.2. This instance included 24 registered nurses with varied requirements for contracted hours. The distribution of full-time equivalent (FTE) contracts was designed to represent a nursing team comprised 50% full-time and 50% part-time staff, resulting in the following breakdown: 16 nurses working full time (1.0 FTE) with 150 hours per month, 4 nurses working part time (0.8 FTE) with 120 hours per month, and 4 nurses working part time (0.5 FTE) with 75 hours per month.

To provisionally check that this configuration would result in a realistic number of assigned hours, nursing hours-per-patient-day (HPPD) were derived. Traditionally, nursing HPPD is calculated by dividing the total number of scheduled nursing hours by the product of the number of planning days and the average number of occupied beds (NHS England, 2024). Therefore, based on an estimate of 30 occupied beds, 3180 hours (i.e., the sum of all monthly contracted hours) would yield a HPPD of 3.79. In a previous study by Griffiths *et al.* (2018) that explored the impacts of historical staffing levels on linked patient outcomes, general acute wards had planned nursing HPPD levels ranging between 3.37-3.99 and contained between 30-36 beds, confirming that this instance was appropriately designed. Lastly, the following coverage requirements for each staffing block were used (previously visualised in Figure 9): block 1 required a minimum of 6 nurses, block 2 ≥ 7 nurses, block 3 ≥ 8 nurses, block 4 ≥ 5 nurses, block 5 ≥ 3 nurses, and block 6 ≥ 2 nurses.

Alongside this manually-derived instance, 20 additional instances with randomly generated coverage requirements were created (Table 12). Coverage requirements for each staffing block in this set of instances were generated according to two criteria:

- **Ward Size**, i.e., either a 'small' or 'large' sized number of available nurses; note, smaller numbers of nurses required for each staffing block were more likely to be selected as there was a higher probability of minimal or no increases between blocks (as explained in Table 13).
- **Day vs. Night** nurse staffing levels, i.e., either 'same' (similar nurse numbers during the day and night) or 'half' (nurse numbers during the night approximately halved).

In essence, each ward was assigned a coverage requirement for the first staffing block, based on small versus large ward sizing; 'small' wards had a range of 1-5 nurses for this initial block, while 'large' wards had a range of 5-10 nurses. As coverage requirements for successive blocks were generated, a series of probabilities were used to represent the likelihood of requirements increasing/decreasing by some pre-defined amount. Probabilities for changes in block coverage were purposively designed to minimise large/unrealistic fluctuations.

Table 12. Randomly generated ward instances

Instance*	Block	N Nurses	Team Size	Min T_7†	Instance*	Block	N Nurses	Team Size	Min T_7†	Instance*	Block	N Nurses	Team Size	Min T_7†	Instance*	Block	N Nurses	Team Size	Min T_7†
ward s_s_0	1	1	17	7	**ward s_h_0**	1	2	6	5	**ward l_s_0**	1	8	33	6	**ward l_h_0**	1	9	38	4
	2	3				2	2				2	5				2	9		
	3	3				3	1				3	5				3	9		
	4	3				4	1				4	6				4	11		
	5	3				5	1				5	6				5	11		
	6	4				6	1				6	7				6	5		
ward s_s_1	1	5	26	7	**ward s_h_1**	1	1	8	4	**ward l_s_1**	1	8	35	6	**ward l_h_1**	1	5	19	5
	2	5				2	2				2	8				2	5		
	3	5				3	2				3	8				3	5		
	4	4				4	2				4	7				4	3		
	5	5				5	2				5	6				5	4		
	6	6				6	1				6	7				6	3		
ward s_s_2	1	4	26	7	**ward s_h_2**	1	3	19	5	**ward l_s_2**	1	5	23	7	**ward l_h_2**	1	5	23	4
	2	4				2	4				2	4				2	6		
	3	5				3	4				3	4				3	6		
	4	6				4	5				4	4				4	6		
	5	6				5	6				5	5				5	6		
	6	6				6	3				6	5				6	3		
ward s_s_3	1	2	11	8	**ward s_h_3**	1	3	12	5	**ward l_s_3**	1	6	32	7	**ward l_h_3**	1	10	31	4
	2	1				2	4				2	5				2	7		
	3	1				3	2				3	5				3	7		
	4	1				4	2				4	7				4	7		
	5	1				5	2				5	7				5	8		
	6	3				6	2				6	7				6	4		
ward s_s_4	1	3	15	6	**ward s_h_4**	1	1	5	6	**ward l_s_4**	1	9	52	6	**ward l_h_4**	1	6	26	5
	2	3				2	1				2	11				2	6		
	3	4				3	1				3	12				3	7		
	4	2				4	1				4	11				4	6		
	5	2				5	1				5	11				5	7		
	6	3				6	1				6	11				6	4		

* = wards were assigned A_B_N names according to the following convention: A equals s=small/l=large (size), B equals s=same/h=half (night staffing levels), and N equals the instance number
† = the minimum number of night shifts (shift type T_7) that should be worked by each nurse in order to ensure equitable distribution of night work, calculated by multiplying the coverage requirement for staffing block 6 and number of planning days (28) and dividing this product by the size of the nursing team

Table 13. Generating coverage requirements for staffing blocks*

Ward Size	Change Range	Probability Range	Description
Small	[0, 3)	[0.50, 0.40, 0.10]	50% chance coverage stays the same in the next block, 40% chance coverage changes (+/-) by 1 nurse in the next block, 10% chance coverage changes (+/-) by 2 nurses in the next block
Large	[0, 4)	[0.50, 0.35, 0.10, 0.05]	50% chance coverage stays the same in the next block, 35% chance coverage changes (+/-) by 1 nurse in the next block, 10% chance coverage changes (+/-) by 2 nurses in the next block, 5% chance coverage changes (+/-) by 3 nurses in the next block

* For wards with halved day/night coverage requirements, the coverage required for block 6 (night) was determined by calculating the mean of coverage required for blocks 1-5 and dividing this value this by 2 (rounded up)

Following this, a smaller optimisation model was used to solve for the minimum number of full-time nurses required for each of these wards for a 28-day planning period (i.e., the 'Team Size' column in Table 12). The following constraints were carried over from the main model: assigning one shift per nurse per day (constraint 1), maximum monthly and weekly working hours per nurse (constraints 2 and 3), forbidden shift combinations (constraint 4), and minimum numbers for staffing blocks (constraint 13). The following decision variables, constraints, and objective were also used:

$y_i \in \{0,1\}, \quad \forall i \in I$	Binary decision variable; 1 if nurse i is used in the model, 0 otherwise.	
$\min \sum_{i \in I} y_i$	Objective function; minimise the total number of nurses needed for each instance	
$x_{idt} \leq y_i, \quad \forall i \in I, \forall d \in D, \forall t \in T$	Constraint; linking shift assignment (x_{idt}) with nurse usage (y_i)	(14)
$y_i \leq y_{i-1}, \quad \forall i = 2, \ldots, I$	Symmetry-breaking constraint; ensuring nurses are used in order (i.e., nurse 1 is used before nurse 2, etc.)	(15)
$\sum_{d \in D} \sum_{t \in T} H_t \cdot x_{i,d,t} \geq H_{FTE} \cdot y_i, \quad \forall i \in I$	Constraint; if nurse i is used, then their full contracted hours must be fulfilled across the planning period	(16)

6.2.5 Experiments

A series of experiments were conducted to test the model's solving capacity across three practical scenarios (Table 14). Baseline, FTE, and Preference Profile test solutions were derived using the Gurobi solver; coding was facilitated through the *gurobipy* package (which provides a python coding interface for Gurobi) and the full coding file can be found in Appendix C.1. To solve the model, Gurobi's branch-and-bound algorithm systematically was used to reduce the feasible solution space by improving upper and lower bounds, where the lower bound indicated the best solution that is theoretically feasible, while the upper bound represents the best-known solution confirmed so far.

Table 14. Model Experiments

Experiment	Data/Instance(s)	Test Description
Baseline Test	ward_prime	Models' ability to minimise adverse working configurations for a nursing team with varied working hours contracts
FTE Tests	ward _ s_s_0, s_s_1, s_s_2, s_s_3, s_s_4; s_h_0, s_h_1, s_h_2, s_h_3, s_h_4; l_s_0, l_s_1, l_s_2, l_s_3, l_s_4; l_h_0, l_h_1, l_h_2, l_h_3, l_h_4	Models' ability to minimise adverse working configurations as nurses are added to the available staffing pool (i.e., staffing wards beyond the absolute minimum)
Preference Profile Test	ward_prime	Models' ability to minimise adverse working configurations when nurses with varied working hours contracts are assigned different shift preference profiles

For the Baseline test, penalty coefficients for each decision variable were applied in accordance with the decisions outlined in Table 11 of section 5.5.1, which integrated the results of Study 1 and 2 together.

These penalties were also used for the FTE tests, where 60 solutions were produced: each ward was solved with the minimum number of staff required ('*FTE min*') as well as with one ('*FTE min +1*') and with two ('*FTE min +2*') extra nurses. To increase model flexibility, constraint 2 (defined in section 6.2.3.3) was modified for each additional nurses in '+1' and '+2' iterations so that they could work ≤150 monthly hours (i.e., they could work a part time configuration). For each ward, the solution of "FTE min" iteration should, by definition, also be a feasible solution for "FTE min +1"iteration, since it fulfilled all coverage requirements and assigned feasible working patterns. Therefore when solving '+1' and '+2' iterations, a 'warm start' solution was provided to the solver to speed up computation. This was done through Gurobi's *MIP Start* function, which provided each iteration with the best solution found for the previous FTE configuration.

For the Preference Profile Tests, four distinct groups of shift/scheduling preferences were created, each reflecting the categories first described in section 4.5.1 of this thesis. Two cases of these tests were explored, with each only differing in the penalty associated with number of shifts assigned for nurses in the 'social disruption' profile (case A: neutral penalty, case B: moderate penalty). Details for each preference profile are included in Table 15. To enable comparison of model performance and outputs, the staffing blocks and team composition of the ward_prime instance was re-employed. Each nurse in this instance was randomly assigned to one the four penalty profiles according to the following distribution: 50.00% as 'standard', 16.67% as 'intense shifts', 16.67% as 'inadequate rest', and 16.67% as 'social disruption'.

It is important to note that solving MILPs is inherently challenging, primarily because they are classified as NP-*hard*, meaning no known algorithm can solve them in polynomial time (i.e., where problem complexity is a polynomial function of its input size). Furthermore, due to the high number of variables typically incorporated (e.g., producing a solution for the Baseline Test using the ward_prime instance requires the calculation of 8,136 variables), it is often not practicable to solve them to optimality (Burke *et al.*, 2004). However, the solving process can sometimes find solutions that can be proven as at least feasible, i.e., within a confirmed solution space where model constraints are mathematically satisfied. With this in mind, all experiments were limited to one hour of solving time and the best feasible solution found in this timeframe was reported and interpreted.

Table 15. Profiles used in the Preference Profiles Tests

Profile Name	Description	Decision Variable, α_x†
Standard* *profile also applied to all nurses in Baseline and FTE Tests	All-inclusive penalisation of adverse shift assignments according to integration of results from Study 1 and Study 2. Applicable to all nurses who don't otherwise have specific shift or scheduling preferences.	$\alpha_9 = 125$ ('large') $\alpha_1 = 25$ ('moderate') $\alpha_2 = 25$ ('moderate') $\alpha_3 = 125$ ('large') $\alpha_4 = 25$ ('moderate') $\alpha_5 = 5$ ('small') $\alpha_6 = 25$ ('moderate') $\alpha_7 = 5$ ('small') $\alpha_8 = 1$ ('neutral')
Intense Shifts	Heavier penalisation on assignments that involve long working hours, excessive night work, and lengthy consecutive spells of working days. Applicable to nurses who prefer schedules that avoid the accumulation of fatigue or exhaustion.	$\alpha_9 = 125$ ('large') $\alpha_1 = 125$ ('large') $\alpha_2 = 125$ ('large') $\alpha_3 = 25$ ('moderate') $\alpha_4 = 25$ ('moderate') $\alpha_5 = 1$ ('neutral') $\alpha_6 = 5$ ('small') $\alpha_7 = 1$ ('neutral') $\alpha_8 = 1$ ('neutral')
Inadequate Rest	Heavier penalisation on assignments that result in interrupted rest and frequent shift rotations. Applicable to nurses who prefer schedules with adequate rest periods and are more consistent and predictable (in terms of shift type and timing).	$\alpha_9 = 125$ ('large') $\alpha_1 = 5$ ('small') $\alpha_2 = 5$ ('small') $\alpha_3 = 5$ ('small') $\alpha_4 = 5$ ('small') $\alpha_5 = 125$ ('large') $\alpha_6 = 25$ ('moderate') $\alpha_7 = 125$ ('large') $\alpha_8 = 1$ ('neutral')
Social Disruption	Heavier penalisation on assignments that can impact work-life balance, such as having too many working days or shifts that interrupt traditional social periods. Applicable to nurses who prefer schedules that enable longer periods away from work.	$\alpha_9 = 125$ ('large') $\alpha_{10} = 1$ ('neutral') $\alpha_1 = 1$ ('neutral') $\alpha_2 = 125$ ('large') $\alpha_3 = 5$ ('small') $\alpha_4 = 25$ ('moderate') $\alpha_5 = 5$ ('small') $\alpha_6 = 5$ ('small') $\alpha_7 = 5$ ('small') $\alpha_8 = 125$ ('large')

† $\alpha_1 =$ penalty assigned to long shift deviations, δ_i^1; $\alpha_2 =$ penalty assigned to night shift deviations, δ_i^2 ;

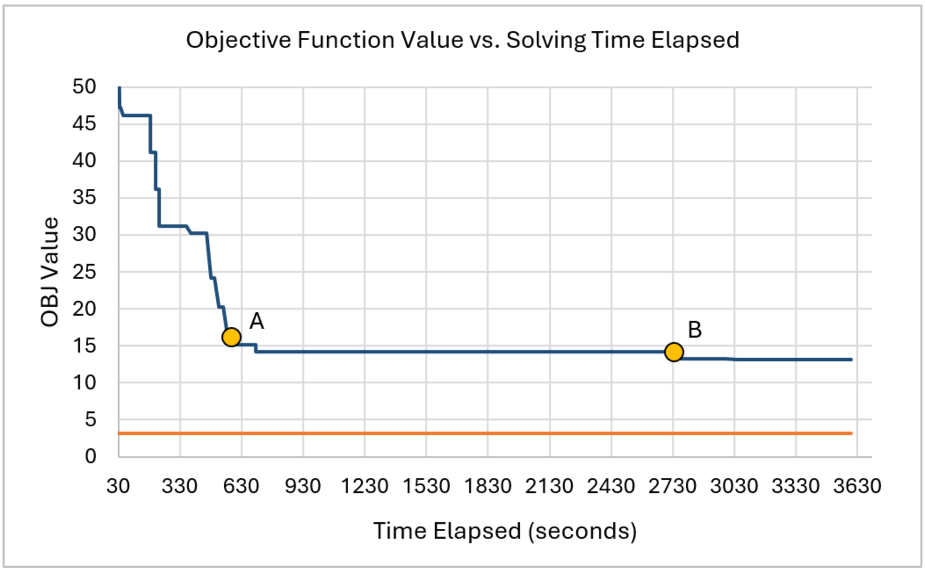
α_3 = penalty assigned to intense spell deviations, δ_i^3; α_4 = penalty assigned to long spell deviations, δ_i^4;
α_5 = penalty assigned to night-to-day rotation deviations, δ_i^5; α_6 = penalty assigned to short return deviations, δ_i^6;
α_7 = penalty assigned to day-to-night deviations, δ_i^7; α_8 = penalty assigned to weekend shift deviations, δ_i^8;
α_9 = penalty assigned to any overtime assigned, δ_i^9;α_{10} = penalty assigned to sum of all shifts assigned, δ_i^{10}

6.3 Results

6.3.1 Baseline test

In terms of model performance, the objective function value (i.e., the sum of all hours assigned and penalties incurred) reduced drastically within the first 30 seconds. Figure 10 shows further reductions made up until the maximum solving time; the final solution value of 13.18 was achieved at the 45 minute mark (point B). Based on this reference point, an 'acceptable' value of 15.18 was achieved around the 10 minute mark (point A).

Figure 10. Reductions in objective function value (baseline test)



The lower bound of the solution was 3.18 (orange line in Figure 10), which represented the sum of all the hours assigned across all 28 days and 24 nurses (3180 hours). In terms of the solution's staffing blocks, 87% of blocks achieved planned targets exactly. All other blocks were either staffed with 1 extra (11% of blocks) or 2 extra (2% of blocks) nurses, summing to a total of 66 'overstaffed' hours across the whole schedule, which is less than the equivalent of a 0.5 FTE nurse (75 monthly hours). This excess is relatively acceptable, given that total staffing hours were minimised and all nurses were assigned their exact contracted hours.

Figure 11 visualises the model solution in terms of the shifts assigned to each nurse. In these individualised schedules, day shifts (green) and night shifts (blue) are each labelled by shift type number, with darker shades indicating longer shift lengths. Overall, proportions for the different shift types used by the model were generally evenly distributed: long days (07:00-19:30, N=87, 28%), 10-hour days (07:00-17:00, N=60, 19%), 8-hour lates (13:00-21:00, N=35, 11%), 8-hour earlies (09:00-17:00, N=21, 7%), 6.5-hour lates (13:00-19:30, N=25, 8%), 6.5-hour earlies (07:00-13:30, N=28, 9%). Night and weekend shifts were distributed equitably across the team, though some nurses (i.e., nurse 1, 3, 5, 6, and 15) had no night shifts assigned. While this experiment was not designed to include individual preferences for specific shift types, this outcome serves as a useful proxy for nurses who prefer to avoid working night shifts altogether. The penalty value of the model was 10; these penalties arose from 10 day-to-night rotations (i.e., changing from a day shift to a night shift within a 7-day period), with one assigned to each of 10 nurses. No other adverse shift configurations (i.e., those with higher penalties) were assigned, and this confirmed that the model was able to successfully generate shift patterns that incorporate nurses' general shift/scheduling preferences, as well as minimise configurations that negatively impact their wellbeing and work-life balance.

Figure 11. Baseline test solution – nurses' individual rosters*

Nurse	FTE	Week	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	1.0 FTE	Week 1	6		4	3	4	2	
		Week 2	5		4	5	3		4
		Week 3		6			5		
		Week 4		4		5		5	6
2	1.0 FTE	Week 1				6	6	5	5
		Week 2		6	5		6		6
		Week 3	5	6	5				
		Week 4			7	7			
3	1.0 FTE	Week 1	5	6	3				6
		Week 2	6		6	3		6	
		Week 3		3			5		
		Week 4	6		5	1	3	2	
4	1.0 FTE	Week 1	7	7		7			
		Week 2				6	6	5	
		Week 3	6	4	2		1		2
		Week 4	1	2	2		5		3
5	1.0 FTE	Week 1		6	6		5		6
		Week 2	4		6	4			6
		Week 3			2	6	3		5
		Week 4	5	2				4	
6	1.0 FTE	Week 1	3	4	1	6	6		
		Week 2		6		4			
		Week 3			5	6	4	6	
		Week 4	5			5	1	6	
7	1.0 FTE	Week 1	1		6	4	5		5
		Week 2		7		7	7		
		Week 3					6	4	5
		Week 4		6	6			5	
8	1.0 FTE	Week 1	7		7				
		Week 2				1	4	6	6
		Week 3		6	4	1	2	6	
		Week 4	6	1	4			7	
9	1.0 FTE	Week 1						5	6
		Week 2		6	1	4	4		
		Week 3	6		1	5	4		4
		Week 4	5	7			7	7	
10	1.0 FTE	Week 1	1	2	2	6		4	4
		Week 2	6	1			7		7
		Week 3		7					
		Week 4		5	5	2	6	1	
11	1.0 FTE	Week 1		5	5	5		6	
		Week 2		4	3	5	6		
		Week 3	1		7	7		7	
		Week 4						6	6
12	1.0 FTE	Week 1		7		7		7	
		Week 2						6	5
		Week 3	6		6	6	1		
		Week 4		3	5	5	4		5
13	1.0 FTE	Week 1			5	1	6	2	
		Week 2		5	5		5	3	5
		Week 3	5	2		6			7
		Week 4	7		7				
14	1.0 FTE	Week 1							5
		Week 2	5	6	4	1			5
		Week 3		6	6	4		6	
		Week 4		5		7	7		7
15	1.0 FTE	Week 1		1		5	5	3	6
		Week 2	6		6	5		6	
		Week 3	4	1			6		3
		Week 4	4				6		
16	1.0 FTE	Week 1	4	6		2	3	6	
		Week 2	5	3			1	5	
		Week 3	3	7	7		7		
		Week 4					4	2	4
17	0.8 FTE	Week 1	5						
		Week 2	7		7	7			
		Week 3				3		3	6
		Week 4			6	6		1	6
18	0.8 FTE	Week 1	2	6					
		Week 2		7	7			7	
		Week 3						5	1
		Week 4	6		1	4	5		5
19	0.8 FTE	Week 1					7	7	
		Week 2	7						
		Week 3		6	3			5	6
		Week 4		1	4	6	6		
20	0.8 FTE	Week 1			7		7		7
		Week 2							6
		Week 3	2		1	2		6	6
		Week 4	2	6	1				
21	0.5 FTE	Week 1							7
		Week 2							7
		Week 3	7						
		Week 4				6		6	6
22	0.5 FTE	Week 1	2	3			2	5	
		Week 2	1						
		Week 3	7			7	7		
		Week 4							
23	0.5 FTE	Week 1							
		Week 2	2	2		2	5	4	
		Week 3							
		Week 4	7	7					7
24	0.5 FTE	Week 1	6		6			6	
		Week 2						7	
		Week 3						7	7
		Week 4							

* Day shifts are highlighted in green whereas night shifts are highlighted in dark blue; each assigned shift is labelled by shift type number, with darker shades indicating longer shift lengths. Shift types included 1 = 6.5 hours (early day – 07:00-13:30); 2 = 6.5 hours (late day – 13:00-19:30); 3 = 8 hours (early day – 09:00-17:00); 4 = 8 hours (late day – 13:00-21:00); 5 = 10 hours (day – 07:00-17:00); 6 = 12.5 hours (day – 07:00-19:30); 7 = 12.5 hours (night – 19:00-07:30).

6.3.2 FTE tests

As previously stated, the purpose of these experiments was to further assess the model's capacity to produce ergonomic shift patterns when the number of available staff increases across 20 randomly-generated ward instances. Table 16 and Table 17 contain performance and solution summaries for small and large ward instances respectively. To facilitate interpretation of solutions, the model's objective function was adjusted to subtract the total assigned hours; therefore any positive objective values returned represented the penalty value of the solution.

Table 16. Performance/solution summary for 'small' ward experiments

Instance		Performance			Solution			Shift Types Assigned (N)						
Ward Name	N Staff	Obj Value	Lower Bound	Time in H:M:S	N Shifts	N Hours	N Pen	1	2	3	4	5	6	7
s_h_0	6	243	0	1:00:00	90	900	23	31	3	0	3	3	22	28
	7	4	0	1:00:00	98	1019.5	4	20	3	0	5	18	22	30
	8	0	0	0:01:27	100	1069.5	0	11	2	0	10	23	24	30
s_h_1	8	8	0	1:00:00	121	1200	8	15	5	10	30	5	28	28
	9	6	0	1:00:00	131	1286.5	6	16	4	13	35	6	29	28
	10	5	0	1:00:00	142	1377.5	5	18	4	12	42	9	29	28
s_h_2	19	144	4	1:00:00	297	2850	48	59	15	3	85	9	42	84
	20	97	0	1:00:00	305	2957	35	51	18	6	86	11	47	86
	21	15	0	1:00:00	302	3048.5	15	28	12	9	83	29	56	85
s_h_3	12	474	0	1:00:00	172	1800	42	42	2	16	2	2	52	56
	13	12	0	1:00:00	191	1939.5	12	36	11	13	10	25	40	56
	14	8	0	1:00:00	193	1995	8	29	7	17	10	32	42	56
s_h_4	5	5	0	1:00:00	73	750	5	12	4	0	12	5	12	28
	6	3	0	1:00:00	80	825	3	10	6	0	12	10	13	29
	7	0	0	0:01:30	87	913	0	7	4	0	13	20	15	28
s_s_0	17	188	0	1:00:00	252	2550	40	33	31	23	25	0	28	112
	18	32	0	1:00:00	260	2637.5	20	28	36	23	25	5	31	112
	19	19	0	1:00:00	264	2725	15	27	31	18	23	17	35	113
s_s_1	26	830	0	1:00:00	380	3901*	120	67	30	0	41	33	41	168
	27	194	0	1:00:00	395	3987.5	66	70	29	6	52	38	32	168
	28	149	0	1:00:00	405	4075	56	75	31	0	57	38	36	168
s_s_2	26	2940	1480	1:00:00	369	3910.5*	124	30	76	0	13	3	79	168
	27	559	0	1:00:00	396	4032.5	84	44	61	0	55	16	52	168
	28	135	0	1:00:00	408	4113.5	49	47	60	2	64	19	48	168
s_s_3	11	59	0	1:00:00	167	1650	20	51	0	0	27	4	1	84
	12	21	0	1:00:00	174	1750	13	44	3	0	29	5	9	84
	13	10	0	1:00:00	181	1850	10	34	7	0	27	18	11	84
s_s_4	15	29	0	1:00:00	211	2250	17	9	22	0	12	59	24	85
	16	12	0	1:00:00	219	2325.5	12	10	24	0	14	58	28	85
	17	7	0	1:00:00	223	2419.5	7	3	20	0	15	65	35	85

* = overtime hours assigned (i.e., some full-time nurses assigned 0.5-2 hours above their contract)

Table 17. Performance/solution summary for 'large' ward experiments

Instance		Performance			Solution			Shift Types Assigned						
Ward Name	N Staff	Obj Value	Lower Bound	Time in H:M:S	N Shifts	N Hours	N Pen	1	2	3	4	5	6	7
l_h_0	38	226	8	1:00:00	587	5700	68	115	21	0	172	19	120	140
	39	146	4	1:00:00	593	5783.5	54	107	26	1	172	21	126	140
	40	99	0	1:00:00	594	5889	46	93	20	0	174	30	136	141
l_h_1	19	108	0	1:00:00	284	2850	39	48	16	0	38	58	38	86
	20	50	0	1:00:00	288	2950	25	36	16	0	39	65	48	84
	21	13	0	1:00:00	287	3029	13	22	13	0	38	71	58	85
l_h_2	23	131	4	1:00:00	366	3450	43	87	23	9	86	15	62	84
	24	77	0	1:00:00	369	3527	31	74	24	11	89	19	67	85
	25	42	0	1:00:00	376	3647	22	66	18	15	92	27	72	86
l_h_3	31	344	20	1:00:00	509	4650	80	194	3	0	114	7	79	112
	32	195	16	1:00:00	512	4740	62	185	2	0	114	10	89	112
	33	79	12	1:00:00	515	4888	38	152	3	0	116	39	92	113
l_h_4	26	141	0	1:00:00	400	3900	51	73	25	0	91	41	58	112
	27	96	0	1:00:00	405	3970.5	40	68	26	0	94	42	63	112
	28	69	0	1:00:00	413	4074.5	33	64	30	4	88	44	71	112
l_s_0	33	3423	2180	1:00:00	435	4957.5*	152	65	5	0	10	6	153	196
	34	759	0	1:00:00	503	5097	88	129	12	0	71	10	85	196
	35	150	0	1:00:00	518	5164.5	58	136	12	1	84	16	73	196
l_s_1	35	2083	37	1:00:00	520	5253.5	153	100	86	1	13	27	97	196
	36	461	0	1:00:00	547	5395.5	95	110	73	0	52	44	72	196
	37	198	0	1:00:00	556	5470	74	112	71	5	56	43	73	196
l_s_2	23	624	0	1:00:00	345	3451.5	65	87	21	0	44	6	47	140
	24	171	0	1:00:00	360	3576	47	85	22	0	56	12	45	140
	25	68	0	1:00:00	359	3625	31	74	14	0	61	24	45	141
l_s_3	32	3166	1295	1:00:00	452	4811*	144	55	67	0	21	5	108	196
	33	516	0	1:00:00	491	4939.5*	82	83	62	0	64	16	70	196
	34	162	0	1:00:00	502	5039	62	77	62	1	75	24	67	196
l_s_4	52	5067	2100	1:00:00	690	7810.5	246	36	70	34	4	3	235	308
	53	2109	0	1:00:00	755	7950	159	84	83	48	56	7	169	308
	54	248	0	1:00:00	806	8089.5	88	126	86	51	102	10	123	308

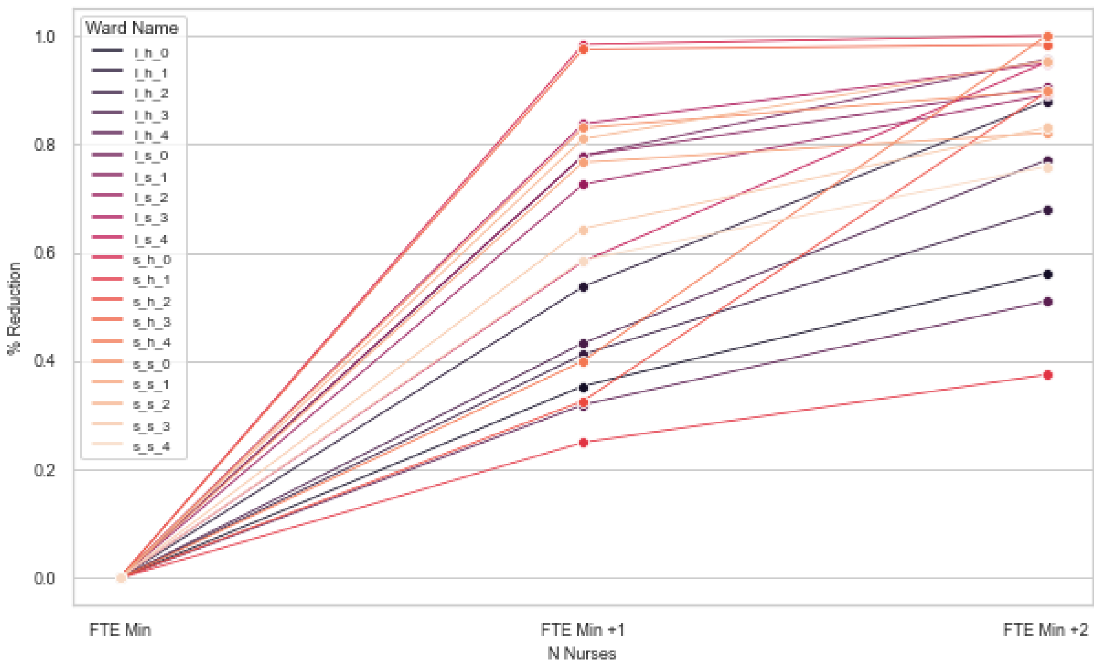
* = overtime hours assigned (i.e., some full-time nurses assigned 0.5-2 hours above their contract)

While some *FTE min* solutions had lower bounds with high values, the majority of *FTE min +1* and *FTE min +2* solutions had a bound of zero, indicating that in these instances a solution without incurred penalties was potentially possible. Overall, solutions for wards using similar day/night staffing configurations incurred significantly higher penalty counts and values compared to solutions for wards using halved day/night staffing configurations. This outcome is expected, as the increased number of required night shifts inherently raises the likelihood of violations for constraints involving this shift type, including number of long shifts, consecutive working spells, shift rotations, and short returns.

