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Advancing Anaesthetist Rostering Quality: A Practical Approach Towards Fairness and Efficiency

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ABSTRACT The Anaesthetist Rostering Problem (ARP) presents significant challenges in healthcare management due to complex constraints and regulations. Existing models for the ARP often fail to address the complexities of real-world hospital environments, particularly in integrating monthly and weekly schedules across multiple locations. This study addresses the key question: How can we develop anaesthetist rosters that improve both staff fairness and operational efficiency while meeting complex hospital requirements? To address this challenge, we propose a novel mixed-integer linear programming model with updated constraints, parameters, and an enhanced evaluation function. We implemented the model at Hospital Canselor Tuanku Muhriz (HCTM), Malaysia, to handle various shift types across multiple locations for both monthly and weekly rosters. The proposed model optimises the roster by satisfying mandatory constraints first (such as legal requirements), and then minimising soft constraint violations, such as employee preferences, through iterative refinement. The evaluation function assesses roster quality by minimising penalties for soft constraint violations. We modified the evaluation function and constraints to accommodate HCTM's specific shift patterns and rest requirements, enhancing fairness, flexibility, and workload distribution. The model reduced penalties by 69.57% for monthly rosters and 64.37% for weekly rosters compared to manual scheduling. Statistical analysis proved significant enhancement in monthly rosters and weekly rosters. The model improves workload fairness and scheduling efficiency, bridging theoretical models and practical applications. It contributes to healthcare workforce management by offering better resource allocation and increased staff satisfaction.

INDEX TERMS scheduling, Anaesthetist Rostering Problem (ARP), mathematical model, personnel rostering.

I. INTRODUCTION

Surgical services constitute a major component of healthcare costs [1, 2], requiring effective management strategies [3]. Optimising anaesthetist rostering is crucial for efficient surgical operations and cost reduction [2, 4]. This study addresses the Anaesthetist Rostering Problem (ARP) by developing a model to optimise anaesthetist rosters and lower hospital expenditure.

Despite extensive research on healthcare rostering, such as Nurse Rostering Problems (NRP) [5-7] and Physician Rostering Problems (PRP) [8], many hospitals, including Hospital Canselor Tuanku Muhriz (HCTM) in Malaysia, still

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use manual rostering. This outdated approach often leads to inefficient rosters. Automated optimisation significantly improves shift distribution, reduces preparation time, and cuts costs [9].

Current scheduling methods have practical limitations when used in real hospitals [10-14]. They often restrict anaesthetists to one shift or location per day, prioritise qualifications over preferences, and inadequately handle break assignments and diverse requests. Real-world ARPs, such as at HCTM, require managing concurrent shifts, multiple locations, and anaesthetist preferences [15-17].

Recent studies have made notable progress in addressing specific aspects of the ARP. Hsu et al. [18] introduced a model using job shop scheduling to minimise operation completion times, while Sun et al. [19] developed a framework for managing clinical demand uncertainty and ensuring equitable workloads. Kraul et al. [20] focused on optimising program completion for resident anaesthetists, and Abdullah et al. [21] addressed multi-location rostering at HCTM. However, despite these advances, none of these models fully meet the complex requirements of HCTM. This study seeks to answer the question: How can we generate a high-quality roster that significantly enhances both fairness and efficiency while addressing HCTM's multifaceted needs?

To bridge these gaps, we propose a comprehensive weekly and monthly ARP model specifically tailored to HCTM. The hospital, affiliated with The National University of Malaysia [22-24], presents unique challenges in rostering due to diverse requests, the need to manage concurrent shifts across multiple locations, and teaching responsibilities. The aim of this new model is to balance these demands, prevent overwork, and ensure an efficient allocation of resources.

Our model integrates key requirements, addressing both mandatory and optional requests, multiple shifts, and anaesthetist preferences. As Erdst et al. [25] note, mathematical models must account for industry-specific characteristics, and Silver [26] emphasises that modelling is crucial for solving real-world optimisation problems. Although this model has been developed specifically for HCTM, it can serve as a template for other hospitals facing similar rostering challenges.

In summary, by addressing the limitations of existing models, this study proposes a robust solution that balances fairness, efficiency, and real-world complexities. The model not only meets the intricate demands of HCTM but also provides a framework that can be adapted to improve rostering practices in other healthcare institutions.

The rest of the paper is laid out as follows. The associated literature is reviewed in section II. Section III presents a detailed description of the problem and the mathematical formulation model. Section IV discusses the analysis of the case study, and the paper concludes in Section V.

II. LITERATURE REVIEW

This section reviews relevant work on NRP [5-7] and PRP [8], focusing on shift types and work regulations applicable to ARP. As previous work in PRP forms the basis for many ARP models, we use PRP as a benchmark for our ARP mathematical model.

A. MONTHLY ROSTER

On-call shifts are crucial in healthcare but present significant scheduling challenges due to the need for continuous service [27-30]. The ARP, introduced in 1992 [31], initially focused on managing weekly shift rosters, including on-call shifts. Rousseau et al. [32] later extended this to the PRP, defining on-call shifts as one per weekend or holiday, followed by an 8-hour mandatory rest period, laying the foundation for on-call shift management in healthcare.

Later research improved upon these initial approaches. Brunner et al. [10] developed a detailed structure for on-call shifts at a German hospital, with a 24-hour shift model comprising 8 hours of work and 16 hours of standby during weekdays, and continuous 24-hour standby on weekends. They mandated at least 12 hours of rest between shifts and limited physicians to one on-call shift per week. Brunner et al. [11] later optimised this model to reduce costs while adhering to labour regulations, and Stolletz and Brunner [13] further integrated fairness and physician preferences into the shift allocation process.

Further improvements focused on practical workplace needs. Fugener et al. [12] required a day off after on-call shifts and prohibited consecutive workdays for the same physician. Shamia et al. [33] limited on-call shifts to once every two weekends and capped them at three days per physician. They also stipulated that only one physician should be assigned per department. Huang et al. [34] introduced qualification-based shift assignments, restricting on-call shifts within departments and adding buffer times around approved leave to prevent overwork.

To address workload balance, Schoenfelder and Pfefferlein [14] introduced a weekly cap of 60 on-call hours to ensure equitable distribution. Hidri et al. [35] focused on intensive care unit (ICU) physicians, proposing a systematic scheduling approach that avoided consecutive weekend on-call shifts, improving rest and preventing physician burnout.

B. WEEKLY ROSTER

The HCTM weekly roster mainly involves morning, evening and office hours shifts. Rousseau et al. [32] indicate a required break of at least 16 hours for physicians assigned to night or evening shifts. Brunner et al. [10, 11] stress the need for sufficient physician coverage during each shift period, allowing for flexible start times during workdays while maintaining a minimum shift duration. They introduce time window restrictions to prevent consecutive