Across instances, the addition of nurses beyond the absolute minimum led to substantial reductions in penalties. As shown in Figure 12, the percentage reduction in objective function value was notably steep when comparing *FTE min* with *FTE min+1* solutions. These extra nurses were assigned a mean of 106.75 hours (SD=27.35) and a median of 9.5 shifts (IQR 7-13.25), with differences observed when comparing the means of small and large wards (101.05 vs 112.45 hours; 8 vs 11 shifts), as well as wards with halved day/night versus similar day/night staffing configurations (94.85 vs 118.65 hours; 8.5 vs 12.5 shifts). Inspection of the penalties incurred in *FTE min+1* solutions revealed distinct patterns, where wards using halved day/night staffing configurations yielded only rotation-related penalties (most of which were day-to-night rotations), while wards using similar day/night configurations additionally sustained some long shift, night shift, and short return penalties.

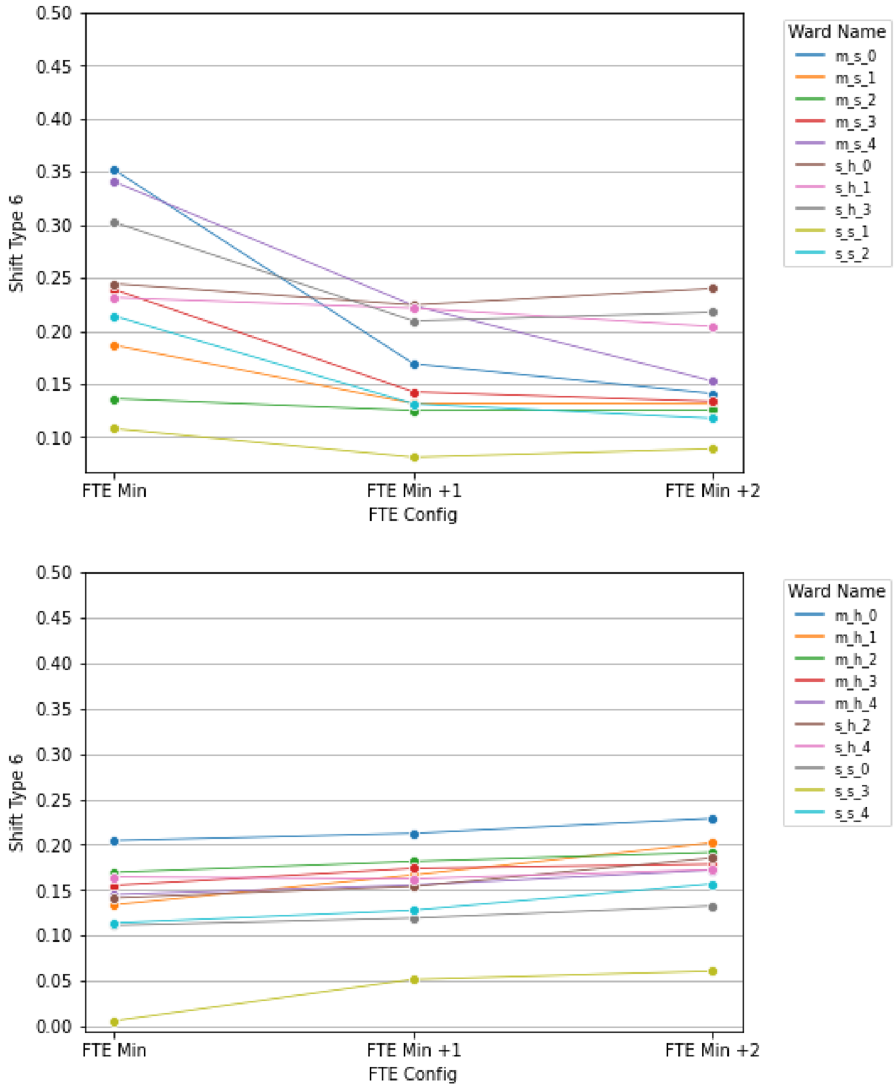
While these results are interpreted with caution as optimality could not be proven (i.e., the model could not prove that the solution was mathematically optimal within a reasonable timeframe), adding one nurse above the minimum requirement nevertheless prevented the assignment of several adverse shift configurations. The addition of a second nurse to the available staffing total led to further penalty reductions, however improvements were less pronounced.

Figure 12. FTE Tests - % reduction of penalty values when adding 1, 2 nurses



In 10 of the wards, the proportion of shift type 6 (12.5-hour day shifts) decreased when comparing *FTE Min* with *FTE Min+1* and *FTE Min+2* solutions. As demonstrated in Figure 13, wards m_s_0 and m_s_4 had the largest reductions; in these instances long day shifts were replaced with 6.5-hour earlies (07:00-13:30) and 8-hour lates (13:00-21:00). In contrast, in wards where the proportion of 12.5-hour day shifts increased with each additional nurse, these changes were more subtle and were complemented by increases in the proportion of 10-hour day shifts (07:00-17:00). Therefore, increases in staffing numbers enabled more flexible scheduling options, reducing over-reliance on long shifts in favour of shorter shift lengths.

Figure 13. FTE Tests - change in % of shift type 6 (long day shifts) when adding nurses



6.3.3 Preference Profile test

The lower bound for each solution was 52 (case A, where the penalty associated with number of shifts assigned was set to neutral) and 1216 (case B, where the penalty was set to moderate), which each represented the number of shifts assigned to the four 'social disruption' nurses (52 shifts (A), 48 shifts (B)). Final feasible solution values of 66 and 1230 were achieved around the 30-minute mark, indicating that both instances incurred a small number of penalties. While both solutions were feasible, case A returned slightly more overstaffed blocks and no overtime, whereas case B returned fewer overstaffed blocks and 1.5 hours of overtime.

Solution rosters are visualised in Figure 14 and Figure 15. Table 18 further compares the shift types assigned in Baseline versus Preference Profile tests for nurses who were assigned a new penalty profile. Considerable changes in shift types assigned were noted, particularly for 'social disruption' nurses. For example, Nurse 1 had a 25% reduction in the total number of shifts assigned, and when comparing case study A and B solutions, a mix of 10-hour and 12-hour day shifts were replaced with exclusively 12-hour days. This change resulted in the assignment of four long shifts above threshold, indicating that these penalties served as a trade-off for minimising the number of working days. While this arrangement theoretically meets the needs of nurses who prefer fewer working days and longer breaks between shifts, working exclusively long shifts poses risks to wellbeing, as evidenced in Study 2 (section 5.3.3). Notably, the only other penalties incurred were rotation-related, none of which were assigned to nurses in the 'inadequate rest' profile. This reinforced the model's capacity to assign ergonomic shift patterns while also accommodating nurses' preferences for scheduling.

Table 18. Solution comparison for nurses with altered penalty profiles

			Shift Types								
Nurse	Solution	Profile	1	2	3	4	5	6	7	Tot	Penalties Incurred
1 (1.0 FTE)	Baseline	Standard	0	1	2	5	5	3	0	16	none
	PP - Case A	Social Disruption	0	0	0	0	5	5	3	13	1 night-to-day rotation
	PP - Case B		0	0	0	0	0	12	0	12	4 long shifts > threshold
2 (1.0 FTE)	Baseline	Standard	0	0	0	0	5	6	2	13	none
	PP - Case A	Social Disruption	0	0	0	0	5	8	0	13	none
	PP - Case B		0	0	0	0	0	9	3	12	4 long shifts > threshold, 1 night-to-day rotation
3 (1.0 FTE)	Baseline	Standard	1	1	4	0	3	6	0	15	none
	PP - Case A	Intense Shifts	0	1	2	0	4	4	3	14	1 night-to-day rotation
	PP - Case B		0	0	3	3	4	2	3	15	1 day-to-night rotation
5 (1.0 FTE)	Baseline	Standard	0	2	1	3	3	6	0	15	none
	PP - Case A	Inadequate Rest	1	3	3	0	5	0	0	16	none
	PP - Case B		1	4	3	2	4	3	0	17	none
7 (1.0 FTE)	Baseline	Standard	1	0	0	2	4	4	3	14	1 day-to-night rotation
	PP - Case A	Intense Shifts	0	1	0	2	4	4	3	14	1 day-to-night rotation
	PP - Case B		2	3	3	2	4	3	0	17	none
10 (1.0 FTE)	Baseline	Standard	3	3	0	2	2	3	3	16	1 day-to-night rotation
	PP - Case A	Inadequate Rest	1	0	1	1	4	5	2	14	none
	PP - Case B		0	1	2	0	4	5	2	14	none
13 (1.0 FTE)	Baseline	Standard	1	2	1	0	6	2	3	15	1 day-to-night rotation
	PP - Case A	Social Disruption	0	0	0	0	5	8	0	13	none
	PP - Case B		0	0	0	0	0	0	12	12	4 long shifts > threshold
14 (1.0 FTE)	Baseline	Standard	1	0	0	2	4	4	3	14	1 day-to-night rotation
	PP - Case A	Social Disruption	0	0	0	0	5	8	0	13	none
	PP - Case B		0	0	0	0	0	0	12	12	4 long shifts > threshold
15 (1.0 FTE)	Baseline	Standard	2	0	2	2	3	6	0	15	none
	PP - Case A	Intense Shifts	2	1	0	1	6	2	0	15	1 night-to-day rotation
	PP - Case B		1	1	2	2	3	3	3	15	1 day-to-night rotation
18 (0.8 FTE)	Baseline	Standard	2	1	0	1	3	2	0	12	none
	PP - Case A	Inadequate Rest	0	1	2	0	1	4	3	11	none
	PP - Case B		1	0	0	2	1	4	3	11	none
21 (0.5 FTE)	Baseline	Standard	0	0	0	0	0	3	3	6	none
	PP - Case A	Intense Shifts	1	2	0	1	1	0	3	8	none
	PP - Case B		0	0	0	0	0	3	3	6	none
22 (0.5 FTE)	Baseline	Standard	1	2	1	0	1	0	3	8	none
	PP - Case A	Inadequate Rest	0	0	0	0	0	3	3	6	none
	PP - Case B		3	0	0	1	1	0	3	8	none

Figure 14. Preference Profiles Test – case A solution – nurses' individual rosters*

Nurse 1 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6			5	6		
Week 2	5	6	5				
Week 3			7		7		7
Week 4				5	6	5	6

Nurse 2 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		5	6	6		5	
Week 2				5	6	5	6
Week 3		5	6		6	6	
Week 4					6		

Nurse 3 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			7			7	7
Week 2			6	5	5	3	
Week 3			3	5	6	5	
Week 4	6	2	6				

Nurse 4 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1					5	5	4
Week 2		6		1	6		6
Week 3	5	3	1	4		3	
Week 4	7	7			7		

Nurse 5 | 1.0 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	3		3	2		5	6
Week 2		2			1	6	
Week 3	5	2			3		6
Week 4	5	5		6	5		

Nurse 6 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		6	4	6	7		
Week 2	7	7					
Week 3		4		6		4	3
Week 4	3			1	3	6	4

Nurse 7 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	5	4	2	5	6		
Week 2			5	7		7	7
Week 3							6
Week 4		5	4	6		6	

Nurse 8 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			5	3	4		6
Week 2	4			6		4	6
Week 3	6		6		4		7
Week 4		7	7				

Nurse 9 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1				6	3	6	3
Week 2			6	6	3		4
Week 3	4	6				5	
Week 4	7		7	7			

Nurse 10 | 1.0 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6	6	5				
Week 2			7	7			
Week 3				6	5	6	6
Week 4		1	5	3		4	5

Nurse 11 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	7						
Week 2	6	4	1	3			5
Week 3	5	1		3	6		5
Week 4	4			6	7		7

Nurse 12 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	4	6			6	6	
Week 2		5	4	6	4		3
Week 3		7	7		7		
Week 4					4		6

Nurse 13 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6					6	
Week 2	6		5			6	
Week 3	6	5			6		6
Week 4	5		5		5	6	

Nurse 14 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			6		5		6
Week 2	6				6	5	
Week 3				6	5		5
Week 4			5	6	6		6

Nurse 15 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		5	1	5	1	6	
Week 2	5	5					
Week 3		7		7		7	
Week 4		2	5	4		6	5

Nurse 16 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		6	4			4	5
Week 2	5	6		2	4		
Week 3	6		4	5		6	
Week 4			2		6		6

Nurse 17 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		7			7	7	
Week 2						6	5
Week 3		6	4	1			4
Week 4	6	6					

Nurse 18 | 0.8 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	7	7					
Week 2		3	6		5	6	
Week 3	6	2			3	6	
Week 4						7	

Nurse 19 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6		6	4	2		
Week 2					7		7
Week 3	7						
Week 4		5	6	6		3	

Nurse 20 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1							5
Week 2	6	1	2	4			6
Week 3		5	5	2			
Week 4				7		7	7

Nurse 21 | 0.5 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			7	7			7
Week 2							
Week 3			5			2	
Week 4	1	4	2				

Nurse 22 | 0.5 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		6					6
Week 2							
Week 3	7			7		7	
Week 4						6	

Nurse 23 | 0.5 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1				7			
Week 2		7	7				
Week 3			6				
Week 4	6	6					

Nurse 24 | 0.5 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	5						
Week 2	7				7	7	
Week 3							
Week 4	2	1	1				3

* Day shifts are highlighted in green whereas night shifts are highlighted in dark blue; each assigned shift is labelled by shift type number, with darker shades indicating longer shift lengths. Shift types included 1 = 6.5 hours (early day – 07:00-13:30); 2 = 6.5 hours (late day – 13:00-19:30); 3 = 8 hours (early day – 09:00-17:00); 4 = 8 hours (late day – 13:00-21:00); 5 = 10 hours (day – 07:00-17:00); 6 = 12.5 hours (day – 07:00-19:30); 7 = 12.5 hours (night – 19:00-07:30).

Figure 15. Preference Profiles Test – case B solution – nurses' individual rosters*

Nurse 1 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1				6	6		6
Week 2	6		6				6
Week 3		6		6			6
Week 4			6		6	6	

2 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			6	6		6	
Week 2	6	6			6		
Week 3	6		6	6			
Week 4				7		7	7

3 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	5			5	3		3
Week 2	6	4	5		4	3	
Week 3	7	7			7		
Week 4					4	6	5

4 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		4	3		5	4	5
Week 2		3	5	6			2
Week 3	6	1			6	7	
Week 4	7	7					

5 | 1.0 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	1	5	2		4	5	
Week 2		2	6		5		3
Week 3				2	5		3
Week 4	4	6		2	3		6

6 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	1	3	1	7	7		
Week 2	7						
Week 3	4	5	4	3			6
Week 4	2		6	3	5	3	

7 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	4	2	2			6	6
Week 2	3	5	3		1		6
Week 3	5	2				4	
Week 4	1	3		5	5		

8 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	5	7			7	7	
Week 2						6	5
Week 3	5	6	5		6		
Week 4	6	4			4		2

9 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1					5	5	6
Week 2	5			6	6		
Week 3	6	5	5			6	
Week 4	7			7	7		

10 | 1.0 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			7	7			
Week 2				6	3	6	5
Week 3	3		2	5		5	6
Week 4	6	5	6				

11 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	3		4	5		3	4
Week 2	5	5		5	5		4
Week 3	7			7	7		
Week 4					6		5

12 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			6		6	6	5
Week 2	4	6		4		4	
Week 3		4	6		4	7	
Week 4		7	7				

13 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		6			6		6
Week 2			6		6	6	
Week 3		6			6	6	
Week 4	6		6				6

14 | 1.0 FTE | social conflicts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1		6		6		6	
Week 2	6	6		6			
Week 3	6					6	6
Week 4		6		6		6	

15 | 1.0 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	7		7				
Week 2			4	6		5	6
Week 3		6	3	5	2		4
Week 4	3	5	1				7

16 | 1.0 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6	5	5				7
Week 2		7	7				
Week 3			1	6	6	5	
Week 4	5		4	6			4

17 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	7	7					
Week 2		1		3	4	6	1
Week 3			6	6	3	3	
Week 4						7	

18 | 0.8 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1						7	
Week 2		7		7			
Week 3				4	1	6	5
Week 4		6	4		6	6	

19 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	2	6	1	3			
Week 2				7		7	7
Week 3							5
Week 4	5	6		5		2	

20 | 0.8 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	6	5		4	6		
Week 2					7	7	
Week 3			7				
Week 4			5	6		4	5

21 | 0.5 FTE | intense shifts

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1						6	
Week 2			6			6	
Week 3							7
Week 4			7		7		

22 | 0.5 FTE | inadequate rest

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1							7
Week 2							7
Week 3			7				
Week 4			4	1	1	5	1

23 | 0.5 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1			6	6			
Week 2					7		
Week 3				7			7
Week 4							6

24 | 0.5 FTE | standard

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Week 1	2						
Week 2	7		7				
Week 3		7					
Week 4			1	4		5	1

* Day shifts are highlighted in green whereas night shifts are highlighted in dark blue; each assigned shift is labelled by shift type number, with darker shades indicating longer shift lengths. Shift types included 1 = 6.5 hours (early day – 07:00-13:30); 2 = 6.5 hours (late day – 13:00-19:30); 3 = 8 hours (early day – 09:00-17:00); 4 = 8 hours (late day – 13:00-21:00); 5 = 10 hours (day – 07:00-17:00); 6 = 12.5 hours (day – 07:00-19:30); 7 = 12.5 hours (night – 19:00-07:30).

6.4 Discussion

Using the results and insights derived from Study 1 and 2, the aim of this final study was to develop a mathematical optimisation model that generates nursing team rosters with shift assignments that inherently accommodate nurses' wellbeing and preferences for working time. The model successfully produced feasible schedules across multiple experimental scenarios within one hour of solving time – a significant improvement compared to the time-intensive process of creating initial roster drafts using traditional/manual methods.

Previous research studying the Nurse Scheduling Problem (NSP) primarily focuses on developing new solution techniques and algorithms to achieve more computationally efficient solutions (Drake, 2014a). In contrast, this study sought to create a novel model formulation for nurse scheduling by incorporating elements relevant to nurse deployment in practice, including more varied options for shift types, more realistic representations of coverage across the 24-hour ward day, and more constraints designed to limit the assignment of adverse shift configurations. This study therefore fills two research gaps identified in Chapter 2 (Literature Review): 1) the need for scheduling models that are formulated with real-world considerations and data, and 2) the need for actionable guidance for creating 'ideal' and 'optimised' nurse rosters that go beyond solely meeting service-demand.

As previously discussed, the use of long shifts in nursing is controversial, as its assumed benefits (e.g., fewer working days, improved work-life balance, reduced staffing costs) often clash with documented drawbacks (increased fatigue, burnout, and sickness absence) (Dall'Ora, Ejebu and Griffiths, 2022). Across all solutions, a more equitable distribution of shift types was used, confirming that the introduction of more unique shift lengths (e.g., 6.5 hour shifts, 10 hour shifts) allowed greater flexibility in resulting shift patterns. This contrasts the findings of the historical roster data analysed as part of Study 2, where >75% of all recorded day shifts lasted 12 hours or longer. Furthermore, the majority of adverse shift configurations present in the historical data – excessive night work, intense/long spells of working days, inadequate rest periods between consecutive shifts – were not assigned in the Baseline solution. FTE test solutions further emphasise the benefits of this model's formulation, particularly in terms of changes in penalties when nurse numbers were increased. The addition of a single nurse working around 100 hours/10 shifts often led to considerable decreases in penalties, demonstrating that this allocation was a relatively reasonable adjustment for improving roster quality. Popular methods for estimating the size of nursing teams in NHS acute wards, such as those described by Hurst (2003) (e.g., the professional judgement method, the nurses per occupied-bed method, the acuity-quality method) usually include uplift calculations to account for expected leave and sickness rates. However, given ongoing efforts to improve nurses' working conditions (which includes the organisation of their working hours), these results show the potential value of also integrating shift pattern ergonomics into nursing establishment planning.

Another innovative feature of this methodology was the incorporation of preference profiles in the last phase of experiments. Unlike previous models that treat shift preferences as individual requests for days on or off, this model incorporated broader preferences by creating categories that capture nurses' varied scheduling requirements. This approach signals a potential change in the way shift preferences could be managed during the scheduling process, where strategies that anticipate nurses' recurring needs replace continuous/reactive modifications. Adjustment of penalty values in the Preference Profile tests led to significant changes in shift assignments for nurses allocated to the 'social disruption' profile, which valued schedules that had longer rest periods. Ultimately, the use of lower penalty values effectively reduced working days while also avoiding fatigue-inducing shift configurations. Previous research that introduced work-time control for shift working health care staff – e.g., through self-rostering or participatory/team rostering methods - reported increased choice of more 'adverse' shift assignments, such as longer shift lengths and more night work (Karhula *et al.*, 2020). The method explored here alternatively provides a structured approach to respecting nurses' working time preferences while minimising difficult shift assignments and safeguarding coverage requirements.

6.4.1 Limitations

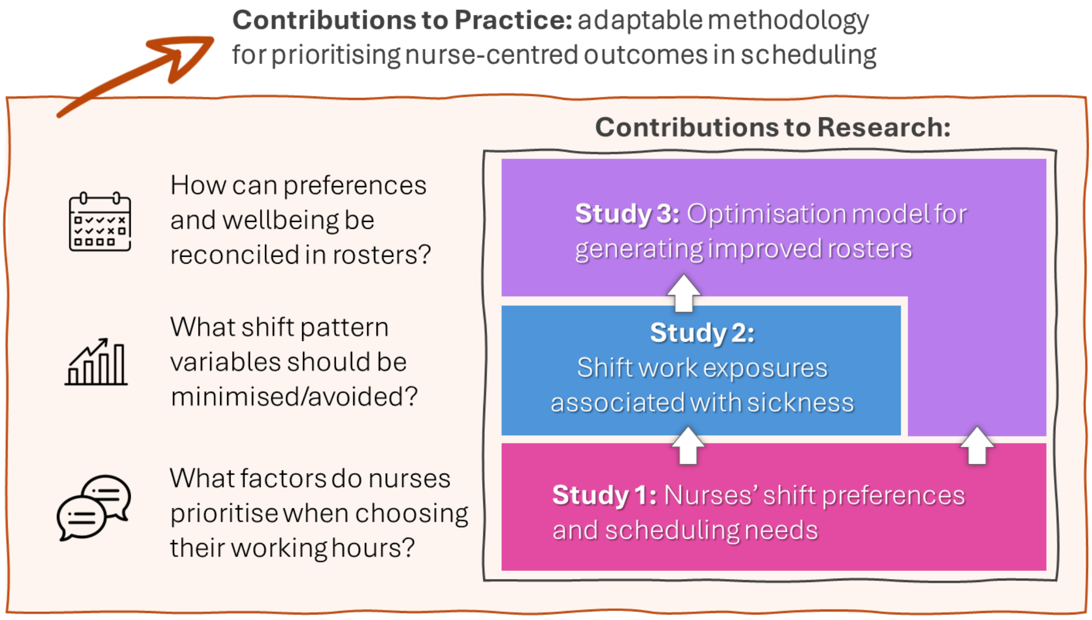
First, the solutions generated in this study were feasible but could not be proven to be optimal, necessitating careful interpretation of results. Future research could employ more advanced solving techniques that are primed for handling problems with large variable counts, such as column generation (i.e., a solving algorithm that explores only the most promising variables, or 'columns'), or metaheuristics (e.g., genetic algorithms, simulated annealing, tabu search). Such developments could further enhance this model's applicability, supporting its use in settings where rapid solution turnaround times are necessary.

Second, the extent to which nurses are willing to adapt to new shift patterns (as shown in Figure 11, Figure 14, and Figure 15) remains uncertain. However, it is important to emphasise that this study's aim was to demonstrate the feasibility of a new model for nurse scheduling and initiate a dialogue around the value of rosters that are optimised for nurses' shift preferences and wellbeing. The model's ability to generate solutions across diverse scenarios stress its flexibility, and therefore, fine-tuning of constraints to allow for additional scheduling preferences is also likely feasible.

Chapter 7 Discussion

The overall aim of this doctoral research was to explore strategies for optimising shift patterns for nurses working in acute hospital wards. To support this aim, two research questions were developed: 1) What factors must be considered when designing optimised shift patterns, and 2) How can these factors be balanced to ensure nurses' preferences and wellbeing are equally prioritised? This final chapter first summarises the key findings from each of the three studies undertaken to address these research questions. It then explores the broader contributions of the thesis through a discussion of implications for practice, methodological strengths and limitations, and opportunities for future research. A visual summary of these points is also included in Figure 16.

Figure 16. Thesis contributions to nurse scheduling research and practice



7.1 Summary of Key Findings

Circling back to the literature gaps first identified in section 2.3, the findings of this research offer multiple individual contributions to improving nurse scheduling practices, including: a deeper understanding of frequent working time preferences among nurses, greater insight into the longitudinal effects of shift work exposures on wellbeing, and the development of a novel mathematical model for automated nurse scheduling. More specifically, studies 1 and 2 identified the key factors necessary for creating improved shift patterns, both in terms of what nurses themselves value as well as the shift configurations that should be minimised (from a wellbeing perspective) during shift planning, while study 3 confirmed that these factors could be successfully reconciled while also maintaining nurse staffing requirements.

What factors do nurses consider when expressing shift preferences? (Study 1)

> **Key Finding**: Reasons for nurses' shift preferences underscore the importance of organising schedules in ways that support a good work-life balance. Most relevantly, scheduling practices such as minimising adverse shift configurations, ensuring consistent and predictable working patterns, and facilitating control over working time were identified as enablers for nurses' various preferences and priorities.

Study 1 involved the analysis of nearly 900 survey responses from a national sample of nursing staff who were asked about their experiences and perceptions of shift work. Thematic analysis results showed that factors driving nurses' shift preferences often arose from their personal priorities outside of work, including maintaining their own health and wellbeing, protecting social time and relationships, and organising caregiving responsibilities. Importantly however, descriptive results showed that working short, long, or rotating shifts offered no clear advantages in addressing these priorities. In contrast, broader scheduling practices were repeatedly identified as enablers, including ergonomic shift planning, consistency and predictability in schedules, and working time control. As discussed in section 4.4, these practices have previously demonstrated benefits for healthcare workers in different settings and thus offer a useful starting point for developing rostering strategies that proactively integrate nurses' scheduling needs.

What shift work exposures are associated with sickness absence? (Study 2)

> **Key Finding:** Analysis of 1.4 million historical records of nurses' shifts and sickness episodes from two NHS hospital Trusts revealed that long working hours, excessive night work, consecutive working spells, and inadequate rest periods significantly increased the odds of sickness absence in weekly and monthly exposure windows.

From Study 1, nurses' specific examples of 'difficult/adverse' and 'inconsistent' shift patterns (e.g., avoiding "too many working days in a row", wanting "longer rest periods" away from work, needing "more consistent patterns of work" to make life easier to plan) were transformed into shift pattern exposure variables relevant for further exploration in Study 2. This study used logistic mixed regression models to estimate the influence of exposure variables in terms of the change in odds of a shift being cancelled due to sickness. In the 7-day model, intense consecutive spells, quick returns, and shift rotations significantly increased the odds of sickness, with quick returns and shift rotations also showing longer term effects in the 28-day model. Nonlinear analyses of the proportion of long and night shifts worked revealed that the highest proportions (≥80%) were significantly associated with the greatest odds of sickness absence in both 7-day and 28-day lookback windows.

How can scheduling reconcile nurses' preferences with wellbeing? (Study 3)

> **Key Finding:** This final study presented a new, structured approach to nurse scheduling using mathematical optimisation, i.e., where nurses' scheduling needs/preferences were weighted against the reduction of harmful shift assignments and maintenance of nurse staffing levels. Improved schedules were produced across a series of experimental scenarios, including: rostering a team of nurses with varied working hours contracts, rostering 20 randomly generated wards with varied coverage requirements and team sizes, and rostering with customised penalisation of shift assignments depending on the 'preference profile' assigned to each individual nurse.

As outlined in section 2.2.2, current methods for nurse scheduling in practice are often time-consuming, fixate on prioritising ward coverage, and usually account for nurses' working time preferences reactively (if at all). Previous research using OR methods have attempted to address these practical challenges in various ways, such as using historical data to inform the generation of new schedules (Mihaylov *et al.*, 2016), incorporating nurse preferences through priority rankings (Lin *et al.*, 2014), or adapting constraint formulation based on shift type/intensity (Nurmi, Kyngäs and Kyngäs, 2022). Given these gaps and advancements, a new nurse scheduling model was formulated that incorporated results from Study 1 and 2 as well as the shift types and nurse staffing levels used in real NHS acute care wards. This model was designed to flexibly assign which ever shift type was most appropriate to satisfy fixed time "blocks" of coverage alongside a number of shift pattern constraints. The Baseline test produced a solution that successfully minimised penalties, equitably distributed shifts, and met staffing requirements. The FTE tests further demonstrated the value of incorporating shift ergonomics into nurse establishment planning, particularly for reducing over-reliance on 12-hour shifts and eliminating other adverse shift configurations. The Preference Profile test enabled tailoring of penalties to accommodate varied scheduling needs, producing more individualised schedules that minimised potential conflicts by introducing new trade-offs.

7.2 Broader Contributions to Policy/Practice

7.2.1 Prioritising nurse wellbeing in scheduling

To address ongoing health workforce shortages and to safeguard the quality of patient care delivered on hospital wards, it is vital to monitor the wellbeing of the nursing workforce (Health and Safety Executive (HSE), 2006; The King's Fund, 2024). In England's NHS, two national data indicators provide valuable insight around this: 1) records of reasons for leaving the nursing workforce, and 2) rates/causes of nurses' sickness absence.

A growing number of nurses in the UK cite work-life balance as a key reason for leaving their roles (NHS Digital, 2022), highlighting the need to explore practical strategies for improving work-life balance, particularly in the context of shift schedule design. As discussed in Study 1, the concept of work-life balance is both broad and complex, encompassing diverse factors such as childcare responsibilities, personal health, and social time. These priorities often translate into varying individual shift preferences that are a challenge to equitably accommodate. This makes the case for a more comprehensive approach that enables nurses to feel a sense of balance and control over their working lives. Similarly, recent data reveal rising sickness absence rates among nurses (e.g., 4.5% in July 2019 versus 5.5% in July 2024), with anxiety, stress, depression, and other mental health conditions accounting for over 25% of FTE days lost due to illness (NHS Digital, 2024). High levels of sickness absence place considerable strain on managers and wards. Reorganising rosters to accommodate unplanned absences require added time and administrative effort, often forcing manual reassignment of shifts or the use of costly short-term staffing solutions (e.g., use of overtime or bank/agency staff). When these options are insufficient, understaffed wards pose risks to patient safety and place further strain on remaining staff.

In resource-constrained wards, ergonomic shift planning and accommodation of nurses' working time preferences are often overshadowed by the need to satisfy staffing requirements. Consequently, rosters are planned with more adverse shift configurations and patterns - long working hours, inadequate rest periods, and lengthy spells of consecutive working days - all of which are associated with higher rates of nurse sickness and dissatisfaction with working hours and work-life balance (as evidenced in Study 1 and 2). This, in turn, reduces the availability of nurses, either temporarily due to sickness or permanently as nurses leave their roles, further exacerbating ward shortages and perpetuating a negative, self-reinforcing cycle.

In contrast, this research demonstrates the feasibility of prioritising nurse wellbeing through improved scheduling practices. By analysing nurses' preferences for working time and using historical data on shift patterns linked to sickness absence, a scheduling model was developed that equally prioritised wellbeing, work-life balance, and staffing requirements. Therefore, ward managers and schedulers should take care to design rosters that minimise the use of adverse shift configurations, i.e., those associated with fatigue, increased sickness risk, and work-life balance disruption, as this will ultimately support healthier working environments and has strong potential to reduce nurse absence/turnover rates.

7.2.2 A framework for reconciling scheduling priorities

Although there are well-documented risks for nurses working shifts, shift work remains an essential component of 24-hour acute care wards. Organisations must therefore adopt scheduling policies/practices that mitigate these risks while also balancing priorities such as meeting ward staffing demands, maintaining care quality and safety, and responding to increased pressure to provide flexible working options for nurses (as discussed in section 2.3). However, these goals often conflict with one another (e.g., adequate staffing levels require increased operational costs, fulfilling nurses' shift preferences may leave critical periods understaffed), making it challenging to ensure all relevant outcomes are met.

Existing guidance from various sources offer fragmented recommendations that often lack actionable specificity. For example, general recommendations include "guarantee that staffing levels are met on a shift-to-shift basis" (McIntyre and NHS Improvement, 2016; National Quality Board, 2016), "analyse data trends on staff absenteeism and turnover and qualitative data from staff regarding fatigue and safety" (NHS Staff Council, 2020) and "ensure rostering patterns take into account best practices on safe shift working" (Royal College of Nursing, 2021a). Similarly, individual Trusts may outline policies for creating "safe" and "efficient" rosters, but these policies often lack clear definitions of these terms, and specific rules regarding ideal shift planning/ergonomics are either inconsistent or are absent (Drake, 2019). While newer rostering technologies offer the potential for more informed decision-making (e.g., e-rostering software that displays live views on patient acuity, ward demands, staff leave entitlements, and contractual working limits), their utility is limited without clear guidance on how to systematically balance these elements against one another.

In response, the findings of this thesis provide hospital policymakers a framework for integrating competing considerations - maintaining adequate nurse staffing levels, mitigating the adverse effects of shift work, and accommodating nurses' scheduling needs – in order to design rosters that are safe for patients and ergonomic for nurses. Central to this achievement was the development of a mathematical optimisation model informed by a phased approach to data collection. Therefore, through integration of both qualitative and quantitative data to inform scheduling practices, any proposed improvements to shift patterns are both grounded in nurses' experiences and are corroborated by a measurable wellbeing factor/outcome (i.e., sickness absence).

7.3 Strengths & Limitations

7.3.1 Nurse-centred scheduling strategies

In section 1.1.3, the concept of organising nurses' shift work was introduced from staff-, ward-, and organisational perspectives. While each of these perspectives was considered to some extent throughout this thesis, a core strength of this research arises from its nurse-centred approach to designing improved shift patterns. Consequently, conclusions drawn for the research questions first outlined in section 3.2.1 (i.e., What factors should be considered? How should these factors be balanced?) focused on the elements that are most pertinent to nurses' needs and experiences.

One limitation of the findings from this thesis is the absence of other nurse-specific factors that are known to influence individual shift work tolerance, such as demographic characteristics (e.g., age, gender, years of service, seniority) and latent attributes (e.g., chronotype (i.e., an individual's preferred activity-rest cycle over the 24-hour period), psychological traits, and social support) (Ritonja *et al.*, 2019). Consideration of these elements could provide a deeper understanding of how nurses respond differently to various shift patterns, particularly in terms of their resulting preferences and susceptibility to ill-health. However, rostering methods in practice often do not incorporate such detailed individual data, largely due to logistical challenges and the more immediate need to improve operational efficiency. Fortunately, nurses' expressed working time needs often reflect their personal characteristics (Ejebu, Dall'Ora and Griffiths, 2021) (e.g., tolerance of night work, wanting consistent hours) making preferences a more practical starting point for nurse-centred scheduling.

7.3.2 Work-time control

An important aspect of this research was its recognition of shift preferences as a concept that extends beyond individual requests for days on or off. Study 1 established that nurses' needs could also be accommodated through more general scheduling practices that pre-emptively safeguard ergonomic, consistent, and flexible shift assignments. Nurses in this study also often framed the concept of work-time control as an ability to choose more predictable or less difficult shift patterns, signalling that many flexible working requests could be met by a more proactive approach to scheduling. Some specific aspects of choice were also directly explored in this survey (i.e., asking nurses to what extent they are able to choose their hours, to what extent their shifts are determined by their employer, determining which nurses are having their preferences met), which provided important context for successive analysis stages.

However, variables directly related to work-time control could not be examined in the regression analysis in Study 2. Including choice as a controlling factor (e.g., whether nurses had an ‘active’ flexible working request) could have enhanced interpretation of resulting variable relationships, particularly in determining if the shift configurations worked in 7-day and 28-day exposure windows resulted from personal choice. However, even if choice could not be directly measured, associations between certain shift configurations and increased odds of sickness were still uncovered while accounting for nurse-specific behaviours (through inclusion of random effects) and other ‘choice’ related variables such as number of hours worked as ‘bank’ and the number of previous sickness episodes. Therefore, although work-time control may offer benefits in certain contexts (previously covered in sections 2.2.2.2 and 4.4), emphasis should ideally first be placed on ergonomic shift planning. Nurses’ more specific preferences for working time could be incorporated thereafter, as demonstrated through the Preference Profile Test in Study 3 of this thesis (section 6.3.3).

7.3.3 Defining working time exposures

Nurses' shift patterns are characterised by a number of linked elements, including shift length, timing, rotation, total and distribution of weekly working hours, and recovery periods. As such, research exploring the downstream effects of shift work necessitate precise definitions of exposure, both in terms of type and timing. Consequently, each shift configuration selected from Study 1 for analysis in Study 2 was defined using the framework developed by Härmä *et al.* (2015), which provided strategies for deriving accurate working time exposures from register/payroll data. Use of this framework additionally ensured that all exposure variables were multi-dimensional and primed for analysing the impact of shift work on health-related outcomes. In terms of exposure timing, both 7-day and 28-day lookback windows were chosen to capture transient and lagged effects. They also strategically aligned with practical scheduling norms, such as weekly working hour contracts and monthly roster planning cycles.

Previous research has shown the impact of other work-time variables, such as within-shift breaks and overtime hours, on staff wellbeing (e.g., burnout, fatigue, workplace injury) (Bae and Fabry, 2014; Lyubykh *et al.*, 2022). However, measuring these exposures through administrative sources is challenging as a result of multiple potential sources of variability. For example, within-shift breaks contain differences on timing during the shift, whether they are taken at all, as well as their overall quality. Similarly, the impact of overtime hours may vary depending on whether they are imposed by employers, are chosen to be worked out of a sense of obligation to patients, or if they occur as an extension of an existing shift versus separate shifts that exceed contracted hour limits. Nonetheless, it is important to note that the focus of this doctoral research was to improve the *planning* of shifts, making investigation of these post-planning working time variables out of scope.

7.3.4 Optimising Nurse Scheduling

When designing the optimisation model tested in Study 3, care was taken to align model resources and parameters with real-world deployment configurations. This was achieved through a descriptive analysis of the historical roster dataset from Study 2, which provided details on feasible shift types (i.e., lengths, start/end times) and hour-by-hour fluctuations in minimum nursing numbers. This approach was a key strength of this research phase, as it revealed how competing rostering priorities, such as compliance with legal working hour restrictions, meeting patient and service demands, and minimising costs, were reconciled in practice. In essence, alignment with this data offered a more detailed approach to model formulation that was representative of real NHS acute wards.

However, it is important to note that this formulation relied on a single-day, cross-sectional snapshot of all acute wards in the dataset. This strategy may have limited perspective on the full range of possible nurse staffing configurations and shift types, and thus could have excluded information on variations that occur on different days of the week (e.g., weekdays versus weekends) as well as seasonal fluctuations in demand (e.g., increased demand during influenza season). Nonetheless, the experiments conducted in this study demonstrated the model's capacity to derive solutions using varying team sizes, staffing blocks, and day versus night configurations. Therefore, it is plausible that with further adjustment and fine-tuning, the model could adapt to different contexts beyond the dataset used in this study. The model's foundational principles remain robust and provide an adaptable framework for improving nurse rostering while balancing operational demands.

7.4 Future Opportunities for Research

Building on the findings and contributions of this doctoral research, there are several opportunities for further development. Each of these new research avenues have the overall aim of improving scheduling practices and increasing the utility of automated rostering technologies. Specifically, this includes: incorporation of all nursing staff in optimisation modelling, deriving new exposure variables for analysing 'consistency' in historical data, further engagement with ward managers and nurses around their experiences with rostering, utilising preference profiles as an alternative to current self-rostering methods, and integrating strategies for improved shift planning into e-rostering technology.

This doctoral research focused solely on improving shift patterns for registered nurses, a safety-critical profession that constitutes a large portion of healthcare staff in acute wards. However, an opportunity exists to expand model scope by incorporating the rostering of other members of the nursing workforce. Each staffing group (e.g., registered nurses, health care assistants, nursing associates) contribute their unique skillsets to the delivery of patient care, making a strong case for using optimisation or heuristic methods to assign shifts that account for skill-mix considerations. This expansion would require the addition of new model constraints, for example, those that prioritise the scheduling of senior registered nurses during 'core' care hours, or ensuring adequate healthcare assistant coverage during periods of intense ward activity. Although consideration of multiple staff categories would add significant complexity to the model, it would also enhance the model's potential utility in practice, ensuring that patients benefit from a strategically deployed, multi-role workforce.

Study 1 of this thesis emphasised the importance of shift pattern 'consistency'; nurses wanted consistent and predictable working hours in order to safeguard their health/wellbeing, personal responsibilities, and ability to engage meaningfully in their lives outside of work. Therefore, it would be valuable to explore new definitions of consistency (and inconsistency) in historical shift data, particularly in terms of their effects on nurses' absence rates and turnover intentions. Study 2 of this thesis explored some elements related to consistency, primarily the number of shift rotations and short returns in lookback windows. Additional variables could include those discussed in Härmä *et al.* (2015), e.g., mean absolute deviation in shift lengths and shift starting/end times, as well as patterns of days on/off (e.g., comparing the pattern ON-ON-ON-OFF-OFF-OFF-OFF with the pattern ON-OFF-ON-OFF-OFF-ON-OFF). Further analysis could include using advanced analytical techniques, such as pattern recognition (e.g., k-means clustering), which could lead to identification of new patterns of work linked with nurse wellbeing. All of these findings could then further inform scheduling strategies, helping to prioritise predictable schedules that minimise disruption to nurses' work-life balance.

While this research prioritised nurse-focused perspectives, more thorough exploration of the experiences of ward managers and nurses could help to further clarify the operational complexities of rostering. For example, focus groups with staff responsible for rostering could uncover how competing scheduling priorities are addressed in practice. As discussed in section 2.2.2.1, much of this knowledge remains tacit and follows 'rule-of-thumb' ideology; formally investigating these phenomena could help validate and increase transparency in scheduling practices, and would further aid in the development of organisational rostering policies that are actionable. Likewise, interviews with registered nurses could uncover the trade-offs they usually make (or are willing to make) when it comes to the organisation of their working time. These compromises could be further evaluated against one another through surveys that ask nurses to prioritise certain working patterns over others (i.e., through discrete choice experiments, where participants are asked to choose between several pairs of hypothetical scenarios) (de Bekker-Grob, Ryan and Gerard, 2012), thereby producing quantitative data related to preferences that would be valuable for refining optimisation model constraints on shift assignments.

Traditional methods for facilitating nurses' working time preferences often place considerable burden on managers, requiring them to balance competing requests alongside protecting minimum staffing levels. Conversely, self-rostering methods transfer this burden onto nurses by introducing new challenges related to competitive and inequitable 'auction' dynamics. In contrast, the concept of preference profiling explored in this thesis offers a new alternative. This concept could be modified to better reflect the original goal of self-rostering (i.e., shared ownership of the scheduling process). For example, rather than bidding for individual shifts, nurses could bid for complete monthly schedules that are proactively designed to reflect groups of preferences, good shift ergonomics, equitable distribution of desirable/undesirable shifts, and coverage requirements. A sophisticated self-rostering system such as this would also benefit from testing and evaluation in practice, particularly for outcomes related to staff satisfaction and team cohesion.

Building on this, the results of this research can be applied to emerging advancements in rostering practices and technologies. One compelling example is the use of schedule evaluation tools, such as the 'traffic light' system developed by the Finnish Institute of Occupational Health (FIOH). This system categorises staff workload based on the presence of specific working time exposures, offering clear and actionable guidance. For instance, a schedule containing 5 consecutive night shifts is flagged as 'overload, not recommended,' while a schedule with 40 or fewer weekly working hours is rated as 'recommended.' A five-year post-implementation evaluation of this tool demonstrated its effectiveness in reducing occupational accidents and psychological distress (Härmä *et al.*, 2022). Adapting such a system for NHS settings (e.g., using the methodology developed in this thesis) could provide an improved approach to monitoring/minimising illness within the nursing workforce.

There is also an opportunity to advance this research according to the data-driven principles of Fatigue Risk Management Systems (FRMS), which are organisational tools designed to identify, prevent, and address safety risks associated with fatigue (Sprajcer *et al.*, 2022). Though widely adopted in other safety-critical industries such as transport, aviation, and manufacturing, FRMSs have been underutilised in healthcare despite the sector's reliance on 24-hour service delivery. However, recent initiatives such as those undertaken by the Chartered Institute for Ergonomic & Human Factors and Fatigue Risk Management Science (FRMSc) (CIEHF, 2024) are helping to bridge this gap through the development of software that uses continuous staff/

patient safety data to inform warnings and penalties associated with fatigue-inducing shift assignments and workloads.

7.5 Final Conclusions

This thesis presents a series of findings that make significant contributions to both research and practice. Studies 1 and 2 deepen current understanding of nurses' shift work preferences and highlight the longitudinal implications of adverse shift work organisation, underscoring the need for improved rostering practices that proactively prioritise nurse wellbeing. Study 3 builds on these findings by introducing a novel model for optimised nurse scheduling, demonstrating feasibility in reconciling competing rostering priorities.

The findings of this thesis provide important implications for both practice and policy. For ward managers, this research emphasises the value of designing rosters that minimise the use of adverse shift configurations (i.e., those that are associated with the accumulation of fatigue, increase the risk of sickness, or disruption to work-life balance). Care should be taken to prioritise good shift ergonomics when constructing schedules, as this has the potential to improve nurses' day-to-day working conditions and to support reductions in sickness absence and turnover rates on the long term. However, managers often lack clear guidance on how to achieve these objectives, highlighting the need for organisations and policymakers to produce actionable frameworks to support them in this process. The methodology developed in this thesis offers a useful foundation for developing such guidance, as evidenced by the final scheduling model that successfully reconciled competing priorities through qualitative/ quantitative data integration and mathematical optimisation.

Furthermore, this research demonstrates significant future potential for further advancements in nurse scheduling, such as identifying working patterns that promote roster consistency, incorporating preference profiles as an alternative to traditional self-rostering, and gathering quantitative data on the trade-offs nurses make when choosing their working hours – all of which could aid the development of new scheduling tools that monitor/prevent nurse fatigue and its downstream effects.

Collectively, this work provides an adaptable framework for prioritising nurse-centred outcomes in scheduling. This information is valuable for improving the current challenges faced by England's NHS, where the effects of persistent staffing shortages are compounded by rising demands on hospital and community care systems.

Appendix A | Chapter 4 Supplementary Files

A.1 Original survey questions

What shifts do you normally work? Please think about what is typical for your working week.

- A mix of early, late/twilight and night shifts
- A mix of early and late/twilight shifts (no nights)
- A mix of long days and nights
- Early shifts only
- Late/twilight shifts only
- Long days only
- Night shifts only
- Standard working day (e.g., working 9 AM – 5 PM or 8 AM – 4 PM)
- Other (please specify)

What is the length of shift that you work most often in your main job (in hours)?

To what extent are you able to choose when you work?

- Not at all
- A Little
- To some extent
- A large extent
- Completely

To what extent is your choice of when to work determined by your employer?

- Not at all
- A Little
- To some extent
- A large extent
- Completely

How satisfied are you with your shift patterns overall?

- Very satisfied
- Moderately satisfied
- Neither satisfied nor dissatisfied
- Moderately dissatisfied
- Very dissatisfied

What shift length would you like to work ideally (in hours)?

What type of rota would you prefer to work?

- A mix of day and night shifts
- Shifts in the morning only
- Shifts in the afternoon or evening
- Day shifts only (irrespective of morning or evening)
- Night shifts only
- Other (please specify)

By working [**long/short/rotating]** shifts, I have (or would have):

	Disagree	**Agree**	**I don't think [X] influences this aspect**	**N/A**
Enough days off to recover from work fatigue	☐	☐	☐	☐
Enough breaks during shifts	☐	☐	☐	☐
Ability to pace myself throughout the shift	☐	☐	☐	☐
Good staffing levels during the shift	☐	☐	☐	☐
Good teamwork	☐	☐	☐	☐
Good relationship with my patients/clients	☐	☐	☐	☐
Ability to provide good quality of care	☐	☐	☐	☐
Good professional development opportunities during the shift	☐	☐	☐	☐
Efficient childcare organisation	☐	☐	☐	☐
Reduced childcare costs	☐	☐	☐	☐
Ability to do additional paid work (e.g., bank or agency)	☐	☐	☐	☐
Low travel costs (e.g., fuel, bus fares, train fares, parking)	☐	☐	☐	☐
Quality time with family/friends/social interactions	☐	☐	☐	☐
A healthy diet / exercise pattern	☐	☐	☐	☐

A.2 Published manuscript: "The important factors nurses consider when choosing shift patterns: A cross-sectional study"

This section includes the manuscript published from Study 1 (Chapter 4) in the *Journal of Clinical Nursing* (Emmanuel *et al.*, 2024).

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EMPIRICAL RESEARCH MIXED METHODS

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The important factors nurses consider when choosing shift patterns: A cross-sectional study

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Abstract

Aim: To gain a deeper understanding of what is important to nurses when thinking about shift patterns and the organisation of working time.

Design: A cross-sectional survey of nursing staff working across the UK and Ireland collected quantitative and qualitative responses.

Methods: We recruited from two National Health Service Trusts and through an open call via trade union membership, online/print nursing profession magazines and social media. Worked versus preferred shift length/pattern, satisfaction and choice over shift patterns and nurses' views on aspects related to work and life (when working short, long, rotating shifts) were analysed with comparisons of proportions of agreement and crosstabulation. Qualitative responses on important factors related to shift preferences were analysed with inductive thematic analysis.

Results: Eight hundred and seventy-three survey responses were collected. When nurses worked long shifts and rotating shifts, lower proportions reported being satisfied with their shifts and working their preferred shift length and pattern. Limited advantages were realised when comparing different shift types; however, respondents more frequently associated 'low travel costs' and 'better ability to do paid overtime' with long shifts and 'healthy diet/exercise' with short shifts; aspects related to rotating shifts often had the lowest proportions of agreement. In the qualitative analysis, three themes were developed: 'When I want to work', 'Impacts to my life outside work' and 'Improving my work environment'. Reasons for nurses' shift preferences were frequently related to nurses' priorities outside of work, highlighting the importance of organising schedules that support a good work-life balance.

Relevance to Clinical Practice: General scheduling practices like adhering to existing shift work guidelines, using consistent and predictable shift patterns and facilitating flexibility over working time were identified by nurses as enablers for their preferences and priorities. These practices warrant meaningful consideration when establishing safe and efficient nurse rosters.

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Patient or Public Contribution: This survey was developed and tested with a diverse group of stakeholders, including nursing staff, patients, union leads and ward managers.

Reporting Method: The Strengthening the Reporting of Observational Studies (STROBE) checklist for cross-sectional studies was used to guide reporting.

KEYWORDS
flexible working, nursing, preferences, rostering, scheduling, shift work, working patterns

1 | INTRODUCTION

Nurses' shift patterns are characterised by various aspects, including shift length, timing and rotation, total/distribution of weekly working hours and recovery periods—all of which should be organised in ways that protect nurse wellbeing. In Europe and the United Kingdom, official guidance and regulations offer shift pattern design strategies to reduce harm, for example, capping weekly working hours, limiting consecutive working days and ensuring a minimum of 11 h of rest between shifts (Health and Safety Executive (HSE), 2006). Complimentary to this guidance exists a well-established body of evidence highlighting the impacts of shift work and night work on employee physical health, mental health and social wellbeing (Arlinghaus et al., 2019; Grzywacz, 2016; Moreno et al., 2019), as well as on their performance and safety while at work (Dall'Ora et al., 2016; Folkard & Tucker, 2003; Wagstaff & Sigstad Lie, 2011). Given all these elements, the task of organising shifts into rosters is often challenging, especially with competing priorities like maintaining service delivery and managing staffing numbers and skill mix.

Some nursing roles may offer more autonomy over when and how long to work, as well as pay premiums when working during unsocial hours (e.g. night shifts and weekend shifts; NHS Employers, 2022; NHS Staff Council, 2020). Subsequently, nurses themselves may prefer to work certain shift configurations or modified weekly working hours to suit their personal needs in and outside of the workplace. A popular example includes nurses who prefer to work long shifts (i.e. shifts lasting 12 h or more), as it is thought to enable better patient care continuity and more days off from work when compared to working short shifts (i.e. shifts lasting 8 h or less; Ball et al., 2015). Nonetheless, research has also shown that working long shifts can lead to harmful outcomes for patients as well as increased burnout and job dissatisfaction for nurses (Dall'Ora et al., 2022). The conflict between these viewpoints stresses a need for closer examination of the relationships between different shift configurations and nurses' choices over working time.

A recent literature review of studies exploring nurses' views and preferences around shift patterns (Ejebu et al., 2021) highlighted that nurses had varied opinions about the benefits and drawbacks of different shift types, for both themselves and for patients. Views also differed according to personal characteristics and attributes (e.g. age, having childcare responsibilities) rather than shift types alone. This review concluded that the factors that lead nurses to prefer certain shifts are not well understood, as there are likely many work- and life-related priorities that are considered when expressing shift preferences. Understanding these mechanisms is critical for successfully operationalising nurses' preferences in the rostering process, which is a key target for employers wanting to promote flexible working practices as a means of attracting and retaining nurses.

Therefore, the aim of this study was to gain a deeper understanding of what is important to nurses when thinking about their shift patterns and the organisation of their working time.

What does this paper contribute to the wider global community?

- Nurses consider many factors when expressing their shift preferences, with most relating to their priorities outside of work, such as protecting personal health and wellbeing, making time for social activities and relationships and managing childcare responsibilities.
- Nurses valued rostering practices that supported their priorities and a good work-life balance, including using existing guidance on shift pattern organisation, ensuring shift patterns are consistent and predictable and facilitating flexibility over working hours.

2 | METHODS

2.1 | Participants

We undertook an anonymous cross-sectional survey distributed to nursing staff across the United Kingdom and Ireland. Respondents eligible for survey participation included all nursing staff working in the following roles: registered nurse (i.e. those who completed a nursing degree at the university level), health care assistant or support worker (those with varied and/or informal training who assist with hygiene, feeding and other elements of basic care) and nursing associate (those who completed a formal 2-year diploma and help bridge the gap between registered nurses and assistants/support workers). Nurses working in roles that did not involve care provision (e.g. managerial or academic positions) were not eligible for participation.

2.2 | Survey design

The survey was developed in consultation with a diverse group of stakeholders to ensure questions were relevant to the target population, including registered nurses, health care assistants and nursing union leads. Variables related to characterising shift patterns were selected from a key literature review summarising the impact of shift work on workers' performance and wellbeing (Dall'Ora et al., 2016). Further details on survey development and distribution are published elsewhere (Dall'Ora, Ejebu, et al., 2023), and the full survey dataset is publicly available (Dall'Ora, Griffiths, & Ejebu, 2023). The Strengthening the Reporting of Observational Studies (STROBE) checklist for cross-sectional studies was used to guide reporting (von Elm et al., 2007; File S1).

We defined shift work as any work scheduled outside of standard daytime hours on weekdays (i.e. before 7:30 AM and after 6:00 PM) or working on weekends. We defined shift length as 'long' (11 or more hours), 'short' (fewer than 9 h) or 'medium' (between 9 and 11 h). After accounting for unpaid break time, shifts of 11 h or more were compatible with a two-shift '12-h' system, whereas shifts of <9 h were compatible with a three-shift '8-h' system with some overlap between shifts. We defined rotating shifts as day and night shifts worked within the same rota.

Descriptive data included respondents' demographics (gender, role, age, geographical location, childcare responsibilities) and the distribution of usual shift characteristics (length, pattern). We also asked nurses to rate their satisfaction with their work pattern, to rate the level of choice they have over their shifts and to indicate their ideal shift length and pattern. To understand perceptions about working different shifts, we asked nurses to indicate if they agreed, disagreed or didn't believe that working short/long/rotating shifts influenced 14 aspects of work and personal life (e.g. having enough breaks during shifts, enough days off to recover from work). For example, when considering 'ability to provide good patient care', nurses were asked to indicate if they agreed, disagreed or didn't believe that working short/long/rotating shifts influenced the aspect in question; the original survey items are included in File S2. To capture a greater breadth of opinions, nurses could indicate their views regardless of the shift types they actually worked. Data for the aspects 'enough breaks during shift' and 'healthy diet' when working rotating shifts were not collected in the online survey and are therefore not included in comparisons.

Qualitative data were collected from a single, open-ended question located at the end of the survey asking, 'If you could choose your shift patterns, what would be the most important factor in that choice'. No limits on response length were imposed.

2.3 | Data collection

Responses were collected between June and October of 2021. We launched the survey through two routes: (1) to a targeted nursing staff population in two large National Health Service (NHS) trusts in the South of England and (2) through open invitation via social media (Twitter/X), nursing union membership contact lists and select nursing journals. With the use of open-ended recruitment channels, we could not estimate a target sample size in advance. However, examination of the resulting confidence intervals provide an alternative estimate for the precision achieved. For example, the proportion of nurses satisfied with their current working pattern was estimated with a margin of error of less than +/− 4% based on the binomial exact 95% confidence interval (Newcombe, 1998).

2.4 | Data analysis

Descriptive data were summarised to understand respondents' demographics and common shift characteristics. To aid direct comparison of nurses' satisfaction with different worked shift patterns, responses were dichotomised to 'satisfied' versus 'not satisfied' (i.e. 'neither satisfied nor dissatisfied', 'moderately dissatisfied' and 'very dissatisfied' responses were grouped to 'not satisfied'). Comparisons of ideal versus worked shift length and shift pattern were analysed with cross-tabulation and Cohen's Kappa to determine if and which nurses' shift preferences were being realised. Percentages of agreement for aspects related to work and life were calculated to compare differences across the three-shift types. As the range of percent missing data for our variables of interest was low (ranging from 0.3% to 10.3%, with most falling below 8.0%), we used pairwise deletion to minimise loss of data from partially completed surveys (Newman, 2014). Quantitative data were analysed using SPSS version 28.

Qualitative data were analysed through thematic analysis (Braun & Clarke, 2012). Open-ended responses were extracted from the response dataset and imported into a separate spreadsheet. All responses were read-through, and general observations about the data and potential categories/themes were recorded. Responses were then re-read to identify codes, or the 'essential' elements contained within each response. We then grouped codes into categories and overarching themes that captured descriptive information within responses and latent connections between responses. We analysed the full dataset inductively so that codes, categories and themes could be constructed directly from nurses' responses. We quantified codes and categories; however, we interpreted the resulting frequencies as a rough measure of what respondents were willing or able to discuss and not as a direct measure of significance (Vaismoradi et al., 2013).

2.5 | Rigour

Core elements regarding researcher trustworthiness and reflexivity were used to establish study rigour (Nowell et al., 2017; O'Brien et al., 2014). The development of codes, categories and themes was completed by the first author, who is a current PhD student with formal training in qualitative methods and experience in analysing short- and long-form survey responses from health care workers. Categories and themes were refined during multiple rounds of peer debriefing with three additional authors who are research experts in NHS workforce organisation, nurses' shift work and patterns and operational research methods in scheduling problems. Responses were analysed through a critical realist lens (McEvoy & Richards, 2006) in the following manner: there are objective phenomena related to shift pattern organisation (e.g. length of working hours, night work, sufficient time to rest between shifts) that will influence nurses' shift preferences and the factors that bring about those preferences, but how nurses perceive and value these phenomena will change across different people, contexts and timepoints. To check analysis validity, categories and themes were repeatedly compared with nurses' original responses as well as against patterns uncovered from quantitative data where possible.

2.6 | Ethical approval

Approval for this study was obtained from the University of Southampton's office for Ethics and Research Governance (approval IDs 65122.A2 and 57489.A2).

3 | RESULTS

3.1 | Description of participants

After the removal of non-eligible responses (e.g. non-nursing staff, working outside the UK and Ireland), a total of 873 valid responses remained; 790 responses (90.5%) were collected through the open call, and 83 responses (9.5%) were collected from the targeted Trust population. Registered nurses made up the majority of respondents ($n=658$, 75.3%), while 188 (21.5%) were health care assistants/support workers and 25 (2.8%) were nursing associates. Respondents were 42 years old on average (range 20–70 years old), and 752 (86.1%) identified as female. Most nurses worked for the NHS (92.2%), worked in hospital inpatient units (66.9%), and reported 'acute adult care' as their primary area of practice (38.3%). Among the 372 (42.6%) respondents who cited having childcare responsibilities, 183 (49.2%) had primary responsibility and 150 (40.3%) shared responsibilities more or less equally with their spouse/partner.

Most nurses reported working long shifts (≥11 h; $N=575$, 66.4%), while 227 (26.2%) worked short shifts (≤9 h), and 64 (7.4%) worked medium shifts (9.1–10.9 h). Just over half of nurses ($N=449$, 52%) usually worked night shifts as part of a rotating schedule. Table 1 provides details on the respondents' 'usual' shift configurations distributed by shift length category. Among the nurses who normally worked long shifts, 287 (50.2%) worked 4 days or more per week, 172 (32.1%) worked 48 h or more per week and 98 (17.2%) worked 4 or more days in a row.

3.2 | Nurses' satisfaction, choice and preference over shifts

The distribution of nurses' satisfaction over their shift patterns was varied: 10.7% were very dissatisfied, 18.3% were moderately dissatisfied, 19.2% were neither satisfied nor dissatisfied, 33.5% were moderately satisfied and 18.3% were very satisfied. When dichotomised, half of nurses ($N=449$, 51.8%) reported being satisfied with their shift patterns overall, with the highest proportion of nurses satisfied when working day shifts (including evening/late shifts) and the lowest proportion when working rotating shifts (60.9% vs. 44.1%, respectively). Regarding choice, 59.1% of nurses reported having little or no choice over their shifts, and 68.5% reported that their shifts were mostly or completely determined by their employer. To determine which nurses are having their preferences met, crosstabulations of worked versus ideal shift pattern and shift length were performed (Table 2). There was only moderate agreement between worked and preferred shift pattern (Cohen's $\kappa=.393$, 95% CI 0.34–0.44, $p<.001$) (Sim & Wright, 2005). Eighty-nine percent of nurses working day shifts and 86% working permanent night shifts were working their preferred shift pattern; however, only 44% working rotating shifts preferred this pattern. Similarly, there was only moderate agreement between worked and preferred shift length (Cohen's $\kappa=.321$, 95% CI 0.27–0.37, $p<.001$). Seventy-eight percent of nurses working short shifts were working the shift length they preferred, but only 56% working long shifts preferred this length. When stratified by age, level of agreement differed for some groups (when compared to the total): more older nurses reported working their ideal shift pattern (age 50–59, Cohen's $\kappa=.547$, 95% CI 0.44–0.66, $p<.001$) and fewer younger nurses reported working their ideal shift length (age 20–29, Cohen's $\kappa=.196$, 95% CI 0.08–0.31, $p<.001$.)

3.3 | Nurses' perceptions when working different shifts

Distributions of nurses' responses when asked about the influence of working short, long and rotating shifts on various aspects of work and life outside of work are included in Table S1 (File S3). Direct comparisons of the proportions of nurses who agreed with each statement are further illustrated in Figure 1.

Proportions of agreement for most items generally fell in the low-middle range, indicating that there was no shift type that clearly provided more advantages for nurses. This was particularly true for aspects related to nurses' lives outside of work, like having enough days off for recovery, efficient childcare costs/arrangements and having a good social life. Some exceptions were noted, including 'low travel costs' and 'better ability to do paid overtime' when working long shifts and 'healthy diet/exercise' when working short shifts. For items related to patient care, a higher proportion of nurses agreed that long shifts offer good patient relationships, whereas a higher proportion agreed that short shifts offer good quality of care. For other work-related aspects, higher proportions agreed that working

TABLE 1 'Usual' shift pattern characteristics distributed by shift length category.

	All shift lengths N (col %)	Short shifts (≤9 h) N (row %)	Medium shifts (9.1–10.9 h) N (row %)	Long shifts (≥11 h) N (row %)
Shift pattern (Main job)				
No shift work (traditional hours)	90 (10.4)	81 (90.0)	5 (5.6)	4 (4.4)
Day shifts only (including evening)	273 (31.6)	89 (32.6)	39 (14.3)	145 (53.1)
Rotating shifts (including night)	449 (52.0)	52 (11.6)	13 (2.9)	384 (85.5)
Night shifts only	51 (5.9)	3 (5.9)	7 (13.7)	41 (80.4)
Total	863 (100.0)	225 (26.1)	64 (7.4)	574 (66.5)
Total weekly working hours (All jobs)				
37.5 h or less (part-time)	184 (22.3)	69 (37.5)	22 (12.0)	93 (50.5)
Between 37.5 and 48 h	411 (49.9)	102 (24.8)	38 (9.2)	271 (65.9)
48 h or greater	229 (27.8)	27 (11.8)	30 (13.1)	172 (75.1)
Total	824 (100.0)	198 (24.0)	90 (10.9)	536 (65.0)
Days worked per week (All jobs)				
≤2 days	60 (6.9)	9 (15.0)	4 (6.7)	47 (78.3)
3 days	278 (32.3)	28 (10.1)	12 (4.3)	238 (85.6)
4 days	278 (32.3)	40 (14.4)	33 (11.9)	205 (73.7)
5 days	189 (22.0)	123 (65.1)	9 (4.8)	57 (30.2)
≥6 days	56 (6.5)	26 (46.4)	5 (8.9)	25 (44.6)
Total	861 (100.0)	226 (26.2)	63 (7.3)	572 (66.4)
Days worked in a row (All jobs)				
≤2 days	336 (39.0)	23 (6.8)	12 (3.6)	301 (89.6)
3 days	234 (27.2)	38 (16.2)	23 (9.8)	173 (73.9)
4 days	102 (11.8)	27 (26.5)	16 (15.7)	59 (57.8)
5 days	135 (15.7)	102 (75.6)	9 (6.7)	24 (17.8)
≥6 days	54 (6.3)	35 (64.8)	4 (7.4)	15 (27.8)
Total	861 (100.0)	225 (26.1)	64 (7.4)	572 (66.4)
Rest days per week (All jobs)				
1–2 days	339 (40.6)	151 (44.5)	21 (6.2)	167 (49.3)
3–4 days	445 (53.4)	53 (11.9)	35 (7.9)	357 (80.2)
5–6 days	50 (6.0)	10 (20.0)	4 (8.0)	36 (72.0)
Total	834 (100.0)	214 (25.7)	60 (7.2)	560 (67.1)

short shifts offer enough breaks and the ability to pace oneself during shifts. Aspects in relation to working rotating shifts usually had the lowest proportion of agreement and were considerably lower (when compared to short or long shifts) for items like 'pacing during shifts', 'enough days off', 'good childcare arrangements' and 'good social life'.

3.4 | Qualitative Themes & Categories—What factors are important to nurses when choosing shifts?

A total of 778 valid responses were collected when nurses were asked, 'If you could choose your shift patterns, what would be the most important factor in that choice?'. Responses usually contained three types of information: the factors themselves, why these factors were important and what would help/hinder attaining that factor (i.e. their preferences). Many nurses described more than one factor, resulting in most responses having multiple codes assigned. Thematic analysis resulted in the generation of 54 unique codes organised into eight categories, which were then grouped into three themes: 'When I want to work', 'Impacts to my life outside work' and 'Improving my work environment'. Themes, categories and codes are described in the following sections and are illustrated in Figure 2; segments of this diagram represent code frequency (i.e. the total number of times a code was assigned across all responses, divided by category (outer ring) and theme (inner ring)), with larger segments indicating higher frequency.

3.4.1 | Theme 1: 'When I want to work'

This theme contains three categories (*shift characteristics*, *scheduling practices* and *days off & rest*) and had a code frequency of $N=614$ (55.4%). Different working time preferences were

TABLE 2 Crosstabulation of worked versus preferred shift pattern* and worked versus ideal shift length.

	Preferred shift pattern			
	Day shifts only (inc. evening) N (row %)	Rotating shifts (inc. night) N (row %)	Permanent night shifts N (row %)	Total N (column %)
Worked shift pattern				
Day shifts only (including evening)	242 (89.6)	25 (9.3)	3 (1.1)	270 (35.4)
Rotating shifts (including night)	209 (47.2)	194 (43.8)	40 (9.0)	443 (58.1)
Permanent night shifts	5 (10.0)	2 (4.0)	43 (86.0)	50 (6.6)
Total	456 (59.8)	221 (29.0)	86 (11.3)	763 (100.0)

	Ideal shift length			
	Short (≤9 h) N (row %)	Medium (9.1–10.9 h) N (row %)	Long (≥11 h) N (row %)	Total N (Column %)
Worked shift length				
Short (≤9 h)	168 (77.8)	21 (9.7)	27 (12.5)	216 (26.0)
Medium (9.1–10.9 h)	35 (57.4)	16 (26.2)	10 (16.4)	61 (7.3)
Long (≥11 h)	166 (29.9)	77 (13.9)	312 (56.2)	555 (66.7)
Total	369 (44.4)	114 (13.7)	349 (41.9)	832 (100.0)

*Only direct comparisons are included (i.e., 'other' and 'no shift work' category responses are excluded)

identified, including individual shift pattern characteristics (e.g. shift length, shift timing and rotation speed, patterns of days off), as well as what should be done during the scheduling process to ensure rotas are fair and safe. Some nurses stated their specific preferences without providing additional context (e.g. 'Monday long day. Tuesday to Friday days off. Saturday & Sunday long day. Following week have the weekend off...' (participant 192)), but in responses that included more information, pathways between factors and resulting shift preferences varied or even contrasted. For example, when citing health and wellbeing, one nurse stated that they'd prefer to work 'only nights, for regular body rhythm, physically and mentally...' (pt. 172), whereas another nurse stated their preference for 'straight days because this suits my health better...' (pt. 276). A summary of nurses' shift preferences is described in the following paragraphs.

Shift characteristics

Many nurses preferred to only work during the day, while others shared their willingness to work night shifts. Some disliked how night shifts were assigned and shared how they would prefer these shifts to be organised—some preferred to work all night shifts in one continuous stretch, while others preferred to work evenly spaced-out night shifts. Nurses also commented on shift start time and end time. While some preferred shifts that started earlier in the day (e.g. 7:00 AM), others wanted to avoid early shift start times, particularly if they were coming off of nightwork. Comments about shift end time centred on wanting to finish shifts on time (i.e. avoid working longer than scheduled) rather than wanting to finish at a particular time of the day. When nurses mentioned shift length, many wanted to work shorter shifts, to avoid working long shifts or to have the flexibility to choose which shift length to work. Reasons for preferring short shifts centred around wanting to not feel exhausted or fatigued (e.g. 'Working 8–9 h shifts maximum where I can practice safely and effectively, without mental and physical exhaustion' (pt. 582)). Preferring long shifts was also prevalent, most frequently to enable shorter work-weeks and more days off (e.g. 'long shifts therefore maximising number of rest days in between' (pt. 732)). However, working too many long shifts in a row (e.g. more than 2–3 in a row) made this shift length less desirable.

Respondents also voiced preferences for patterns of work. Nurses wanted to avoid working day and night shifts within the same week or work earlies/days immediately after working nights (e.g. 'Not rotating from nights to days then back to nights in a short space of time' (pt. 305)). Preferences for the number of shifts worked in a row depended on whether days off or personal wellbeing were prioritised: some preferred to work all shifts together so that rest days were also successive, whereas others preferred to limit consecutive shifts so that they could avoid exhaustion (e.g. 'All shifts back to back, so days off feel more beneficial...' (pt. 168) vs. '...not working consecutive shifts so that I am exhausted by the time I get a day off' (pt. 417)).

Scheduling practices

Beyond the specifics of when to work, many nurses described long-term preferences for their rotas, like needing more consistency and predictability. Consistency could be achieved in different ways, like when shifts were worked in recognisable blocks (e.g. 'know what I am doing each week, either set days or set nights, so I can predict what I am working...' (pt. 580)) or when nurses could predict which days of the week they would be working (e.g. 'set days in and off e.g. 4 on 4 off' (pt. 240)). Nurses specifically disliked working rotas with no discernible order (e.g. '...at the moment it seems random or dictated purely by staffing needs' (pt.

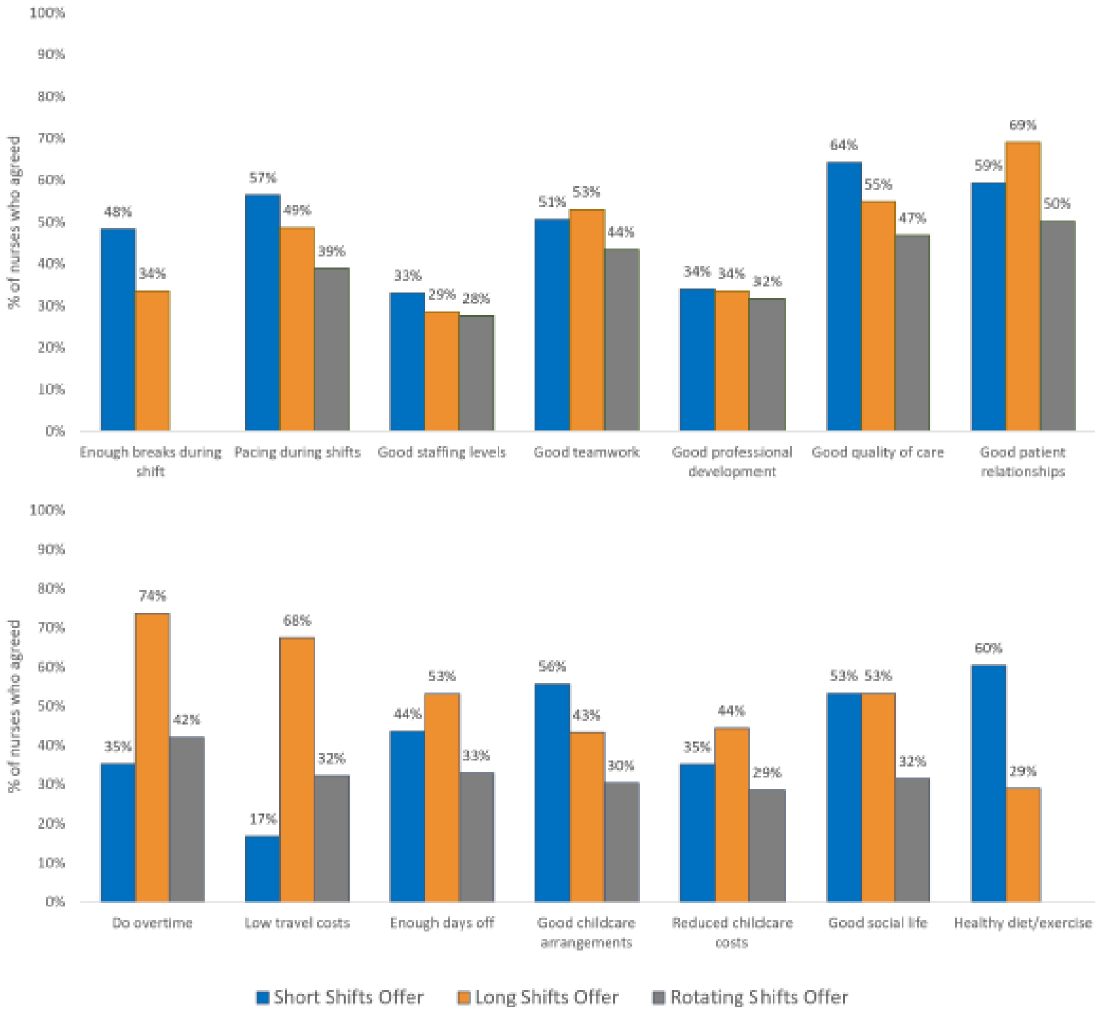

FIGURE 1 Nurses' beliefs related to aspects of work and life outside work—proportions of agreement. [Colour figure can be viewed at wileyonlinelibrary.com]

782]). Alongside rota consistency, appropriate lead time for roster publishing was important (e.g. a minimum of 6–8 weeks; 'Late rota completion is hugely disappointing and makes life outside work harder to organize' (pt. 692)). However, some respondents warned that finalising rosters too far in advance impedes one's ability to plan around unforeseen conflicts.

Flexibility in the scheduling process was represented by nurses' desire to have more choice over their shifts from the start (e.g. 'Allowing people to choose what is right for them' (pt. 520)). For some, flexibility was needed to recover from or change adverse shift patterns (e.g. 'Having the freedom to give myself more days to recover between weekly shifts (pt. 518)', 'Being able to choose patterns where you have enough days to rest and reset between shifts' (pt. 647)). Honouring these flexible requests must also be done equitably, particularly when it comes to undesirable shifts (e.g. '...treating everyone's rota equally and not favouring others' (pt. 375)). Flexibility was also mentioned by one nurse who valued coordinating coverage with colleagues (e.g. 'Opportunity to liaise with colleagues and negotiate when is good for them and myself to work' (pt. 976)).

Days off & rest

Rather than discussing the arrangement of their working time, nearly 200 nurses wrote about how their days off should be organised. Having appropriately arranged days off was needed to make this period meaningful and worthwhile (e.g. '...have 2–3 days off to actually feel like I'm resting' (pt. 715)). For some nurses, days off were specifically needed to recover after work (e.g. 'Having enough time off to recover emotionally and physically between shifts' (pt. 696)), but for others, enough rest

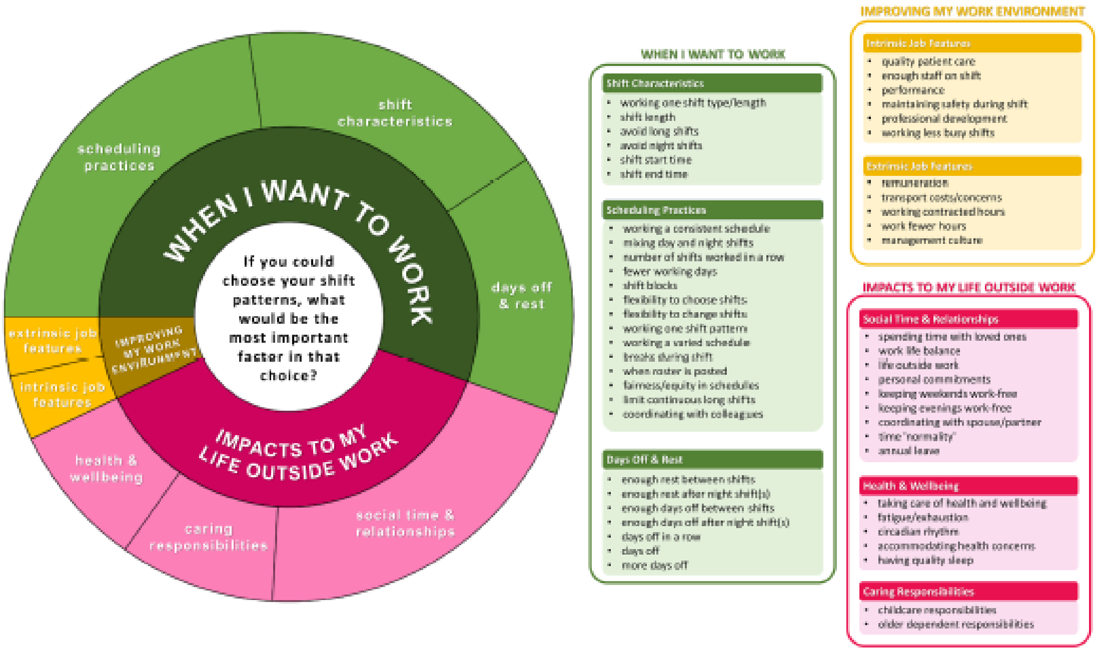

FIGURE 2 Qualitative themes, categories and codes. [Colour figure can be viewed at wileyonlinelibrary.com]

was needed in order to prepare for the next series of shifts (e.g. 'To have my days off to myself to re energise myself for my next shift' (pt. 523)). Most commonly, a single day's rest in between ending a night shift and starting early/day shift was problematic (e.g. 'Enough rest time between day and night shifts. I often have only 24 h between finishing a night shift to going to days and find it really hard' (pt. 628)). The rest period given between shifts within a single stretch was also important for some (e.g. 'Having at least 11 h between shifts, we sometimes finish shifts at 9:30 pm and start the next day at 7 am' (pt. 949)).

In summary, nurses provided rich information on the shifts they preferred. Preferences were diverse, ranging from very specific (e.g. the exact days and times one would like to work) to more general (e.g. wanting to avoid working too many shifts in a row). Nurses also described the scheduling practices that they believed could improve their experiences in the long term—working less adverse shift configurations from the start, improving roster consistency and predictability and having more flexibility to work the hours that they can. These concepts were also identified as enablers for organising one's personal life outside of work, as discussed in the next theme.

3.4.2 | Theme 2: 'Impacts to my life outside work'

This theme explored the first subset of factors that led nurses to have the preferences described in the first theme. Many of these factors related to nurses' personal lives (code frequency of $N=415$, 37.5%), signifying that shift preferences were largely determined by how those shifts might impact priorities outside of work. These priorities were organised into three categories: *social time & relationships*, *caring responsibilities* and *health & wellbeing*. Reasons for having shift preferences were presented as non-negotiable (e.g. 'I consider my children before choosing a shift' (pt. 199), '…I suffer from migraines, so I am unable to work long days and do Monday-Friday…' (pt. 685)) or as desirable if possible (e.g. 'I would like to sleep. After night shifts, I cannot stabilise my sleep…' (pt. 507), 'I would want to come home earlier shorter days to rest, see family, exercise…' (pt. 768)), indicating that some reasons were prioritised higher than others.

Social time & relationships

Of the 58 nurses who mentioned 'work-life balance', 41 simply cited the term itself without any additional context. When more information was provided, work-life balance was related to activities at home (e.g. 'Work life balance, having days off to manage home life and family' (pt. 373)). Nurses also wanted time for other personal commitments and activities, like hobbies, housework, shopping and appointments, exercise and social time with friends. While some individual shift types supported these priorities, above all, rota consistency and flexibility were repeatedly mentioned as enablers for work-life balance and organising personal commitments (e.g. 'Having one day off the same each week so that I could structure activities at home around that day' (pt. 88), 'Consistency in having same 8 shifts to have a decent personal life outside work' (pt. 502), 'Choose what suits my personal life' (pt. 274), 'What works for me and gives me work life balance' (pt. 501)).

Nurses specified that the mere fact of having days off from work did not necessarily result in having quality family time—especially when they felt exhausted as a result of work (e.g. 'Time off with family where I'm not exhausted' (pt. 393), 'Quality time with my children and family without being permanently drained, exhausted, and sad' (pt. 138)). Coordinating schedules with a spouse/partner was also important, particularly if they also worked shifts and conflicts were frequent. Many nurses wanted to protect specific times/days that they believed to be more conducive to social activities and relationships. For these 'normal' social hours—such as evenings and weekends—nurses wanted to minimise the shifts that disturbed these periods and thus preferred working day shifts on weekdays (e.g. 'Ensuring enough social time - i.e. weekend/evenings' (pt. 783), 'Increased time with my family so less night shifts or weekends' (pt. 344), 'It would be early shifts to feel like you have more time with family' (pt. 936)). One nurse also specifically expressed feelings of guilt when working shifts that disturb family time ('…as little disruption as possible to my children's routines at home, also not working on important days like Christmas and bank holidays because I feel guilty for not spending them with my family' (pt. 62)).

Caring responsibilities

Over 100 nurses stated that caring for responsibilities was the most important factor. Some mentioned needing enough time to care for older dependents (i.e. older parents); however, this factor overwhelmingly focused on the task of childcare. Arranging childcare was described as difficult and costly, particularly when reconciling assigned shifts with the operational hours of daycare facilities and schools. Depending on each nurses' individual situation, shift preferences varied (e.g. 'Ability to care for my kids and reducing the stress of trying to sort out childcare as it's very difficult to do so on long days/nights' (pt. 872), 'I would prefer to work longer shifts […] I wouldn't have to pay as much childcare costs for my daughter to go to nursery which would create a lot less stress from my life' (pt. 950), 'Child care is one thing I struggle with, easier when [they're] in school, but the cost of after school care is very expensive and it all stops at 5! So easier to do night shifts…' (pt. 442)). Nurses mentioned that having predictable working hours helped with this task, once again highlighting the importance of consistency (e.g. 'That the pattern could stay the same each week so it would be easier for childcare needs. Many nurseries like set days and when our rota is changing from week to week this can be difficult' (pt. 911)).

Health & wellbeing

For those who mentioned specific long-term health conditions (e.g. chronic pain, migraines), late starts/finishes, long shifts or having too many working days in a row exacerbated illness symptoms. In general, however, rather than connecting health/wellbeing concerns with performance or productivity at work, more nurses focused on their rest days and lives outside of work. As discussed in the first theme, rest days are frequently used to recover from working shifts. For some nurses, recovery explicitly meant having to look after one's own wellbeing (e.g. 'Allowing enough blocked days off to recover mentally and physically from work and look after my health…' (pt. 391), 'Enough time for self-care' (pt. 618)). Similarly, some nurses wanted to have enough time to live healthier lifestyles overall (e.g. 'Having time to recover from work, spend time with family & have a healthy lifestyle' (pt. 888)).

In addition to impacts on general health, many nurses mentioned feeling excessive tiredness, exhaustion and/or fatigue as a result of shift work (particularly when working many long shifts in a row, rotating shifts within short periods of time and overtime). These symptoms spilled over into life outside work and impacted one's ability to engage in social activities (e.g. 'Not feeling tired and being home with family' (pt. 263), 'Personal life, childcare and family. Long days leave me exhausted on my days off' (pt. 236)). Nurses also cited disruption to sleep cycles and wanted to work shifts that established a better routine for their 'body clocks' (e.g. 'Consistent, regular hours so your body clock can get into a routine' (pt. 106), '…not mixing days and nights in a week […] this does not observe HSE best practice guidelines and messes with the body clock and sleep patterns. It should not be allowed to happen' (pt. 471)).

In this theme, nurses described many factors that influence their shift preferences. Overall, the organisation of working time impacted rest periods in problematic ways, often resulting in nurses not having enough time and energy to engage in activities outside of work. Resulting shift preferences aimed to minimise disruption to life outside work, for example, reducing the number of working days, having sufficient time off for rest and recovery, fewer evening/weekend shifts to protect social time or preferring night shifts to ensure availability during childcare days. The high code frequency of this theme suggests that many preferences for working time depended on nurses' priorities outside of work. In contrast, the third and final theme reviews the smaller number of responses related to nurses' experiences at work.

3.4.3 | Theme 3: 'Improving my work environment'

This theme explored the second subset of factors influencing nurses' shift preferences, containing two categories (*intrinsic job features and extrinsic job features*) and a code frequency of N=79 (7.1%). Here, nurses described the performance- and administrative-related factors they prioritised (e.g. 'Workload and staffing levels' (pt. 811), 'Better rates of pay' (pt. 179), 'A shift where I feel I have accomplished the care I have wanted to give for my patients' (pt. 258)). Overall, responses centred around nurses' desire to have their working environment, as well as their ability to fulfil duties at work, improved.

Intrinsic job features

Using terms such as 'care continuity', 'care mistakes', 'patient safety' and 'time spent with patients', some nurses stated that being able to provide high-quality patient care was an important factor. When it came to their resulting preferences, nurses had different opinions on the shift lengths that enabled better patient care. Long shifts (and reduced number of handovers) were seen as beneficial by some (e.g. 'Patient continuity, reduced handovers less likely to miss information…' (pt. 816)). However, several more called out the risks of working long shifts (or more than 8 hours at a time), particularly in terms of their own productivity (e.g. 'Not 12 hours. More mistakes & patients deserve a nurse not pacing themselves!' (pt. 630), '…patient safety should be the main concern and long shifts are not conducive to good patient care. Short shifts are far more productive and safe.' (pt. 710)). Nurses also identified staffing levels as an important factor, and adequate staffing was needed so that nurses could manage their workloads and take their designated breaks during shifts (e.g. 'To not have so much pressure on the shift, with the right amount of staff on and to take my break when needed' (pt. 938)). Having downtime for continuous learning was also identified (e.g. 'Days off and nights as they are a time I can do my e-learning and not rush about all shift' (pt. 795)).

Extrinsic job features

Remuneration was important, with nurses wanting the best arrangements for shifts to optimise working hours and take-home pay. Some nurses preferred to work shifts that had pay premiums or to work additional shifts on their days off to supplement basic pay (e.g. 'Shift that pays best so I can reduce my total hours' (pt. 601), 'The ability to work extra shifts between. I can't live on my basic pay' (pt. 357)). While pay was important, other nurses were careful to balance this priority with spending time with family during normal social hours (e.g. 'To have enough time with family however being well paid' (pt. 370), 'Working weekends brings in extra income but does not allow for spending time with family and friends' (pt. 573)). Commuting costs and concerns were mentioned by a few, and for one nurse, this meant preferring to work fewer shifts per week to minimise travel time ('Long days as I travel 1 hour each way…means less shifts/week if I prefer' (pt. 559)). Lastly, perceived support from management was mentioned, highlighting nurses' need for supervisors who were flexible and respectful of their time (e.g. 'I would like to be able to leave early, if possible, without management making me feel like I am 'committing fraud' given that I don't get breaks or claim for TOIL' (pt. 925)).

In summary, this theme highlighted the importance of organising nurses' working conditions in ways that benefit them and enable them to do their jobs efficiently. Some shift preferences were mentioned; however, nurses prioritised other important work organisation elements, like having adequate numbers of staff and having enough time/opportunity to take breaks and complete training. While all responses were collected in the context of understanding shift pattern preferences, responses in this theme highlighted some complementary intrinsic and extrinsic job features that warrant consideration when examining nurses' perceptions of work and working time.

4 | DISCUSSION

The aim of this study was to gain a deeper understanding of nurses' experiences and preferences when working shifts. Compared to previous research, we report a broader and deeper examination of shift preferences: what shifts nurses usually work and how this is compared with ideal/preferred shifts; nurses views on aspects related to work and life when working long, short and rotating shifts; and the important factors nurses consider when expressing their preferences.

We found that proportions of nurses who were satisfied with their shift patterns were lower when they worked long shifts and rotating shifts. This mirrors previous findings, where nurses working in these configurations were more likely to be dissatisfied with their job overall and more likely to have intentions of leaving their job (Dall'Ora et al., 2015; Ferri et al., 2016; Lu et al., 2012). Mismatching between preferred and worked shifts may partially explain or moderate this dissatisfaction, as we also found a greater disconnect between ideal and actual work hours when nurses worked long shifts and rotating shifts. However, many nurses in this study preferred and were satisfied with what they usually worked, suggesting that for some, preferences and wishes are realised. Responses on aspects of work and life demonstrated some perceived benefits when working certain shifts—greater proportions of nurses agreed that long shifts offer good patient relationships, the ability to do overtime and low travel costs, and that short shifts offer good quality of patient care and a healthy diet/exercise pattern—echoing previous research (Dall'Ora et al., 2022; Nicholls et al., 2017; Richardson et al., 2007). Rotating shifts did not offer clear advantages for any of the domains addressed—this was also reflected in nurses' qualitative responses, where the poor arrangement of shift start/end time and rest time when working rotating shifts were mentioned as difficult in many contexts. Many of the other factors identified as important in qualitative responses—like having good staffing levels, having enough days off for rest and recovery, efficient childcare organisation, having a good social life and having a healthy lifestyle—had low proportions of agreement regardless of shift type. This finding complements previous research exploring the influence of different shift configurations, as the mere fact of working short, long or rotating shifts is unlikely to influence views or preferences alone. Rather, the organisation of shift types and weekly working hours in relation to one another and over the long term likely play more important roles (Dall'Ora et al., 2016).

Focusing on what nurses considered important when choosing shift patterns, a great number of factors were related to their priorities outside of work. Similarly, a considerable number of nurses wrote about how they prefer their days off to be arranged, signifying the importance of having work schedules that support a good work-life balance. Work-life balance is traditionally framed by the conflict arising between work and family roles and responsibilities, including childcare (Greenhaus & Beutell, 1985; Netemeyer et al., 1996). Over 100 nurses in this study cited childcare responsibilities as an important factor. We attributed this high code frequency to two possible explanations: arranging childcare is important for nurses and takes clear precedence when choosing shifts, and/or, given traditional interpretations of work-life balance, nurses feel that childcare is one of the few reasons accepted as valid when expressing shift preferences in practice. Evidence of the latter has been found elsewhere, particularly among hospitals evaluating rostering processes/policies, where an inherent 'hierarchy of preferences' (with childcare taking top priority) was flagged as an obstacle to remove (Harris et al., 2010; NHS Employers, 2020). In contrast, contemporary definitions approach work-life balance more holistically, making room for more priorities, including rest, social time and leisure (Kalliath & Brough, 2008; Pichler, 2009), all of which were also found in nurses' qualitative responses.

Certain configurations of shift patterns and working time, including long weekly working hours, unpredictable shifts and shifts worked during social hours and nights, have been identified as potential stressors on work-life balance (Albertsen et al., 2008; Arlinghaus et al., 2019; Arlinghaus & Nachreiner, 2016; Grzywacz, 2016). Some shift configurations may be actively chosen by nurses to enable work-life balance, like long shifts or compressed working weeks (Dall'Ora et al., 2022). However, consequences can appear in the long term, such as increased fatigue and longer time needed for recovery, which nurses identified in this study as disruptive to their priorities in and outside of work. With increasing numbers of nurses in the UK citing work-life balance as the reason for leaving their current role (NHS Digital, 2022), finding feasible ways of improving work-life balance for nurses, especially when considering the design of their work schedules, remains an important area of inquiry. However, as work-life balance may not always be explicitly defined, researchers and ward managers should take care to understand what factors nurses have in mind when stating this concept, as different priorities attributed to the work-life balance 'umbrella' (e.g. childcare responsibilities vs. rest and recovery) will likely result in conflicting shift preferences.

Incorporating nurses' varied individual preferences is undoubtedly difficult from a scheduling perspective, both in terms of safeguarding ward coverage and ensuring fair consideration of requests. To avoid the difficult and time-consuming task of reconciling these elements in practice, ward coverage is likely to be prioritised, and limited (or no) choice over working time may be offered to nurses, as demonstrated in this study. As an alternative to this challenging status quo, more 'universal' scheduling practices could be applied that still support nurses' individual needs and preferences. In their qualitative responses, nurses mentioned three concepts that could work in this sense: reducing the use of adverse shift patterns, improving consistency in personal rotas and increasing flexibility and control over working time.

Although relevant guidance urges employers to avoid the use of adverse or non-ergonomic shift patterns (e.g. excessive weekly working hours or inadequate rest periods between shifts) (Health and Safety Executive (HSE), 2006), this may not be prioritised in settings that are resource constrained. With the worsening health workforce crisis in the UK, nurses report having to work longer hours and more challenging schedules to ensure some level of minimum ward coverage (Nursing & Midwifery Council, 2022; Royal College of Nursing, 2021). Evidence of this was also present in the current study, as nurses mentioned many difficulties with working non-ergonomic shift patterns. Furthermore, among the nurses who usually worked long shifts, notable proportions also worked at least 4 days per week, more than 4 days in a row and more than 48 h per week—all exceeding guidance. Being made to work difficult shift patterns poses negative implications for rates of sickness absence, job satisfaction and retention, likely as a result of increased burnout, disrupted recovery and poor work-life balance (Dall'Ora et al., 2020; Gifkins et al., 2020; Jacobsen & Fjeldbraaten, 2018).

To support ward managers in creating rosters that are safer for nurses, modern rostering technology could be used to develop ergonomic rotas while also balancing ward coverage, staffing numbers and patient demand. Previous research has demonstrated benefits for health care workers when embedding ergonomic shift work recommendations in rostering software, particularly in terms of reducing adverse working patterns, sleep difficulties and occupational injury (Härmä et al., 2022; Karhula et al., 2021; Shiri & Härmä, 2023), but outcomes related to work-life balance are less understood. Moreover, nurses may still prefer to work more difficult shift patterns when given the choice (Karhula et al., 2018, 2020), but in these cases, risk could still be mitigated thereafter (e.g. if a nurse prefers to work long shifts only, limit the number of long shifts that are worked in a row).

Rota consistency and predictability were also identified as enablers of better experiences in and outside of work. Even if individual preferences differed, the need for consistency frequently united responses and was defined by nurses as working the same shift types or start times, having the same working days and days off each week or having a more predictable shift pattern rotation. In the UK, the issue of working unpredictable shift patterns has been recently prioritised by the NHS Long Term Plan (NHS, 2019) as well as the Royal College of Nursing (Royal College of Nursing, 2020); however, solutions have yet to be identified. Having rosters published in reasonable timeframes facilitates nurses' ability to manage personal commitments (Carter, 2016; Drake, 2018); however, if planned shifts have no discernible pattern or sense of consistency, nurses may still find it difficult to plan and engage in their lives outside of work. Moreover, in a recent analysis of pan-European survey data on working conditions, high levels of employer-enforced worktime variability (i.e. variable weekly working hours, working days per week and daily start/end times) resulted in poorer self-rated health, wellbeing and sleep for workers. The authors also found that high worktime variability (and low worktime control) was a more frequent feature of the health sector when compared to the retail or hospitality sectors (Backhaus, 2022).

Nurses also wanted more flexibility around their shift patterns. Our findings align with nurses' definitions of 'flexible working' in other studies, where flexibility centres more on choice and control rather than short-notice rota changes or increased variability in work tasks (Atkinson & Hall, 2011; Beckers et al., 2012; Nabe-Nielsen et al., 2012). Recent NHS guidance (NHS Staff Council, 2021a, 2021b) has encouraged employers to adopt flexible working policies to give nurses more control over their working time and reduce barriers to requesting alternative arrangements, which could include working fixed patterns, staggered start/finish times and compressed or elongated workhours. This guidance also emphasises that these arrangements should be accessible to everyone, and not only for those with caring responsibilities. Previous research exploring the objective working hours of health care staff with high worktime control showed that these workers chose greater variability in shift types (i.e. more evening and weekend shifts) and length when compared to those with intermediate or low worktime control but did not necessarily compromise ergonomic recommendations for shift patterns (Garde et al., 2012; Karhula et al., 2019).

Other flexible worktime interventions, like self-/team-scheduling (where employees schedule their rota themselves, given pre-established rules) or participatory-scheduling (where coverage needs, guidance on working time arrangements and employees' preferences are combined through formal processes), are gaining popularity in some settings. Previous research exploring the success of such interventions has shown mixed results (Beckers et al., 2012; Wynendaele et al., 2021). Employer and management concerns on implementation and feasibility of such policies and interventions can also hinder uptake and success. Nevertheless, given that nurses in this study mentioned flexibility in the context of choosing shift patterns that are more predictable or less adverse, many flexible working requests could theoretically be addressed by safeguarding ergonomic guidelines and predictable working patterns.

4.1 | Limitations

Although we undertook extensive piloting and cognitive testing to develop the survey, we did not assess test-retest reliability, and therefore the stability of expressed preferences and opinions over time cannot be inferred. Second, respondents were prompted to be brief in their qualitative response (i.e. '...what would be the *most* important factor'), and therefore some context related to shift choice/preference was likely to have been missed. Nonetheless, many respondents still provided multiple and related elements in their responses despite this prompt. Third, given that the survey was anonymous and was in part distributed online, we could not track the possibility of respondents submitting more than one response. However, with the survey's length, the required level of engagement and the absence of participation incentives/rewards, we estimate that the likelihood of the submission of multiple responses was low. Lastly, our survey did not explicitly capture the views and experiences of managers and schedulers. Future research should explore the scheduling process from their point of view, particularly when it comes to managing nurses' shift preferences alongside operational needs, workforce shortages and the recent increased demand to support employee work-life balance.

5 | CONCLUSIONS

Nurses consider and value a variety of factors when thinking about their shift pattern preferences. Many of these factors were related to nurses' priorities outside of work, such as looking after their personal health & wellbeing, protecting social time & relationships and managing caring responsibilities. Our findings contribute to the growing body of research on the importance of nurses' wellbeing in and outside of the workplace by highlighting the need to organise shift patterns in ways that protect and promote a good work-life balance. Working short, long or rotating shifts did not offer clear advantages in terms of fulfilling nurses' priorities when compared to one another, and therefore, assumptions about relevant outcomes when working specific shift types (e.g. 'long shifts are great for work-life balance') should be questioned.

RELEVANCE TO CLINICAL PRACTICE

Nurses described three general scheduling practices that would support their individual priorities and shift preferences: using ergonomic shift pattern recommendations when establishing rosters, ensuring shift patterns are consistent and predictable and facilitating more flexibility and control over working time. These concepts have previously shown benefits for workers in healthcare settings and could be feasibly implemented with existing guidance and modern rostering software. However, the use of these practices must be equally balanced with organisational demands and patient wellbeing, which is challenging given ongoing issues related to nursing staff retention and shortages.

AUTHOR CONTRIBUTIONS

Talia Emmanuel: Conceptualisation, Formal analysis, Writing (original draft). Peter Griffiths: Conceptualisation, Formal analysis, Writing (original draft). Carlos Lamas-Fernandez: Formal analysis, Writing (original draft). Ourega-Zoé Ejebu: Conceptualisation, Project administration, Writing (review & editing). Chiara Dall'Ora: Conceptualisation, Methodology, Project administration, Formal analysis, Writing (original draft).

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing or conflicting interests.

DATA AVAILABILITY STATEMENT

The survey dataset analysed in this study has been deposited in the University of Southampton Institutional Repository, available via https://doi.org/10.5258/SOTON/D2278.

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Appendix A

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Appendix B | Chapter 5 Supplementary Files

B.1 Python code: Shift pattern variable dataset

```
## IMPORTING LIBRARIES ##

import numpy as np

import pandas as pd

from datetime import timedelta

from datetime import datetime

import scipy.stats as stats

from tqdm import tqdm


## LOADING DATASET ##

df =
pd.read_csv('C:/Users/te2n17/Documents/WHOs_Shift_Patterns_CSVs/Raw_Data_CSVs/VER3_merged_shifts_RN_
A-B.csv')


## make sure rows are sorted correctly ##

df.sort_values(by =['Hospital_Id','Staff_Id', 'event_date'], inplace=True, ignore_index=True)


## change data in date-related columns from object(string) to datetime ##

df['event_date'] = pd.to_datetime(df['event_date'])

df['ShiftStart_Datetime'] = pd.to_datetime(df['ShiftStart_Datetime'])

df['ShiftEnd_Datetime'] = pd.to_datetime(df['ShiftEnd_Datetime'])

df['ShiftStart_Date'] = pd.to_datetime(df['ShiftStart_Date'])

df['ShiftEnd_Date'] = pd.to_datetime(df['ShiftEnd_Date'])

df['sickness_start_date_time'] = pd.to_datetime(df['sickness_start_date_time'])


#%%

## STANDALONE (WITHIN ROWS) ##

# shift start time

df['start_time'] = df['ShiftStart_Datetime'].dt.time

# shift end time

df['end_time'] = df['ShiftEnd_Datetime'].dt.time
```

```
#creating night shift column 'night'

df['night'] = df['ShiftEnd_Datetime'].dt.hour <= 8.1

df.loc[df['ShiftEnd_Datetime'].isna(), 'night'] = pd.NA


#calculating shift length, based on 'seconds working'

df['length_hrs'] = df.loc[:, 'Seconds_Working_num']

df['length_hrs'] = df['length_hrs'] / 3600


#calculating shift length, based on shift start/end timestamps

df['length_hrs_stamp'] = (df['ShiftEnd_Datetime'] - df['ShiftStart_Datetime'])/pd.Timedelta(hours=1)


#calculating number of night hours

df['numnighthours'] = np.select([df['night'].eq(True)], [df['length_hrs_stamp']],np.nan)


#calculating number of bank hours

df['numbankhours'] = np.select([df['FulfillmentType'].eq('Bank')], [df['length_hrs_stamp']],np.nan)


#calculating overtime hours per shift

df['overtime_hrs'] = df.loc[:, 'Seconds_Overtime_num']

df['overtime_hrs'] = df['overtime_hrs'] / 3600


#calculating breaktime

df['break_hrs'] = (df['length_hrs_stamp'] - df['length_hrs'])


#categorising shift length, short <8 hours, medium 8.1-10.9 hours, long >11 hours

shift_length_bins = [3.5, 9, 10.9, 18]

shift_length_labels = ['short', 'medium', 'long']

df['shift_length_cat'] = pd.cut(df['length_hrs_stamp'],shift_length_bins,labels = shift_length_labels)


#categorising sickness episode length, short <7 days, long between 7 and 28 days, leave >28 days

SA_length_bins = [df['absence_days'].min()-1, 6.9, 27.9, df['absence_days'].max()+1]

SA_length_labels = ['short', 'long', 'leave']

df['SA_length_cat'] = pd.cut(df['absence_days'], SA_length_bins, labels = SA_length_labels)


#creating quick return column 'quickreturn'
```

```
df['quickreturn'] = df['restperiod'] <= 11.51

df.loc[df['restperiod'].isna(), 'quickreturn'] = pd.NA


#reassigning shifts recorded fully as overtime to new FulfillmentType category: "OT_Local"

OT_rows = (df['FulfillmentType'] == 'Local') & (df['Seconds_Working_num'] > 0) & (df['Seconds_Working_num'] ==
df['Seconds_Overtime_num'])

df.loc[OT_rows, 'FulfillmentType'] = 'OT_Local'


#%%

## PER STAFF (ITERROWS) ##

start_time = datetime.now() #checking running time, START

staff_list = df['Staff_Id'].unique()

df['shortreturn'] = pd.NA

df['firstsickness'] = False

df['DTNshiftrotation'] = pd.NA

df['NTDshiftrotation'] = pd.NA

df['shiftrotation'] = pd.NA


lookback_list = [7, 28, 91]

for l in lookback_list:

  df['lb_start_' + str(l)] = pd.NA #start of lookback period (date)

  df['lb_median_week_hours_' + str(l)] = pd.NA #median working hours per 7-day period

  df['lb_mean_week_hours_' + str(l)] = pd.NA #mean working hours per 7-day period

  df['lb_part_time_' + str(l)] = pd.NA #part time flag


  if l > 30: #if lookback is greater than 30, escape loop

    continue


  df['lb_totalhours_' + str(l)] = pd.NA #total working hours

  df['lb_longweek_'+ str(l)] = pd.NA # long working week 0/1 flag

  df['lb_all_OThours_' + str(l)] = pd.NA #continuous - sum of working hours recorded as overtime

  df['lb_any_OThours_' + str(l)] = pd.NA #binary - any working hours recorded as OT

  df['lb_all_EXhours_' + str(l)] = 0 #continuous - sum of extra hours worked as OT in the same shift

  df['lb_any_EXhours_' + str(l)] = pd.NA #continuous - any extra hours worked as OT in the same shift

  df['lb_numshifts_' + str(l)] = pd.NA #total number of shifts

  df['lb_numlongshifts_' + str(l)] = pd.NA #total number of long shifts
```

```
    df['lb_numnightshifts_' + str(l)] = pd.NA #total number of night shifts
    df['lb_numnighthours_' + str(l)] = pd.NA #total number of night hours
    df['lb_medshiftlength_' + str(l)] = pd.NA #median shift length
    df['lb_numquickreturns_' + str(l)] = pd.NA #number of quick returns
    df['lb_numshortreturns_' + str(l)] = pd.NA #number of short returns
    df['lb_workspells_' + str(l)] = pd.NA #number of workspells
    df['lb_intense_workspells_' + str(l)] = pd.NA #number of intense workspells
    df['lb_long_workspells_' + str(l)] = pd.NA #number of long workspells
    df['lb_shiftrotation_' + str(l)] = pd.NA #number of shift rotations
    df['lb_DTNshiftrotation_' + str(l)] = pd.NA #number of day-to-night shift rotations
    df['lb_NTDshiftrotation_' + str(l)] = pd.NA #number of night-to-day shift rotations
    df['lb_numsickepisodes_'+ str(l)] = pd.NA #number of sickness episodes
    df['lb_numsickdays_'+ str(l)] = pd.NA #number of sickness days


for ii, nurse in tqdm(enumerate(staff_list)):
    df2 = df.loc[df['Staff_Id'] == nurse]
    count = 0
    previdx = -1
    for idx, row in df2.iterrows():
        count += 1
        if count == 1:
            if df.at[idx, 'case_control'] == 1: # if sickness episode row
                df.at[idx, 'firstsickness'] = pd.NA #if the first row of a Staff_Id is a sickness episode, assign NA
            previdx = idx
            continue


        #short returns (<48 hours between ending a night shift and starting a day shift)
        if df.at[idx,'night'] == False and df.at[previdx,'night']:
            if df.at[idx,'restperiod'] <= 47.5:
                df.at[idx,'shortreturn'] = True


        if df.at[idx,'case_control'] == 1 and df.at[previdx,'case_control'] == 0:
            df.at[idx, 'firstsickness'] = True


        #if df.at[previdx,'case_control'] == 1:
```

```
    rotperiod = (df.at[idx, 'event_date'] - df.at[previdx, 'event_date']).days


    #Rotation; 0/1 flag if any rotation occurs

    if df.at [idx, 'case_control'] == 0 and df.at [previdx, 'case_control'] == 0 and df.at[idx, 'night'] != df.at[previdx, 'night']
and rotperiod < 7.001:

      df.at[idx, 'shiftrotation'] = 1


    #DTN shift rotation; 0/1 flag if a day-to-night shift rotation occurs

    if df.at[idx, 'night'] == True and df.at[previdx, 'night'] == False and rotperiod < 7.001:

      df.at[idx, 'DTNshiftrotation'] = 1


    #NTD shift rotation; 0/1 flag if a night-to-day shift rotation occurs

    if df.at[idx, 'night'] == False and df.at[previdx, 'night'] == True and rotperiod < 7.001:

      df.at[idx, 'NTDshiftrotation'] = 1


  #########################

    #### LOOKBACK VARIABLES ####


    for l in lookback_list:

      lookback = l

      lb_cutoff = lookback

      cutoff_timestamp = df.at[idx, 'event_date'] - pd.Timedelta(days=lb_cutoff)

      cutoff_timestamp = cutoff_timestamp.replace(hour=0, minute=0, second=0)

      df.at[idx, 'lb_start_' + str(l)] = cutoff_timestamp


      df3 = df2[df2['event_date'] <= cutoff_timestamp]

      lb_valid = True

      if len(df3) < 1:

        lb_valid = False

      if lb_valid:


        df4 = df.loc[df['Staff_Id'] == nurse]

        df4 = df4[df4['event_date'] >= cutoff_timestamp]

        df4 = df4[df4['event_date'] <= df.at[idx, 'event_date'] - pd.Timedelta(minutes=1)]
```

```
## WEEKLY WORKING HOURS##


nweeks = int(l/7) #creating df5, which looks at 7 day periods within the lookback period

weekly_hours = np.zeros(nweeks)

for week in range(nweeks):

   wstart = cutoff_timestamp + pd.Timedelta(days=7*week)

   wend = cutoff_timestamp + pd.Timedelta(days=7*(week+1))

   if week == nweeks - 1:

      wend = df.at[idx, 'event_date']

   df5 = df4[df4['event_date'] >= wstart]

   df5 = df5[df5['event_date'] <= wend]

   weekly_hours[week] = df5['length_hrs_stamp'].sum()

df.at[idx, 'lb_longweek_' + str(l)] = (weekly_hours > 48.001).sum()

df.at[idx, 'lb_median_week_hours_' + str(l)] = np.median(weekly_hours)

df.at[idx, 'lb_mean_week_hours_' + str(l)] = np.mean(weekly_hours)


if df.at[idx, 'lb_median_week_hours_' + str(l)] < 26.001: #part-time flag based on median weekly working hours

   df.at[idx, 'lb_part_time_' + str(l)] = True

else:

   df.at[idx, 'lb_part_time_' + str(l)] = False


if l > 30: #if lookback is greater than 30, escape loop

   continue


df.at[idx, 'lb_totalhours_' + str(l)] = df4['length_hrs_stamp'].sum()

# if df.at[idx, 'lb_totalhours_' + str(l)] > 48.001:

#    df.at[idx, 'lb_longweek_' + str(l)] = True


## OVERTIME ##


df.at[idx, 'lb_all_OThours_' + str(l)] = df4['overtime_hrs'].sum()

if df.at [idx, 'lb_all_OThours_' + str(l)] > 0:

   df.at [idx, 'lb_any_OThours_' + str(l)] = True

else:

   df.at [idx, 'lb_any_OThours_' + str(l)] = False
```

```
if df.at[idx, 'FulfillmentType'] == 'Local':
   df.at[idx, 'lb_all_EXhours_' + str(l)] = df4['overtime_hrs'].sum()

if df.at[idx, 'lb_all_EXhours_' + str(l)] > 0:
   df.at [idx, 'lb_any_EXhours_' + str(l)] = True
else:
   df.at [idx, 'lb_any_EXhours_' + str(l)] = False

## BANK ##

fulfill_lb = df4['FulfillmentType'].value_counts()
if 'Bank' in fulfill_lb.keys():
   df.at[idx, 'lb_numbankshifts_' + str(l)] = fulfill_lb['Bank']
else:
   df.at[idx, 'lb_numbankshifts_' + str(l)] = 0
df.at[idx, 'lb_bankhours_' + str(l)] = df4['numbankhours'].sum()

## N SHIFTS, LONG SHIFTS, NIGHT SHIFTS/HOURS, MED SHIFT LENGTH ##

df.at[idx, 'lb_numshifts_' + str(l)] = len(df4[df4 ['case_control'] == 0])
#checking: dummy_df = df.loc[90:105, ['FulfillmentType', 'event_date', 'lb_numshifts_7']]

df.at[idx, 'lb_numlongshifts_' + str(l)] = df4['shift_length_cat'].value_counts()['long']

df.at[idx, 'lb_medshiftlength_' + str(l)] = df4['length_hrs_stamp'].median()
#df.at[idx, 'lb_propshiftslong_' + str(l)] = df4['lb_numlongshifts_' + str(l)] / df4['lb_numshifts_' + str(l)]

df.at[idx, 'lb_numnightshifts_' + str(l)] = df4['night'].fillna(0).astype(int).sum() #number of night shifts
df.at[idx, 'lb_numnighthours_' + str(l)] = df4['numnighthours'].sum() #number of night hours
#df.at[idx, 'lb_propshiftsnight_' + str(l)] = df4['lb_numnightshifts_' + str(l)] / df4['lb_numshifts_' + str(l)]

## QUICK RETURNS, SHORT RETURNS ##

df.at[idx, 'lb_numquickreturns_' + str(l)] = df4['quickreturn'].fillna(0).astype(int).sum()
```

```
df.at[idx, 'lb_numshortreturns_' + str(l)] = df4['shortreturn'].fillna(0).astype(int).sum()


## SHIFT ROTATIONS ##


df.at[idx, 'lb_shiftrotation_'+ str(l)] = df4['shiftrotation'].fillna(0).astype(int).sum()
df.at[idx, 'lb_DTNshiftrotation_'+ str(l)] = df4['DTNshiftrotation'].fillna(0).astype(int).sum()
df.at[idx, 'lb_NTDshiftrotation_'+ str(l)] = df4['NTDshiftrotation'].fillna(0).astype(int).sum()


## SICK DAYS & EPISODES IN LOOKBACK ##


df.at[idx, 'lb_numsickepisodes_' + str(l)] = len(df4[df4 ['case_control'] == 1])


df4s = df4[df4 ['case_control'] == 1] # SA episodes only
df.at[idx, 'lb_numsickdays_' + str(l)] = df4s['absence_days'].sum()


## WORK SPELLS (CONSECUTIVE DAYS) ##


df4w = df4[df4 ['case_control'] == 0]


count_wspell = 0
count_intense_wspells = 0
count_long_wspells = 0


duration_current_wpsell = 0
duration_current_long_wpsell = 0


intense_duration = 0
position = -1
wspell_counted = False


if len(df4w) >= 1:
  for i4, r4 in df4w.iterrows():
    position += 1
    intense = r4['night'] or r4['shift_length_cat'] == 'long'
```

```
if position == 0: # First shift
    wspell_counted = False
    duration_current_wpsell = 1
    duration_current_long_wpsell = 1
    if intense:
        intense_duration += 1

else: # Subsequent shifts
    new_spell = False
    if pd.isna(r4['restperiod']):
        new_spell = True
    elif r4['restperiod'] >= 24:
        new_spell = True

    if not new_spell:
        duration_current_wpsell += 1
        duration_current_long_wpsell += 1
        if intense:
            intense_duration += 1
        else:
            intense_duration = 0

        if not wspell_counted and duration_current_wpsell >= 2:
            count_wspell += 1
            wspell_counted = True

        if duration_current_long_wpsell >= 6:
            count_long_wspells =+ 1
            duration_current_long_wpsell = 0

        if intense_duration >= 3:
            count_intense_wspells += 1
            intense_duration = 0
    else:
        wspell_counted = False
```

```
                duration_current_wpsell = 1

                duration_current_long_wpsell = 1

                intense_duration = 0

                if intense:

                   intense_duration += 1


        df.at[idx, 'lb_workspells_' + str(l)] = count_wspell

        df.at[idx, 'lb_intense_workspells_' + str(l)] = count_intense_wspells

        df.at[idx, 'lb_long_workspells_' + str(l)] = count_long_wspells


        df.at[idx, 'lb_workspells_' + str(l)] = count_wspell

        df.at[idx, 'lb_intense_workspells_' + str(l)] = count_intense_wspells

        df.at[idx, 'lb_long_workspells_' + str(l)] = count_long_wspells


    ##########################

    previdx = idx #move to the next row

end_time = datetime.now() #checking running time, END

print('Duration: {}'.format(end_time - start_time))


#%%

## CLEANING & ORDERING COLUMNS ##

ordered_cols = 'Hospital_Id', 'Ward_Id', 'Staff_Id', 'FulfillmentType', 'Band_Numeric', 'JobType', 'RN_NA', 'ShiftStart_Datetime', 'ShiftEnd_Datetime', 'ShiftStart_Date', 'ShiftEnd_Date', 'event_date', 'start_time', 'end_time', 'case_control', 'Unavailability_Episode_Id', 'Unavailability_Reason', 'sickness_start_date_time', 'absence_days', 'SA_length_cat', 'Seconds_Working_num', 'Seconds_Contract_num', 'Seconds_Overtime_num', 'overtime_hrs', 'length_hrs', 'length_hrs_stamp', 'shift_length_cat', 'break_hrs', 'night', 'numnighthours', 'numbankhours', 'restperiod', 'quickreturn', 'shortreturn', 'shiftrotation', 'DTNshiftrotation', 'NTDshiftrotation', 'lb_start_7', 'lb_totalhours_7', 'lb_mean_week_hours_7', 'lb_median_week_hours_7', 'lb_longweek_7', 'lb_numshifts_7', 'lb_numlongshifts_7', 'lb_medshiftlength_7', 'lb_numnightshifts_7', 'lb_numnighthours_7', 'lb_numquickreturns_7', 'lb_numshortreturns_7', 'lb_numbankshifts_7', 'lb_bankhours_7', 'lb_all_OThours_7', 'lb_any_OThours_7', 'lb_all_EXhours_7', 'lb_any_EXhours_7', 'lb_workspells_7', 'lb_intense_workspells_7', 'lb_long_workspells_7', 'lb_shiftrotation_7', 'lb_DTNshiftrotation_7', 'lb_NTDshiftrotation_7', 'lb_numsickepisodes_7', 'lb_numsickdays_7', 'lb_start_28', 'lb_totalhours_28', 'lb_mean_week_hours_28', 'lb_median_week_hours_28', 'lb_longweek_28', 'lb_numshifts_28', 'lb_numlongshifts_28', 'lb_medshiftlength_28', 'lb_numnightshifts_28', 'lb_numnighthours_28', 'lb_numquickreturns_28', 'lb_numshortreturns_28', 'lb_numbankshifts_28', 'lb_bankhours_28', 'lb_all_OThours_28', 'lb_any_OThours_28', 'lb_all_EXhours_28', 'lb_any_EXhours_28', 'lb_workspells_28', 'lb_intense_workspells_28', 'lb_long_workspells_28', 'lb_shiftrotation_28', 'lb_DTNshiftrotation_28', 'lb_NTDshiftrotation_28', 'lb_numsickepisodes_28', 'lb_numsickdays_28', 'lb_start_91', 'lb_mean_week_hours_91', 'lb_median_week_hours_91', 'lb_part_time_91'

ordered_df = df.loc[:, ordered_cols]

ordered_df.to_csv('OrderedCols_FullDataset-13Mar2024.csv')
```

B.2 Data dictionary: Shift pattern variable dataset

Source*	Level**	Column Name	Description	Notes
1	NA	'Hospital_Id'	Hospital ID	A, B
1	NA	'Ward_Id'	Ward ID	
1	NA	'Staff_Id'	Staff ID	
1	NA	'FulfillmentType'	Type of fulfillment	Local, Local OT, Bank
1	NA	'Band_Numeric'	Band	
1	NA	'JobType'	Job Title	
1	NA	'RN_NA'	RN or NA	RNs included only
1	NA	ShiftStart_Datetime'	Date + timestamp for start of shift	
1	NA	ShiftEnd_Datetime'	Date + timestamp for end of shift	
1	NA	ShiftStart_Date'	Date for start of shift	
1	NA	'ShiftEnd_Date'	Date for end of shift	
2	1	'event_date'	Date + timestamp for start of shift OR start of SA episode	
2	1	start_time'	Timestamp for start of shift	
2	1	end_time'	Timestamp for end of shift	
2	1	'case_control'	Worked shift or SA episode	0 == worked shift, 1 == sickness absence episode
1	NA	'Unavailability_Episode_Id'	SA episode ID	
1	NA	'Unavailability_Reason'	SA reason category	
1	NA	'sickness_start_date_time'	Date + tiemstamp for start of SA episode	
1	NA	'absence_days'	Number of sick days in SA epsiode	
2	1	'SA_length_cat'	Category of SA epsiode	short (<7 days), long (7-28 days), leave (>= 28days)
1	NA	Seconds_Working_num'	Total seconds recorded as working	
1	NA	'Seconds_Contract_num'	Total seconds scheduled	
1	NA	Seconds_Overtime_num'	Total seconds recorded as overtime	In general: working-scheduled = overtime
2	1	'overtime_hrs'	Overtime hours	
2	1	length_hrs'	Length of shift, based on 'Seconds_Working_num'	excluding breaks

2	1	length_hrs_stamp'	Length of shift, based on difference between 'ShiftEnd_Datetime' - 'ShiftStart_Datetime'	including breaks
2	1	shift_length_cat'	category of shift length, based on 'length_hrs_stamp'	short (<9 hours), medium (9.1-10.9 hours), long (>11 hours)
2	1	'break_hrs'	break time hours, calculated as difference between 'length_hrs_stamp' - 'length_hrs'	
2	1	'night'	night shift, TRUE if 'ShiftEnd_Datetime' is before 08:00	
2	1	'numnighthours'	Length of night shift	
2	1	'numbankhours'	Length of bank shift	
2	2	restperiod'	Intershift recovery period	
2	2	'quickreturn'	TRUE if 'restperiod' was <11.5 hours	
2	2	'shortreturn'	TRUE if < 47.5 hours between ending a night shift and starting a day shift	
2	2	'shiftrotation'	TRUE if current shift is a rotation from previous shift	only true if period between shifts is >= 7 days
2	2	'DTNshiftrotation'	TRUE if a day-to-night shift rotation occurred	only true if period between shifts is >= 7 days
2	2	'NTDshiftrotation'	TRUE if a night-to-day shift rotation occurs	only true if period between shifts is >= 7 days
2	3	'lb_start_7'	start of the 7-day lookback period	current row is not counted
2	3	lb_totalhours_7'	sum of all hours worked in the lookback	
2	3	'lb_mean_week_hours_7'	mean hours worked in the lookback	
2	3	'lb_median_week_hours_7'	median hours worked in the lookback	
2	3	lb_longweek_7'	number of long weeks (>= 48 hours) over each 7-day period in the lookback	
2	3	lb_numshifts_7'	number of shifts in the lookback	
2	3	lb_numlongshifts_7'	number of long shifts in the lookback	
2	3	lb_medshiftlength_7'	median shift length in the lookback	
2	3	lb_numnightshifts_7'	number of night shifts in the lookback	
2	3	lb_numnighthours_7'	number of night hours in the lookback	
2	3	lb_numquickreturns_7'	number of quick returns in the lookback	
2	3	lb_numshortreturns_7'	number of short returns in the lookback	
2	3	lb_numbankshifts_7'	number of bank shifts in the lookback	
2	3	lb_bankhours_7'	number of bank hours in the lookback	

2	3	lb_all_OThours_7'	sum of all hours recorded as overtime in the lookback	
2	3	'lb_any_OThours_7'	TRUE if any overtime was worked in the lookback	
2	3	'lb_all_EXhours_7'	sum of all extra hours only (when staff worked longer than scheduled) in the lookback	can interpret this value as "true" overtime hours in lookback
2	3	'lb_any_EXhours_7'	TRUE if any extra hours were worked in the lookback	can interpret this value as "true" overtime worked in lookback
2	3	'lb_workspells_7'	number of spells of consecutive shifts in the lookback	groups of shifts separated by <= 24 hours
2	3	lb_intense_workspells_7'	number of intense workspells in the lookback	intense workspell occurs when >= 3 long or night shifts worked consecutively
2	3	lb_long_workspells_7'	number of intense workspells in the lookback	long workspell occurs when >= 6 shifts (any type) worked consecutively
2	3	lb_shiftrotation_7'	number of shift rotations in the lookback	
2	3	lb_DTNshiftrotation_7'	number of day-to-night shift rotations in the lookback	
2	3	lb_NTDshiftrotation_7'	number of night-to-day shift rotations in the lookback	
2	3	'lb_numsickepisodes_7'	number of SA episodes in the lookback	
2	3	'lb_numsickdays_7'	number of sick days in the lookback	
2	3	'lb_start_28'	start of the 28-day lookback period	current row is not counted
2	3	lb_totalhours_28'	sum of all hours worked in the lookback	
2	3	'lb_mean_week_hours_28'	mean weekly hours worked in the lookback	per 7-day period in the lookback
2	3	'lb_median_week_hours_28'	median weekly hours worked in the lookback	per 7-day period in the lookback
2	3	'lb_numshifts_28'	number of shifts in the lookback	
2	3	'lb_numlongshifts_28'	number of long shifts in the lookback	
2	3	'lb_medshiftlength_28'	median shift length in the lookback	
2	3	'lb_numnightshifts_28'	number of night shifts in the lookback	
2	3	'lb_numnighthours_28'	number of night hours in the lookback	
2	3	'lb_numquickreturns_28'	number of quick returns in the lookback	
2	3	'lb_numshortreturns_28'	number of short returns in the lookback	
2	3	lb_numbankshifts_28'	number of bank shifts in the lookback	
2	3	lb_bankhours_28'	number of bank hours in the lookback	
2	3	'lb_all_OThours_28'	sum of all hours recorded as overtime in the lookback	
2	3	'lb_any_OThours_28'	TRUE if any overtime was worked in the lookback	

2	3	lb_all_EXhours_28'	sum of all extra hours only (when staff worked longer than scheduled) in the lookback	
2	3	lb_any_EXhours_28'	TRUE if any extra hours were worked in the lookback	
2	3	'lb_workspells_28'	number of spells of consecutive shifts in the lookback	groups of shifts separated by <= 24 hours
2	3	'lb_intense_workspells_28'	number of intense workspells in the lookback	intense workspell occurs when >= 3 long or night shifts worked consecutively
2	3	'lb_long_workspells_28'	number of intense workspells in the lookback	long workspell occurs when >= 6 shifts (any type) worked consecutively
2	3	'lb_shiftrotation_28'	number of shift rotations in the lookback	
2	3	'lb_DTNshiftrotation_28'	number of day-to-night shift rotations in the lookback	
2	3	'lb_NTDshiftrotation_28'	number of night-to-day shift rotations in the lookback	
2	3	lb_numsickepisodes_28'	number of SA episodes in the lookback	
2	3	lb_numsickdays_28'	number of sick days in the lookback	
2	3	'lb_start_91'	start of the 91-day lookback period	
2	3	lb_mean_week_hours_91'	mean hours worked in the lookback	
2	3	'lb_median_week_hours_91'	median hours worked in the lookback	
2	3	lb_part_time_91'	TRUE if median weekly hours was <= 26	per 7-day period in the lookback

* 1 = raw data from original *Workforce Health Outcomes* staffing study (Griffiths *et al.*, 2023); 2 = created for current dataset
** 1 = calculated within each row; 2 = calculated per nurse, between the current row and the previous row; 3 = calculated per nurse, across a lookback period (7, 28, 91 days)

B.3 R code: Shift pattern descriptives, regression models

```
library(dplyr)

library (lme4)

library(car)

###################################################

data <-
read.csv("C:/Users/te2n17/Documents/WHOs_Shift_Patterns_CSVs/ShiftPatterns_Final_Data(15Mar2024).csv")

data <- subset(data, is.na(lb_totalhours_28) | lb_totalhours_28 <= 240)

# .7 are on 7-day lookback windows

# .28 are on 28-day lookback windows

# .91 are on 91-day lookback windows

###################################################

# DATA CLEANING


# change Staff_Id, Ward_Id, and Hospital_Id to factors

data$Staff_Id = as.factor(data$Staff_Id)

data$Ward_Id = as.factor(data$Ward_Id)

data$Hospital_Id = as.factor(data$Hospital_Id)


# change DV and other binary/categorical variables to appropriate data structure

data$case_control = as.factor(data$case_control)

levels(data$case_control) <- c("shift", "SA_episode")

data$lb_part_time_91 = as.factor(data$lb_part_time_91)

data <- data %>% mutate(lb_part_time_91 = na_if(lb_part_time_91, ""))

data$lb_part_time_91 <- droplevels(data$lb_part_time_91)

data$lb_any_EXhours_7  = as.factor(data$lb_any_EXhours_7 )

data <- data %>% mutate(lb_any_EXhours_7  = na_if(lb_any_EXhours_7 , ""))

data$lb_any_EXhours_7  <- droplevels(data$lb_any_EXhours_7 )

data$lb_any_EXhours_28  = as.factor(data$lb_any_EXhours_28 )

data <- data %>% mutate(lb_any_EXhours_28  = na_if(lb_any_EXhours_28 , ""))

data$lb_any_EXhours_28  <- droplevels(data$lb_any_EXhours_28 )

data$lb_longweek_7 = as.factor(data$lb_longweek_7)
```

```
####################################################

# NEW VARIABLES

# create proportion variables for long shifts, night shifts in past 7 and 28 days
# categorise these variables based on following percentages: 0, 1-25, 26-50, 51-75, 75-99, 100

breaks <- c(-Inf, 0.01, 0.26, 0.51, 0.76, 1.00, 1.01)
labels <- c("0", "0.01-0.25", "0.26-0.50", "0.51-0.75", "0.76-0.99", "1.00")

data$lb_proplongshifts_7 <- NA

data$lb_proplongshifts_7 <- (data$lb_numlongshifts_7/data$lb_numshifts_7)

data$lb_catproplongshifts_7 <- cut(data$lb_proplongshifts_7, breaks = breaks, labels = labels, right = FALSE)

data$lb_catproplongshifts_7 = as.factor(data$lb_catproplongshifts_7)

data$lb_proplongshifts_28 <- NA

data$lb_proplongshifts_28 <- (data$lb_numlongshifts_28/data$lb_numshifts_28)

data$lb_catproplongshifts_28 <- cut(data$lb_proplongshifts_28, breaks = breaks, labels = labels, right = FALSE)

data$lb_catproplongshifts_28 = as.factor(data$lb_catproplongshifts_28)

data$lb_propnightshifts_7 <- NA

data$lb_propnightshifts_7 <- (data$lb_numnightshifts_7/data$lb_numshifts_7)

data$lb_catpropnightshifts_7 <- cut(data$lb_propnightshifts_7, breaks = breaks, labels = labels, right = FALSE)

data$lb_catpropnightshifts_7 = as.factor(data$lb_catpropnightshifts_7)

data$lb_propnightshifts_28 <- NA

data$lb_propnightshifts_28 <- (data$lb_numnightshifts_28/data$lb_numshifts_28)

data$lb_catpropnightshifts_28 <- cut(data$lb_propnightshifts_28, breaks = breaks, labels = labels, right = FALSE)

data$lb_catpropnightshifts_28 = as.factor(data$lb_catpropnightshifts_28)


# create new variables for summary statistics PER NURSE

subset_data <- subset(data, lb_part_time_91 == 'False') # full time rows only

subset_data$year <- substr(subset_data$event_date, 1, 4)

subset_data$year = as.factor(subset_data$year)


per_nurse_summary <- subset_data %>%

 group_by(Staff_Id, Hospital_Id, year) %>%

 summarize(

  mean_totalhours_7 = mean(lb_totalhours_7, na.rm = TRUE),

  mean_totalhours_28 = mean(lb_totalhours_28, na.rm = TRUE),

  median_totalhours_7 = median(lb_totalhours_7, na.rm = TRUE),

  median_totalhours_28 = median(lb_totalhours_28, na.rm = TRUE),

  mean_shifts_7 = mean(lb_numshifts_7, na.rm = TRUE),

  mean_shifts_28 = mean(lb_numshifts_28, na.rm = TRUE),
```

```
median_shifts_7 = median(lb_numshifts_7, na.rm = TRUE),
median_shifts_28 = median(lb_numshifts_28, na.rm = TRUE),
mean_medshiftlength_7 = mean(lb_medshiftlength_7, na.rm = TRUE),
mean_medshiftlength_28 = mean(lb_medshiftlength_28, na.rm = TRUE),
median_medshiftlength_7 = median(lb_medshiftlength_7, na.rm = TRUE),
median_medshiftlength_28 = median(lb_medshiftlength_28, na.rm = TRUE),
mean_numlong_7 = mean(lb_numlongshifts_7, na.rm = TRUE),
mean_numlong_28 = mean(lb_numlongshifts_28, na.rm = TRUE),
median_numlong_7 = median(lb_numlongshifts_7, na.rm = TRUE),
median_numlong_28 = median(lb_numlongshifts_28, na.rm = TRUE),
mean_proplong_7 = mean(lb_proplongshifts_7, na.rm = TRUE),
mean_proplong_28 = mean(lb_proplongshifts_28, na.rm = TRUE),
median_proplong_7 = median(lb_proplongshifts_7, na.rm = TRUE),
median_proplong_28 = median(lb_proplongshifts_28, na.rm = TRUE),
mean_numnight_7 = mean(lb_numnightshifts_7, na.rm = TRUE),
mean_numnight_28 = mean(lb_numnightshifts_28, na.rm = TRUE),
median_numnight_7 = median(lb_numnightshifts_7, na.rm = TRUE),
median_numnight_28 = median(lb_numnightshifts_28, na.rm = TRUE),
mean_propnight_7 = mean(lb_propnightshifts_7, na.rm = TRUE),
mean_propnight_28 = mean(lb_propnightshifts_28, na.rm = TRUE),
median_propnight_7 = median(lb_propnightshifts_7, na.rm = TRUE),
median_propnight_28 = median(lb_propnightshifts_28, na.rm = TRUE),
mean_longspells_7 = mean(lb_long_workspells_7, na.rm = TRUE),
mean_longspells_28 = mean(lb_long_workspells_28, na.rm = TRUE),
median_longspells_7 = median(lb_long_workspells_7, na.rm = TRUE),
median_longspells_28 = median(lb_long_workspells_28, na.rm = TRUE),
mean_intensespells_7 = mean(lb_intense_workspells_7, na.rm = TRUE),
mean_intensespells_28 = mean(lb_intense_workspells_28, na.rm = TRUE),
median_intensespells_7 = median(lb_intense_workspells_7, na.rm = TRUE),
median_intensespells_28 = median(lb_intense_workspells_28, na.rm = TRUE),
mean_quickreturns_7 = mean(lb_numquickreturns_7, na.rm = TRUE),
mean_quickreturns_28 = mean(lb_numquickreturns_28, na.rm = TRUE),
median_quickreturns_7 = median(lb_numquickreturns_7, na.rm = TRUE),
median_quickreturns_28 = median(lb_numquickreturns_28, na.rm = TRUE),
```

```
    mean_shortreturns_7 = mean(lb_numshortreturns_7, na.rm = TRUE),
    mean_shortreturns_28 = mean(lb_numshortreturns_28, na.rm = TRUE),
    median_shortreturns_7 = median(lb_numshortreturns_7, na.rm = TRUE),
    median_shortreturns_28 = median(lb_numshortreturns_28, na.rm = TRUE),
    mean_rotations_7 = mean(lb_shiftrotation_7, na.rm = TRUE),
    mean_rotations_28 = mean(lb_shiftrotation_28, na.rm = TRUE),
    median_rotations_7 = median(lb_shiftrotation_7, na.rm = TRUE),
    median_rotations_28 = median(lb_shiftrotation_28, na.rm = TRUE),
  ) %>%
  ungroup()

# using per nurse averages, now inspect the whole dataset via grand means
overall_mean_summary <- per_nurse_summary %>%
  summarize(
    overallmean_totalhours_7 = mean(mean_totalhours_7, na.rm = TRUE),
    overallsd_totalhours_7 = sd(mean_totalhours_7, na.rm = TRUE),
    overallmean_totalhours_28 = mean(mean_totalhours_28, na.rm = TRUE),
    overallsd_totalhours_28 = sd(mean_totalhours_28, na.rm = TRUE),

    overallmean_shifts_7 = mean(mean_shifts_7, na.rm = TRUE),
    overallsd_shifts_7 = sd(mean_shifts_7, na.rm = TRUE),
    overallmean_shifts_28 = mean(mean_shifts_28, na.rm = TRUE),
    overallsd_shifts_28 = sd(mean_shifts_28, na.rm = TRUE),

    overallmean_medshiftlength_7 = mean(mean_medshiftlength_7, na.rm = TRUE),
    overallsd_medshiftlength_7 = sd(mean_medshiftlength_7, na.rm = TRUE),
    overallmean_medshiftlength_28 = mean(mean_medshiftlength_28, na.rm = TRUE),
    overallsd_medshiftlength_28 = sd(mean_medshiftlength_28, na.rm = TRUE),

    overallmean_numlong_7 = mean(mean_numlong_7, na.rm = TRUE),
    overallsd_numlong_7 = sd(mean_numlong_7, na.rm = TRUE),
    overallmean_numlong_28 = mean(mean_numlong_28, na.rm = TRUE),
    overallsd_numlong_28 = sd(mean_numlong_28, na.rm = TRUE),
    overallmean_proplong_7 = mean(mean_proplong_7, na.rm = TRUE),
    overallsd_proplong_7 = sd(mean_proplong_7, na.rm = TRUE),
    overallmean_proplong_28 = mean(mean_proplong_28, na.rm = TRUE),
```

```
overallsd_proplong_28 = sd(mean_proplong_28, na.rm = TRUE),

overallmean_numnight_7 = mean(mean_numnight_7, na.rm = TRUE),
overallsd_numnight_7 = sd(mean_numnight_7, na.rm = TRUE),
overallmean_numnight_28 = mean(mean_numnight_28, na.rm = TRUE),
overallsd_numnight_28 = sd(mean_numnight_28, na.rm = TRUE),
overallmean_propnight_7 = mean(mean_propnight_7, na.rm = TRUE),
overallsd_propnight_7 = sd(mean_propnight_7, na.rm = TRUE),
overallmean_propnight_28 = mean(mean_propnight_28, na.rm = TRUE),
overallsd_propnight_28 = sd(mean_propnight_28, na.rm = TRUE),

overallmean_longspells_7 = mean(mean_longspells_7, na.rm = TRUE),
overallsd_longspells_7 = sd(mean_longspells_7, na.rm = TRUE),
overallmean_longspells_28 = mean(mean_longspells_7, na.rm = TRUE),
overallsd_longspells_28 = sd(mean_longspells_28, na.rm = TRUE),

overallmean_intensespells_7 = mean(mean_intensespells_7, na.rm = TRUE),
overallsd_intensespells_7 = sd(mean_intensespells_7, na.rm = TRUE),
overallmean_intensespells_28 = mean(mean_intensespells_28, na.rm = TRUE),
overallsd_intensespells_28 = sd(mean_intensespells_28, na.rm = TRUE),

overallmean_quickreturns_7 = mean(mean_quickreturns_7, na.rm = TRUE),
overallsd_quickreturns_7 = sd(mean_quickreturns_7, na.rm = TRUE),
overallmean_quickreturns_28 = mean(mean_quickreturns_28, na.rm = TRUE),
overallsd_quickreturns_28 = sd(mean_quickreturns_28, na.rm = TRUE),

overallmean_shortreturns_7 = mean(mean_shortreturns_7, na.rm = TRUE),
overallsd_shortreturns_7 = sd(mean_shortreturns_7, na.rm = TRUE),
overallmean_shortreturns_28 = mean(mean_shortreturns_28, na.rm = TRUE),
overallsd_shortreturns_28 = sd(mean_shortreturns_28, na.rm = TRUE),

overallmean_rotations_7 = mean(mean_rotations_7, na.rm = TRUE),
overallsd_rotations_7 = sd(mean_rotations_7, na.rm = TRUE),
overallmean_rotations_28 = mean(mean_rotations_28, na.rm = TRUE),
overallsd_rotations_28 = sd(mean_rotations_28, na.rm = TRUE),
```

```
 ) %>%
  ungroup()

# using per nurse averages, now inspect the whole dataset via grand medians
overall_median_summary <- per_nurse_summary %>%
 summarize(
  overallmedian_totalhours_7 = median(median_totalhours_7, na.rm = TRUE),
  overallmedian_totalhours_28 = median(median_totalhours_28, na.rm = TRUE),

  overallmedian_shifts_7 = median(median_shifts_7, na.rm = TRUE),
  overallmedian_shifts_28 = median(median_shifts_28, na.rm = TRUE),

  overallmedian_medshiftlength_7 = median(median_medshiftlength_7, na.rm = TRUE),
  overallmedian_medshiftlength_28 = median(median_medshiftlength_28, na.rm = TRUE),

  overallmedian_numlong_7 = median(median_numlong_7, na.rm = TRUE),
  overallmedian_numlong_28 = median(median_numlong_28, na.rm = TRUE),
  overallmedian_proplong_7 = median(median_proplong_7, na.rm = TRUE),
  overallmedian_proplong_28 = median(median_proplong_28, na.rm = TRUE),

  overallmedian_numnight_7 = median(median_numnight_7, na.rm = TRUE),
  overallmedian_numnight_28 = median(median_numnight_28, na.rm = TRUE),
  overallmedian_propnight_7 = median(median_propnight_7, na.rm = TRUE),
  overallmedian_propnight_28 = median(median_propnight_28, na.rm = TRUE),

  overallmedian_longspells_7 = median(median_longspells_7, na.rm = TRUE),
  overallmedian_longspells_28 = median(median_longspells_7, na.rm = TRUE),

  overallmedian_intensespells_7 = median(median_intensespells_7, na.rm = TRUE),
  overallmedian_intensespells_28 = median(median_intensespells_28, na.rm = TRUE),

  overallmedian_quickreturns_7 = median(median_quickreturns_7, na.rm = TRUE),
  overallmedian_quickreturns_28 = median(median_quickreturns_28, na.rm = TRUE),

  overallmedian_shortreturns_7 = median(median_shortreturns_7, na.rm = TRUE),
```

```
    overallmedian_shortreturns_28 = median(median_shortreturns_28, na.rm = TRUE),


    overallmedian_rotations_7 = median(median_rotations_7, na.rm = TRUE),
    overallmedian_rotations_28 = median(median_rotations_28, na.rm = TRUE)
  ) %>%
  ungroup()

# using per nurse averages, now inspect for differences between hospitals A/B
per_hospital_summary <- per_nurse_summary %>%
  group_by (Hospital_Id) %>%
  summarize(
    hospmean_totalhours_7 = mean(mean_totalhours_7, na.rm = TRUE),
    hospmean_totalhours_28 = mean(mean_totalhours_28, na.rm = TRUE),
    hospmedian_shifts_7 = median(median_shifts_7, na.rm = TRUE),
    hospmedian_shifts_28 = median(median_shifts_28, na.rm = TRUE),
    hospmean_medshiftlength_7 = mean(mean_medshiftlength_7, na.rm = TRUE),
    hospmean_medshiftlength_28 = mean(mean_medshiftlength_28, na.rm = TRUE),
    hospmedian_long_7 = median(median_long_7, na.rm = TRUE),
    hospmedian_long_28 = median(median_long_28, na.rm = TRUE),
    hospmedian_night_7 = median(median_night_7, na.rm = TRUE),
    hospmedian_night_28 = median(median_night_28, na.rm = TRUE),
    hospmean_nighthrs_7 = mean(mean_nighthrs_7, na.rm = TRUE),
    hospmean_nighthrs_28 = mean(mean_nighthrs_28, na.rm = TRUE)
  ) %>%
  ungroup()

# using per nurse averages, now inspect for differences across study years
#per_year_summary <- per_nurse_summary %>%
  #group_by (year) %>%
  #summarize(
    #yearmean_totalhours_7 = mean(mean_totalhours_7, na.rm = TRUE),
    #yearmean_totalhours_28 = mean(mean_totalhours_28, na.rm = TRUE),
    #yearmean_shifts_7 = mean(mean_shifts_7, na.rm = TRUE),
    #yearmean_shifts_28 = mean(mean_shifts_28, na.rm = TRUE),
    #yearmean_medshiftlength_7 = mean(mean_medshiftlength_7, na.rm = TRUE),
    #yearmean_medshiftlength_28 = mean(mean_medshiftlength_28, na.rm = TRUE),
```

```
  #yearmean_long_7 = mean(mean_long_7, na.rm = TRUE),
  #yearmean_long_28 = mean(mean_long_28, na.rm = TRUE),
  #yearmean_night_7 = mean(mean_night_7, na.rm = TRUE),
  #yearmean_night_28 = mean(mean_night_28, na.rm = TRUE),
  #yearmean_nighthrs_7 = mean(mean_nighthrs_7, na.rm = TRUE),
  #yearmean_nighthrs_28 = mean(mean_nighthrs_28, na.rm = TRUE)
 # ) %>%
 # ungroup()

year_overall_mean_summary <- per_nurse_summary %>%
 group_by (year) %>%
 summarize(
  year_overallmean_totalhours_7 = mean(mean_totalhours_7, na.rm = TRUE),
  year_overallsd_totalhours_7 = sd(mean_totalhours_7, na.rm = TRUE),
  year_overallmean_totalhours_28 = mean(mean_totalhours_28, na.rm = TRUE),
  year_overallsd_totalhours_28 = sd(mean_totalhours_28, na.rm = TRUE),

  year_overallmean_shifts_7 = mean(mean_shifts_7, na.rm = TRUE),
  year_overallsd_shifts_7 = sd(mean_shifts_7, na.rm = TRUE),
  year_overallmean_shifts_28 = mean(mean_shifts_28, na.rm = TRUE),
  year_overallsd_shifts_28 = sd(mean_shifts_28, na.rm = TRUE),

  year_overallmean_medshiftlength_7 = mean(mean_medshiftlength_7, na.rm = TRUE),
  year_overallsd_medshiftlength_7 = sd(mean_medshiftlength_7, na.rm = TRUE),
  year_overallmean_medshiftlength_28 = mean(mean_medshiftlength_28, na.rm = TRUE),
  year_overallsd_medshiftlength_28 = sd(mean_medshiftlength_28, na.rm = TRUE),

  year_overallmean_numlong_7 = mean(mean_numlong_7, na.rm = TRUE),
  year_overallsd_numlong_7 = sd(mean_numlong_7, na.rm = TRUE),
  year_overallmean_numlong_28 = mean(mean_numlong_28, na.rm = TRUE),
  year_overallsd_numlong_28 = sd(mean_numlong_28, na.rm = TRUE),
  year_overallmean_proplong_7 = mean(mean_proplong_7, na.rm = TRUE),
  year_overallsd_proplong_7 = sd(mean_proplong_7, na.rm = TRUE),
  year_overallmean_proplong_28 = mean(mean_proplong_28, na.rm = TRUE),
  year_overallsd_proplong_28 = sd(mean_proplong_28, na.rm = TRUE),
```

```
  year_overallmean_numnight_7 = mean(mean_numnight_7, na.rm = TRUE),
  year_overallsd_numnight_7 = sd(mean_numnight_7, na.rm = TRUE),
  year_overallmean_numnight_28 = mean(mean_numnight_28, na.rm = TRUE),
  year_overallsd_numnight_28 = sd(mean_numnight_28, na.rm = TRUE),
  year_overallmean_propnight_7 = mean(mean_propnight_7, na.rm = TRUE),
  year_overallsd_propnight_7 = sd(mean_propnight_7, na.rm = TRUE),
  year_overallmean_propnight_28 = mean(mean_propnight_28, na.rm = TRUE),
  year_overallsd_propnight_28 = sd(mean_propnight_28, na.rm = TRUE),

  overallmean_longspells_7 = mean(mean_longspells_7, na.rm = TRUE),
  overallsd_longspells_7 = sd(mean_longspells_7, na.rm = TRUE),
  overallmean_longspells_28 = mean(mean_longspells_7, na.rm = TRUE),
  overallsd_longspells_28 = sd(mean_longspells_28, na.rm = TRUE),

  year_overallmean_intensespells_7 = mean(mean_intensespells_7, na.rm = TRUE),
  year_overallsd_intensespells_7 = sd(mean_intensespells_7, na.rm = TRUE),
  year_overallmean_intensespells_28 = mean(mean_intensespells_28, na.rm = TRUE),
  year_overallsd_intensespells_28 = sd(mean_intensespells_28, na.rm = TRUE),

  year_overallmean_quickreturns_7 = mean(mean_quickreturns_7, na.rm = TRUE),
  year_overallsd_quickreturns_7 = sd(mean_quickreturns_7, na.rm = TRUE),
  year_overallmean_quickreturns_28 = mean(mean_quickreturns_28, na.rm = TRUE),
  year_overallsd_quickreturns_28 = sd(mean_quickreturns_28, na.rm = TRUE),

  year_overallmean_shortreturns_7 = mean(mean_shortreturns_7, na.rm = TRUE),
  year_overallsd_shortreturns_7 = sd(mean_shortreturns_7, na.rm = TRUE),
  year_overallmean_shortreturns_28 = mean(mean_shortreturns_28, na.rm = TRUE),
  year_overallsd_shortreturns_28 = sd(mean_shortreturns_28, na.rm = TRUE),

  year_overallmean_rotations_7 = mean(mean_rotations_7, na.rm = TRUE),
  year_overallsd_rotations_7 = sd(mean_rotations_7, na.rm = TRUE),
  year_overallmean_rotations_28 = mean(mean_rotations_28, na.rm = TRUE),
  year_overallsd_rotations_28 = sd(mean_rotations_28, na.rm = TRUE),
) %>%
ungroup()
```

```
# using per nurse averages, now inspect the whole dataset via grand medians
year_overall_median_summary <- per_nurse_summary %>%
 group_by (year) %>%
 summarize(
  year_overallmedian_totalhours_7 = median(median_totalhours_7, na.rm = TRUE),
  year_overallmedian_totalhours_28 = median(median_totalhours_28, na.rm = TRUE),

  year_overallmedian_shifts_7 = median(median_shifts_7, na.rm = TRUE),
  year_overallmedian_shifts_28 = median(median_shifts_28, na.rm = TRUE),

  year_overallmedian_medshiftlength_7 = median(median_medshiftlength_7, na.rm = TRUE),
  year_overallmedian_medshiftlength_28 = median(median_medshiftlength_28, na.rm = TRUE),

  year_overallmedian_numlong_7 = median(median_numlong_7, na.rm = TRUE),
  year_overallmedian_numlong_28 = median(median_numlong_28, na.rm = TRUE),
  year_overallmedian_proplong_7 = median(median_proplong_7, na.rm = TRUE),
  year_overallmedian_proplong_28 = median(median_proplong_28, na.rm = TRUE),

  year_overallmedian_numnight_7 = median(median_numnight_7, na.rm = TRUE),
  year_overallmedian_numnight_28 = median(median_numnight_28, na.rm = TRUE),
  year_overallmedian_propnight_7 = median(median_propnight_7, na.rm = TRUE),
  year_overallmedian_propnight_28 = median(median_propnight_28, na.rm = TRUE),

  year_overallmedian_longspells_7 = median(median_longspells_7, na.rm = TRUE),
  year_overallmedian_longspells_28 = median(median_longspells_7, na.rm = TRUE),

  year_overallmedian_intensespells_7 = median(median_intensespells_7, na.rm = TRUE),
  year_overallmedian_intensespells_28 = median(median_intensespells_28, na.rm = TRUE),

  year_overallmedian_quickreturns_7 = median(median_quickreturns_7, na.rm = TRUE),
  year_overallmedian_quickreturns_28 = median(median_quickreturns_28, na.rm = TRUE),

  year_overallmedian_shortreturns_7 = median(median_shortreturns_7, na.rm = TRUE),
  year_overallmedian_shortreturns_28 = median(median_shortreturns_28, na.rm = TRUE),
```

```
  year_overallmedian_rotations_7 = median(median_rotations_7, na.rm = TRUE),

  year_overallmedian_rotations_28 = median(median_rotations_28, na.rm = TRUE)


 ) %>%

 ungroup()


##################################################

# ICC CALCULATIONS

# not performing ICC calculations for Hospital_ID as there are not enough 'groups' i.e., only two hospitals, A and B

# not performing ICC calculations for Ward_ID are inconsistent and IDs are not always representative of actual wards: e.g., staff being coded to a differed Ward_Id only when sick

Staff_ICC <- glmer(case_control ~ 1 + (1|Staff_Id), data = data, family = "binomial" )

performance::icc(Staff_ICC)

#Adjusted ICC = 0.710 - include Staff_Id as clustering, random effects


##################################################

# UNIVARIABLE ANALYSIS - CONTROL VARS

# Use nAGQ = 0 argument in glmer function to cut down processing time - leads to marginally less accurate regression estimates (default is nAGQ = 1)


#### Model 1: part-time status

M1.91 <- glmer(case_control ~ lb_part_time_91 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M1.91)


#### Model 2: total bank hours in lookback

M2.7 <- glmer(case_control ~ lb_bankhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M2.7)


M2.28 <- glmer(case_control ~ lb_bankhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M2.28)


#### Model 3: total overtime hours (any hours coded as 'overtime' in raw data) in lookback

# M3.7 <- glmer(case_control ~ lb_all_OThours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M3.7)

# M3.28 <- glmer(case_control ~ lb_all_OThours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )
```

```
# summary(M3.28)

#### Not including as overtime hours are not recorded uniformly in the underlying raw data (e-rosters)


#### Model 4: number of sickness episodes in lookback

M4.7 <- glmer(case_control ~ lb_numsickepisodes_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M4.7)


M4.28 <- glmer(case_control ~ lb_numsickepisodes_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M4.28)


#### Model 5: total working hours in lookback

M5.7 <- glmer(case_control ~ lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M5.7)


M5.28 <- glmer(case_control ~ lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M5.28)


#### Model Control_7, Control_8: all control variables

Control_7.0 <- glmer(case_control ~ lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 +
(1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(Control_7.0)

vif(Control_7.0)


Control_28.0 <- glmer(case_control ~ lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 +
lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(Control_28.0)

vif(Control_28.0)


####################################################

# UNIVARIABLE ANALYSIS - PREDICTOR VARS

#### Model 6: number of "longweeks" in lookback

M6.7 <- glmer(case_control ~ lb_longweek_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M6.7)

#### analysis for lb_longweek_28 is not possible given unavoidable inaccuracies in calculating this variable
```

```
#### Model 7: number, proportion of LONG shifts in lookback


## COUNTS: linear, quadratic, cubic

M7.7 <- glmer(case_control ~ lb_numlongshifts_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.7)

M7.28 <- glmer(case_control ~ lb_numlongshifts_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.28)


# M7.7.quad <- glmer(case_control ~ lb_numlongshifts_7 + I(lb_numlongshifts_7^2) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M7.7.quad)

# M7.28.quad <- glmer(case_control ~ lb_numlongshifts_28 + I(lb_numlongshifts_28^2) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M7.28.quad)


# M7.7.cub <- glmer(case_control ~ lb_numlongshifts_7 + I(lb_numlongshifts_7^2) + I(lb_numlongshifts_7^3) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M7.7.cub)

# M7.28.cub <- glmer(case_control ~ lb_numlongshifts_28 + I(lb_numlongshifts_28^2) + I(lb_numlongshifts_28^3) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M7.28.cub)


## PROPORTIONS: linear, quadratic, cubic

M7.7.prop <- glmer(case_control ~ lb_proplongshifts_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.7.prop)

M7.28.prop <- glmer(case_control ~ lb_proplongshifts_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.28.prop)


M7.7.prop.quad <- glmer(case_control ~ lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.7.prop.quad)

M7.28.prop.quad <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.28.prop.quad)


M7.7.prop.cub <- glmer(case_control ~ lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + I(lb_proplongshifts_7^3) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.7.prop.cub)
```

```
M7.28.prop.cub <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + I(lb_proplongshifts_28^3)
+ (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M7.28.prop.cub)


#### Model 8: number, proportion of NIGHT shifts in lookback


## COUNTS: linear, quadratic, cubic

M8.7 <- glmer(case_control ~ lb_numnightshifts_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.7)

M8.28 <- glmer(case_control ~ lb_numnightshifts_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.28)



# M8.7.quad <- glmer(case_control ~ lb_numnightshifts_7 + I(lb_numnightshifts_7^2) + (1|Staff_Id), data = data,
nAGQ = 0, family = "binomial" )

# summary(M8.7.quad)

# M8.28.quad <- glmer(case_control ~ lb_numnightshifts_28 + I(lb_numnightshifts_28^2) + (1|Staff_Id), data = data,
nAGQ = 0, family = "binomial" )

# summary(M8.28.quad)



# M8.7.cub <- glmer(case_control ~ lb_numnightshifts_7 + I(lb_numnightshifts_7^2) + I(lb_numnightshifts_7^3) +
(1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M8.7.cub)

# M8.28.cub <- glmer(case_control ~ lb_numnightshifts_28 + I(lb_numnightshifts_28^2) + I(lb_numnightshifts_28^3) +
(1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M8.28.cub)



## PROPORTIONS: linear, quadratic, cubic

M8.7.prop <- glmer(case_control ~ lb_propnightshifts_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.7.prop)

M8.28.prop <- glmer(case_control ~ lb_propnightshifts_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.28.prop)



M8.7.prop.quad <- glmer(case_control ~ lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + (1|Staff_Id), data = data,
nAGQ = 0, family = "binomial" )

summary(M8.7.prop.quad)

M8.28.prop.quad <- glmer(case_control ~ lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + (1|Staff_Id), data =
data, nAGQ = 0, family = "binomial" )

summary(M8.28.prop.quad)
```

```
M8.7.prop.cub <- glmer(case_control ~ lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + I(lb_propnightshifts_7^3) +
(1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.7.prop.cub)

M8.28.prop.cub <- glmer(case_control ~ lb_propnightshifts_28 + I(lb_propnightshifts_28^2) +
I(lb_propnightshifts_28^3) + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M8.28.prop.cub)


#### Model 9: number of long spells in lookback

M9.7 <- glmer(case_control ~ lb_long_workspells_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M9.7)


M9.28 <- glmer(case_control ~ lb_long_workspells_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M9.28)


#### Model 10: number of intense spells in lookback

M10.7 <- glmer(case_control ~ lb_intense_workspells_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M10.7)


M10.28 <- glmer(case_control ~ lb_intense_workspells_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M10.28)


#### Model 11: number of quick returns in lookback

M11.7 <- glmer(case_control ~ lb_numquickreturns_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M11.7)


M11.28 <- glmer(case_control ~ lb_numquickreturns_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M11.28)


#### Model 12: number of short returns in lookback

M12.7 <- glmer(case_control ~ lb_numshortreturns_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M12.7)


M12.28 <- glmer(case_control ~ lb_numshortreturns_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M12.28)
```

```
#### Model 13: number of shift rotations in lookback

M13.7 <- glmer(case_control ~ lb_shiftrotation_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M13.7)


M13.28 <- glmer(case_control ~ lb_shiftrotation_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M13.28)


##################################################

# EACH PREDICTOR VAR with CONTROLLING VARS


#### Model 14: number of long weeks in lookback, with controlling vars

M14.7 <- glmer(case_control ~ lb_longweek_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 +
lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M14.7)

vif(M14.7)


#### Model 15: number, proportion of long shifts in lookback, with controlling vars

## COUNTS: linear, quadratic, cubic

M15.7 <- glmer(case_control ~ lb_numlongshifts_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 +
lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.7)

vif(M15.7)

M15.28 <- glmer(case_control ~ lb_numlongshifts_28 + lb_part_time_91 + lb_bankhours_28 +
lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.28)

vif(M15.28)


# M15.7.quad <- glmer(case_control ~ lb_numlongshifts_7 + I(lb_numlongshifts_7^2) + lb_part_time_91 +
lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M15.7.quad)

# vif(M15.7.quad)

# M15.28.quad <- glmer(case_control ~ lb_numlongshifts_28 + I(lb_numlongshifts_28^2) + lb_part_time_91 +
lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family =
"binomial" )

# summary(M15.28.quad)

# vif(M15.28.quad)
```

```
# M15.7.cub <- glmer(case_control ~ lb_numlongshifts_7 + I(lb_numlongshifts_7^2) I(lb_numlongshifts_7^3) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M15.7.cub)

# vif(M15.7.cub)

# M15.28.cub <- glmer(case_control ~ lb_numlongshifts_28 + I(lb_numlongshifts_28^2) + I(lb_numlongshifts_28^3) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

# summary(M15.28.cub)

# vif(M15.28.cub)



## PROPORTIONS: linear, quadratic, cubic

M15.7.prop <- glmer(case_control ~ lb_proplongshifts_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.7.prop)

vif(M15.7.prop)

M15.28.prop <- glmer(case_control ~ lb_proplongshifts_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.28.prop)

vif(M15.28.prop)



M15.7.prop.quad <- glmer(case_control ~ lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.7.prop.quad)

vif(M15.7.prop.quad)

M15.28.prop.quad <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.28.prop.quad)

vif(M15.28.prop.quad)



M15.7.prop.cub <- glmer(case_control ~ lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + I(lb_proplongshifts_7^3) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.7.prop.cub)

vif(M15.7.prop.cub)

M15.28.prop.cub <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + I(lb_proplongshifts_28^3) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial" )

summary(M15.28.prop.cub)

vif(M15.28.prop.cub
```

Model 16: number, proportion of night shifts in lookback, with controlling vars

COUNTS: linear, quadratic, cubic

M16.7 <- glmer(case_control ~ lb_numnightshifts_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7)

vif(M16.7)

M16.28 <- glmer(case_control ~ lb_numnightshifts_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28)

vif(M16.28)

M16.7.quad <- glmer(case_control ~ lb_numnightshifts_7 + I(lb_numnightshifts_7^2) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7.quad)

vif(M16.7.quad)

M16.28.quad <- glmer(case_control ~ lb_numnightshifts_28 + I(lb_numnightshifts_28^2) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28.quad)

vif(M16.28.quad)

M16.7.cub <- glmer(case_control ~ lb_numnightshifts_7 + I(lb_numnightshifts_7^2) + I(lb_numnightshifts_7^3) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7.cub)

vif(M16.7.cub)

M16.28.cub <- glmer(case_control ~ lb_numnightshifts_28 + I(lb_numnightshifts_28^2) + I(lb_numnightshifts_28^3) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28.cub)

vif(M16.28.cub)

PROPORTIONS: linear, quadratic, cubic

M16.7.prop <- glmer(case_control ~ lb_propnightshifts_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7.prop)

vif(M16.7.prop)

M16.28.prop <- glmer(case_control ~ lb_propnightshifts_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28.prop)

vif(M16.28.prop)

M16.7.prop.quad <- glmer(case_control ~ lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7.prop.quad)

vif(M16.7.prop.quad)

M16.28.prop.quad <- glmer(case_control ~ lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28.prop.quad)

vif(M16.28.prop.quad)

M16.7.prop.cub <- glmer(case_control ~ lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + I(lb_propnightshifts_7^3) + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.7.prop.cub)

vif(M16.7.prop.cub)

M16.28.prop.cub <- glmer(case_control ~ lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + I(lb_propnightshifts_28^3) + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M16.28.prop.cub)

vif(M16.28.prop.cub)

Model 17: number of long spells in lookback, with controlling vars

M17.7 <- glmer(case_control ~ lb_long_workspells_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M17.7)

vif(M17.7)

M17.28 <- glmer(case_control ~ lb_long_workspells_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M17.28)

vif(M17.28)

Model 18: number of intense spells in lookback, with controlling vars

M18.7 <- glmer(case_control ~ lb_intense_workspells_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M18.7)

vif(M18.7)

M18.28 <- glmer(case_control ~ lb_intense_workspells_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial") summary(M18.28)

vif(M18.28)

Model 19: number of quick returns in lookback, with controlling vars

M19.7 <- glmer(case_control ~ lb_numquickreturns_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M19.7)

vif(M19.7)

M19.28 <- glmer(case_control ~ lb_numquickreturns_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M19.28)

vif(M19.28)

Model 20: number of short returns in lookback, with controlling vars

M20.7 <- glmer(case_control ~ lb_numshortreturns_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M20.7)

vif(M20.7)

M20.28 <- glmer(case_control ~ lb_numshortreturns_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M20.28)

vif(M20.28)

Model 21: number of shift rotations in lookback, with controlling vars

M21.7 <- glmer(case_control ~ lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M21.7)

vif(M21.7)

M21.28 <- glmer(case_control ~ lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M21.28)

vif(M21.28)

##

MULTIVARIATE MODELS

Model 22.7: 7-day lookback: all vars (counts, linear)

M22.7 <- glmer(case_control ~ lb_longweek_7 + lb_numlongshifts_7 + lb_numnightshifts_7 + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M22.7)

vif(M22.7)

Model 22.28: 28-day lookback: all vars (counts, linear)

M22.28 <- glmer(case_control ~ lb_numlongshifts_28 + lb_numnightshifts_28 + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M22.28)

vif(M22.28)

Model 23.7: 7-day lookback: all vars (proportions, linear)

M23.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + lb_propnightshifts_7 + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M23.7)

vif(M23.7)

Model 23.28: 28-day lookback: all vars (proportions, linear)

M23.28 <- glmer(case_control ~ lb_proplongshifts_28 + lb_propnightshifts_28 + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M23.28)

vif(M23.28)

Model 24.7: 7-day lookback: all vars (proportions, quadratic)

M24.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M24.7)

vif(M24.7)

Model 24.28: 28-day lookback: all vars (proportions, quadratic)

M24.28 <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M24.28)

vif(M24.28)

Model 25.7: 7-day lookback: all vars (proportions, cubic)

M25.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + I(lb_proplongshifts_7^3) + lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + I(lb_propnightshifts_7^3) + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M25.7)

vif(M25.7)

Model 25.28: 28-day lookback: all vars (proportions, cubic)

M25.28 <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + I(lb_proplongshifts_28^3) + lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + I(lb_propnightshifts_28^3) + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M25.28)

vif(M25.28)

##

Model 26.7: 7-day lookback: all vars (proportions, cubic long, quad night)

M26.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + I(lb_proplongshifts_7^3) + lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_bankhours_7 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M26.7)

vif(M26.7)

Model 26.28: 28-day lookback: all vars (proportions, cubic long, quad night)

M26.28 <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + I(lb_proplongshifts_28^3) + lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_bankhours_28 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = data, nAGQ = 0, family = "binomial")

summary(M26.28)

vif(M26.28)

##

MULTIVARIABLE MODELS - WITH SUBSET DATA - DROPPING LOOKBACKS WITH ANY BANK HOURS

subset_data2 <- subset(data, lb_bankhours_28 == 0) # only retain rows with this exact value

drops to 1150628 rows (removed 236,745 rows, or 17% of rows)

subset_data3 <- data[data$lb_bankhours_28 <= 0,] # drop rows with any bank hours in lookback

drops to 1203621 rows (removed 183,752 rows, or 13% of rows)

SUBSET Model 27.7: 7-day lookback: all vars (counts, linear)

M27.7 <- glmer(case_control ~ lb_longweek_7 + lb_numlongshifts_7 + lb_numnightshifts_7 + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = subset_data3, nAGQ = 0, family = "binomial")

summary(M27.7)

vif(M27.7)

SUBSET Model 27.28: 28-day lookback: all vars (counts, linear)

M27.28 <- glmer(case_control ~ lb_numlongshifts_28 + lb_numnightshifts_28 + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = subset_data3, nAGQ = 0, family = "binomial")

summary(M27.28)

vif(M27.28)

SUBSET Model 28.7: 7-day lookback: all vars (proportions, linear)

M28.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + lb_propnightshifts_7 + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = subset_data2, nAGQ = 0, family = "binomial")

summary(M28.7)

vif(M28.7)

SUBSET Model 28.28: 28-day lookback: all vars (proportions, linear)

M28.28 <- glmer(case_control ~ lb_proplongshifts_28 + lb_propnightshifts_28 + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = subset_data2, nAGQ = 0, family = "binomial")

summary(M28.28)

vif(M28.28)

SUBSET Model 29.7: 7-day lookback: all vars (proportions, quadratic)

M29.7 <- glmer(case_control ~ lb_longweek_7 + lb_proplongshifts_7 + I(lb_proplongshifts_7^2) + lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 + lb_shiftrotation_7 + lb_part_time_91 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = subset_data2, nAGQ = 0, family = "binomial")

summary(M29.7)

vif(M29.7)

SUBSET Model 29.28: 28-day lookback: all vars (proportions, quadratic)

M29.28 <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + lb_long_workspells_28 + lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91 + lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = subset_data2, nAGQ = 0, family = "binomial")

summary(M29.28)

vif(M29.28)

```
#### SUBSET Model 30.7: 7-day lookback: all vars (proportions, cubic)

M30.7 <- glmer(case_control ~  lb_longweek_7 + lb_proplongshifts_7 + I(lb_proplongshifts_7^2) +
I(lb_proplongshifts_7^3) + lb_propnightshifts_7 + I(lb_propnightshifts_7^2) + I(lb_propnightshifts_7^3) +
lb_long_workspells_7 + lb_intense_workspells_7 + lb_numquickreturns_7 + lb_numshortreturns_7 +
lb_shiftrotation_7 + lb_part_time_91 + lb_numsickepisodes_7 + lb_totalhours_7 + (1|Staff_Id), data = subset_data2,
nAGQ = 0, family = "binomial" )

summary(M30.7)

vif(M30.7)

#### SUBSET Model 30.28: 28-day lookback: all vars (proportions, cubic)

M30.28 <- glmer(case_control ~ lb_proplongshifts_28 + I(lb_proplongshifts_28^2) + I(lb_proplongshifts_28^3) +
lb_propnightshifts_28 + I(lb_propnightshifts_28^2) + I(lb_propnightshifts_28^3) + lb_long_workspells_28 +
lb_intense_workspells_28 + lb_numquickreturns_28 + lb_numshortreturns_28 + lb_shiftrotation_28 + lb_part_time_91
+ lb_numsickepisodes_28 + lb_totalhours_28 + (1|Staff_Id), data = subset_data2, nAGQ = 0, family = "binomial" )

summary(M30.28)

vif(M30.28)
```

B.4 Plotting values for nonlinear variable relationships

7-day Lookback	Term	Beta	SE	z value	Sig	Plot Values	Combined Terms*	Exponential (Combined)
Prop of long shifts	Linear	-2.093	0.4432	-4.723	***	0	0.00	1.00
	Quadratic	8.7267	1.1195	7.796	***	0.1	-0.13	0.88
	Cubic	-6.689	0.6975	-9.591	***	0.2	-0.12	0.88
						0.3	-0.02	0.98
						0.4	0.13	1.14
						0.5	0.30	1.35
						0.6	0.44	1.55
						0.7	0.52	1.68
						0.8	0.49	1.63
						0.9	0.31	1.36
						1	-0.06	0.95
7-day Lookback	**Term**	**Beta**	**SE**	**z value**	**Sig**	**Plot Values**	**Combined Terms†**	**Exponential (Combined)**
Prop of night shifts	Linear	-0.438	0.1337	-3.272	**	0	0.00	1.00
	Quadratic	0.5041	0.1353	3.725	***	0.1	-0.04	0.96
						0.2	-0.07	0.93
						0.3	-0.09	0.92
						0.4	-0.09	0.91
						0.5	-0.09	0.91
						0.6	-0.08	0.92
						0.7	-0.06	0.94
						0.8	-0.03	0.97
						0.9	0.01	1.01
						1	0.07	1.07
28-day Lookback	**Term**	**Beta**	**SE**	**z value**	**Sig**	**Plot Values**	**Combined Terms***	**Exponential (Combined)**
Prop of long shifts	Linear	-1.636	0.4296	-3.808	***	0	0.00	1.00
	Quadratic	6.5484	0.9354	7.000	***	0.1	-0.10	0.90
	Cubic	-4.748	0.5439	-8.729	***	0.2	-0.10	0.90
						0.3	-0.03	0.97
						0.4	0.09	1.09
						0.5	0.23	1.25
						0.6	0.35	1.42
						0.7	0.43	1.54
						0.8	0.45	1.57
						0.9	0.37	1.45
						1.0	0.16	1.18
28-day Lookback	**Term**	**Beta**	**SE**	**z value**	**Sig**	**Plot Values**	**Combined Terms†**	**Exponential (Combined)**
Prop of night shifts	Linear	-0.484	0.149	-3.256	**	0	0.00	1.00
	Quadratic	0.546	0.152	3.596	***	0.1	-0.04	0.96
						0.2	-0.07	0.93
						0.3	-0.10	0.91
						0.4	-0.11	0.90
						0.5	-0.11	0.90

		0.6	-0.09	0.91
		0.7	-0.07	0.93
		0.8	-0.04	0.96
		0.9	0.01	1.01
		1	0.06	1.06

* Combined terms calculated via a following formula:

(plot value * linear beta term) + (plot value^2 * quadratic beta term) + plot value^3 * cubic beta term)

† Combined terms calculated via a following formula:

(plot value * linear beta term) + (plot value^2 * quadratic beta term)

Appendix C | Chapter 6 Supplementary Files

C.1 Gurobipy code: Nurse scheduling optimisation model

```
import gurobipy as gp

from gurobipy import GRB

import numpy as np

import pandas as pd

import datetime


#%%


model = gp.Model('TE_NSP_model')


##### DATA #####

from Data_NSP_28 import *


# generating excel workbook with roster and nurses' scheds

from export_schedule_xlsx import generate_solution_xlsx


nurses = set(range(1, n_nurses+1))

days = set(range(1, n_days+1))

days_extended = list(range(1, n_days+1)) + list(range(1, n_days+1)) # 'wrap-around' the model to consider
days 1, 2...when at end of planning horizon


##### DECISION VARIABLES #####


# Primary Decision Variable: if nurse i works shift type t on day d, x=1; otherwise x=0

x = {}

for i in nurses:

  for d in days:

    for t in shift_types:

      x[i, d, t] = model.addVar(vtype=GRB.BINARY, name=f'x_{i}.{d}.{t}')
```

```
# Deviation (Auxiliary) Variables
long_shifts_dev = {}
for i in nurses:
   long_shifts_dev[i] = model.addVar(lb=0, name=f'long_shifts_dev_nurse{i}')

night_shifts_dev = {}
for i in nurses:
   night_shifts_dev[i] = model.addVar(lb=0, name=f'night_shifts_dev_nurse{i}')

intense_spells_dev = {}
for i in nurses:
   for d in days:
      intense_spells_dev[i,d] = model.addVar(lb=0, name=f'intense_spells_dev_nurse{i}_day{d}')

long_spells_dev = {}
for i in nurses:
   for d in days:
      long_spells_dev[i,d] = model.addVar(lb=0, name=f'long_spells_dev_nurse{i}_day{d}')

NTD_rotation_dev = {}
for i in nurses:
   for d in days:
      NTD_rotation_dev[i,d] = model.addVar(lb=0, name=f'NTD_rotation_dev_nurse{i}_day{d}')

DTN_rotation_dev = {}
for i in nurses:
   for d in days:
      DTN_rotation_dev[i,d] = model.addVar(lb=0, name=f'DTN_rotation_dev_nurse{i}')

short_return_dev = {}
for i in nurses:
    for d in days:
```

```
     short_return_dev[i,d] = model.addVar(lb=0, name=f'short_ret_dev_nurse{i}')


weekend_shift_dev = {}

for i in nurses:

   weekend_shift_dev[i] = model.addVar(lb=0, name=f'weekend_dev_nurse{i}')


#fair distribution of nights

total_night_max = int(np.ceil((n_days * nurse_numbers[6]) / len(nurses)))



##### CONSTRAINTS #####


## per day ##

# staffing blocks using >= instead of ==

for d in days:

   for b in staffing_blocks:

      model.addConstr(gp.quicksum(x[i, d, t] for i in nurses for t in shift_types if b in
shift_blocks_mapping[t]) >= nurse_numbers[b], name=f'staff_day{d}_block{b}')


## per nurse ##

# One shift PER DAY

for i in nurses:

   for d in days:

      model.addConstr(gp.quicksum(x[i, d, t] for t in shift_types) <= 1, name=f'one-shift_nurse{i}_day{d}')


# Minimum FTE hours PER MONTH - this must be a minimum as these are contracted hours

for i in nurses:

   model.addConstr(gp.quicksum(shift_length[t] * x[i, d, t] for d in days for t in shift_types) >=
total_hours_FTE * contract[i-1], name=f'minFTEhrs_nurse{i}')


# Maximum hours PER CALENDAR WEEK

for i in nurses:

   for week in weeks:

      model.addConstr(gp.quicksum(shift_length[t] * x[i, d, t] for d in week for t in shift_types) <=
max_weekly_hours, name=f'maxWEEKLYhrs_nurse{i}_week_{week}')
```

```
# Minimum rest: some shifts cannot follow shift type 7 (12N) on consecutive days
for i in nurses:
  for d in days:
    if d < max(days): # everything up to day 27
      next_day = d + 1
    else: # wrap-around from day 28 to day 1
      next_day = 1

    model.addConstr(x[i, d, 7] + x[i, next_day, 1] <= 1, f'minrest_7-1_nurse{i}_day{d}_type{t}') # 12N --> 6E (-0.5 hours rest)
    model.addConstr(x[i, d, 7] + x[i, next_day, 2] <= 1, f'minrest_7-2_nurse{i}_day{d}_type{t}') # 12N --> 6L (5.5 hours rest)
    model.addConstr(x[i, d, 7] + x[i, next_day, 3] <= 1, f'minrest_7-3_nurse{i}_day{d}_type{t}') # 12N --> 8E (1.5 hours rest)
    model.addConstr(x[i, d, 7] + x[i, next_day, 4] <= 1, f'minrest_7-4_nurse{i}_day{d}_type{t}') # 12N --> 8L (5.5 hours rest)
    model.addConstr(x[i, d, 7] + x[i, next_day, 5] <= 1, f'minrest_7-5_nurse{i}_day{d}_type{t}') # 12N --> 10D (-0.5 hours rest)
    model.addConstr(x[i, d, 7] + x[i, next_day, 6] <= 1, f'minrest_7-6_nurse{i}_day{d}_type{t}') # 12N --> 12D (-0.5 hours rest)


# Maximum of 4 weekend shifts per nurse
for i in nurses:
  model.addConstr(gp.quicksum(x[i, d, t] for t in shift_types for d in days if d in weekend_days) <= 4 + weekend_shift_dev[i], name=f'weekend_nurse{i}_day{d}')


# Penalising use of long shifts PER MONTH above certain number
for i in nurses:
  model.addConstr(gp.quicksum(x[i, d, t] for d in days for t in long_shifts) <= total_long_max + long_shifts_dev[i], name=f'long-shifts_nurse{i}_type{t}')


# Penalising use of night shifts PER MONTH above certain number
for i in nurses:
  model.addConstr(gp.quicksum(x[i, d, t] for d in days for t in night_shifts) <= total_night_max + night_shifts_dev[i], name=f'night-shifts_nurse{i}_type{t}')
```

```
# Penalising use of intense workspells PER MONTH from the start
for i in nurses:
   for d in days:
      # if d <= (n_days - 2):
      model.addConstr(gp.quicksum(x[i, dd, t] for dd in days_extended[d-1:d-1 + 3] for t in long_shifts) <= 2
+ intense_spells_dev[i,d], name= f'intense-spell_nurse{i}_day{d}')
   # model.write("test.lp")
   # exit()


# Penalising use of long workspells PER MONTH from the start
for i in nurses:
   for d in days:
      # if d <= (n_days - 5):
      model.addConstr(gp.quicksum(x[i, dd, t] for dd in days_extended[d-1:d-1 + 6] for t in shift_types) <= 5
+ long_spells_dev[i,d], name= f'long-spell_nurse{i}_day{d}')


# Penalising use of NTD rotations PER MONTH from the start
for i in nurses:
   for d in days:
      for dd in range(2, 7):
         # if d <= (n_days - dd):
         model.addConstr(x[i, d, 7] + gp.quicksum(x[i, days_extended[d + dd-1], t] for t in day_shifts) <= 1 +
NTD_rotation_dev[i,d] + gp.quicksum(x[i, days_extended[d + ddd-1], t] for ddd in range (1, dd) for t in
shift_types), name=f'NTDrot_d+{dd}_nurse{i}_day{d}_type{t}')


# Penalising short returns (special case of NTD rotation) PER MONTH from the start
for i in nurses:
   for d in days:
      # if d <= (n_days - dd):
      model.addConstr(x[i, d, 7] + gp.quicksum(x[i, days_extended[d-1 + 2], t] for t in day_shifts) <= 1 +
short_return_dev[i,d] + gp.quicksum(x[i, days_extended[d-1 + 1], t] for t in shift_types),
name=f'short_ret_d+{dd}_nurse{i}_day{d}')


# Penalising use of DTN rotations PER MONTH from the start
for i in nurses:
   for d in days:
```

```
    for dd in range(1, 7):

      # if d <= (n_days - dd):

      model.addConstr(gp.quicksum(x[i, d, t] for t in day_shifts) + (x[i, days_extended[d-1 + dd] , 7]) <= 1 + DTN_rotation_dev[i,d] + gp.quicksum(x[i, days_extended[d-1 + ddd], t] for ddd in range (1, dd) for t in shift_types), name=f'DTNrot_d+{dd}_nurse{i}_day{d}_type{t}')


###### OBJECTIVE #####

# minimise number of working hours

# minimise penalty value of model


model.setObjective(

  # gp.quicksum(x[i, d, t] for i in nurses for d in days for t in shift_types) + # minimising shifts if necessary

  penalty['none'] * (gp.quicksum(shift_length[t] * x[i, d, t] for i in nurses for d in days for t in shift_types) - total_hours_FTE*np.sum(contract)) + # minimising hours used across 28 days, multiply all shift lengths by 0.001 so that model prioritises reducing penalties first!

  penalty['moderate'] * gp.quicksum(long_shifts_dev[i] for i in nurses) +

  penalty['moderate'] * gp.quicksum(night_shifts_dev[i] for i in nurses) +

  penalty['large'] * gp.quicksum(intense_spells_dev[i,d] for i in nurses for d in days) +

  penalty['moderate'] * gp.quicksum(long_spells_dev[i,d] for i in nurses for d in days) +

  penalty['small'] * gp.quicksum(NTD_rotation_dev[i,d] for i in nurses for d in days) +

  penalty['moderate'] * gp.quicksum(short_return_dev[i,d] for i in nurses for d in days) + # penalising short returns (special case of NTD rotation) a little more!

  penalty['neutral'] * gp.quicksum(DTN_rotation_dev[i,d] for i in nurses for d in days)+

  penalty['neutral'] * gp.quicksum(weekend_shift_dev[i] for i in nurses),

  GRB.MINIMIZE

)

##### OPTIMIZE MODEL #####

# limit running time to 60 minutes

model.setParam('TimeLimit', 3600) # limit running time to 60 minutes

start_time = datetime.datetime.now()


model.optimize()


end_time = datetime.datetime.now()

runtime = end_time - start_time
```

```
##### PRINTING RESULTS #####

# empty lists
nurseID = []
N_shifts = []
N_hours = []
assignments = []
block_assignments = []
nurse_week_hours = []

if model.status != GRB.INFEASIBLE:
   for i in nurses:
      total_shifts = 0 # counter for number of shifts
      total_hours = 0 # counter for number of hours from assigned shifts

      for t in shift_types:
         for d in days:
            if x[i, d, t].x > 0.5:
               total_shifts += 1  # add to shift count
               total_hours += shift_length[t]  # add length of shift to count

      # filling lists
      nurseID.append(i)
      N_shifts.append(total_shifts)
      N_hours.append(total_hours)

   df_shift_summary = pd.DataFrame({
      'Nurse': nurseID,
      'N_Shifts': N_shifts,
      'N_Hours': N_hours})

if model.status != GRB.INFEASIBLE:
   for i in nurses:
```

```
        for d in days:
            for t in shift_types:
                if x[i, d, t].x > 0.5: # ensure to catch any rounding errors
                    assignments.append((i, d, t))
                    assignments_df = pd.DataFrame(assignments, columns=['nurse', 'day', 'shift'])


    # printing values for deviation (penalty) variables
    # only print penalty values if they are larger than 0.1


    penalty_data = []


    for i in nurses:
        if long_shifts_dev[i].x > 0.1:
            penalty_data.append({'Penalty Variable': f'long_shifts_dev_nurse{i}', 'Value': long_shifts_dev[i].x})
            print (f'long_shifts_dev_nurse{i}: {long_shifts_dev[i].x}')


        for d in days:
            if intense_spells_dev[i,d].x > 0.1:
                penalty_data.append({'Penalty Variable': f'intense_spells_dev_nurse{i}_day{d}', 'Value':
intense_spells_dev[i, d].x})
                print (f'intense_spells_dev_nurse{i}_day{d}: {intense_spells_dev[i,d].x}')
            if long_spells_dev[i,d].x > 0.1:
                penalty_data.append({'Penalty Variable': f'long_spells_dev_nurse{i}_day{d}', 'Value':
long_spells_dev[i, d].x})
                print (f'long_spells_dev_nurse{i}_day{d}:  {long_spells_dev[i,d].x}')


        if night_shifts_dev[i].x > 0.1:
            penalty_data.append({'Penalty Variable': f'night_shifts_dev_nurse{i}', 'Value': night_shifts_dev[i].x})
            print (f'night_shifts_dev_nurse{i}:  {night_shifts_dev[i].x}')


        total_rots_ntd = 0
        for d in days:
            if NTD_rotation_dev[i,d].x > 0.1:
                total_rots_ntd += 1
```

```
            print (f'\tNTD_rotation_dev_nurse{i}_day{d}: {NTD_rotation_dev[i,d].x}')
        if total_rots_ntd > 0.1:
            penalty_data.append({'Penalty Variable': f'Total NTD_rotations_nurse{i}', 'Value': total_rots_ntd})
            print (f'Total NTD_rotations_nurse{i}: {total_rots_ntd}')

        total_rots_dtn = 0
        total_short_ret = 0
        for d in days:
            if DTN_rotation_dev[i,d].x > 0.1:
                total_rots_dtn += 1
            if short_return_dev[i,d].x > 0.1:
                total_short_ret += 1
                penalty_data.append({'Penalty Variable': f'short_return_dev_nurse{i}_day{d}', 'Value':
short_return_dev[i, d].x})
                print (f'\tDTN_rotation_dev_nurse{i}_day{d}: {DTN_rotation_dev[i,d].x}')
        if total_rots_dtn > 0.1:
            penalty_data.append({'Penalty Variable': f'Total DTN_rotations_nurse{i}', 'Value': total_rots_dtn})
            print (f'Total DTN_rotations_nurse{i}: {total_rots_dtn}')

        if total_short_ret > 0.1:
            penalty_data.append({'Penalty Variable': f'Total_Short_Ret_nurse{i}', 'Value': total_short_ret})
            penalty_data.append({'Penalty Variable': f'weekend_shift_dev_nurse{i}', 'Value':
weekend_shift_dev[i].x})
            print (f'Total_Short_Ret_nurse{i}: {total_short_ret}')

        if weekend_shift_dev[i].x > 0.1:
            print (f'weekend_shift_dev_nurse{i}: {weekend_shift_dev[i].x}')

    penalty_df = pd.DataFrame(penalty_data)

if model.status != GRB.INFEASIBLE:
    print('Feasible solution found! Check shift_summary_df for hour totals and excel workbook for nurse
rosters')
```

```
    nurses_shift_types = assignments_df[['nurse', 'shift']].value_counts().reset_index(name='count') # what shift types are each nurse working?

    nurses_shift_types = nurses_shift_types.sort_values(by=['nurse', 'shift'])

    nurses_shift_types = nurses_shift_types.reset_index(drop=True)


    days_shift_types = assignments_df[['day','shift']].value_counts().reset_index(name='count') # what shift types are being worked on each day?

    days_shift_types = days_shift_types.sort_values(by=['day', 'shift'])

    days_shift_types = days_shift_types.reset_index(drop=True)


    shift_type_totals = assignments_df['shift'].value_counts().reset_index(name='total_count') # how many of each shift type was used across the whole roster?

    shift_type_totals.rename(columns={'index': 'shift'}, inplace=True)

    shift_type_totals = shift_type_totals.sort_values(by='shift')

    shift_type_totals = shift_type_totals.reset_index(drop=True)


    total_shifts = len(assignments_df) # how many shifts were used across the whole roster?


    roster_hours = 0

    for i in nurses: # how many hours were used across the whole roster?

        for d in days:

            for t in shift_types:

                if x[i, d, t].X > 0.5:  # If the shift is assigned

                    roster_hours += shift_length[t] * x[i, d, t].X  # Multiply shift length by the assignment


# staffing blocks df - how many nurses have been assigned to each staffing block on each day?

if model.status != GRB.INFEASIBLE:

    for d in days:

        for b in staffing_blocks:

            assigned_nurses = sum(x[i, d, t].X for i in nurses for t in shift_types if b in shift_blocks_mapping[t])

            block_assignments.append({'Day': d, 'Block': b, 'N Nurses': assigned_nurses})

            df_staff_blocks = pd.DataFrame(block_assignments)

            df_staff_blocks = df_staff_blocks.sort_values(by=['Day', 'Block'])

            df_staff_blocks = df_staff_blocks.reset_index(drop=True)
```

```
# nurse_week_hours_df - how many hours have been assigned to each nurse each week?
if model.status != GRB.INFEASIBLE:
  for i in nurses:
    for week_idx, week in enumerate(weeks):
      total_hours = sum(shift_length[t] * x[i, d, t].X for d in week for t in shift_types)
      nurse_week_hours.append({'Nurse': i, 'Week': week_idx + 1, 'Weekly Hrs Total': total_hours})
      df_nurse_week_hours = pd.DataFrame(nurse_week_hours)


  # Create excel workbook with solution – nurse roster
  # Use a timestamp so files are not overwritten
  now = datetime.datetime.now()
  formatted_datetime = now.strftime("%Y-%m-%d_%H-%M-%S")
  filename = f"output_{formatted_datetime}.xlsx"
  output_filename=filename
  generate_solution_xlsx(model, nurses, assignments_df, output_filename, runtime, roster_hours,
total_shifts, penalty_df, df_shift_summary, nurses_shift_types, shift_type_totals, df_staff_blocks)


if model.status == GRB.OPTIMAL:
  print('Even better, an OPTIMAL solution found!')


if model.status == GRB.INFEASIBLE: # produce IIS (constraints that cannot be reconciled)
  print('No feasible solution found.')
  model.computeIIS()
  now = datetime.datetime.now()
  formatted_datetime = now.strftime("%Y-%m-%d_%H-%M-%S")
  model.write(filename = f"model_IIS_{formatted_datetime}.ilp")
```

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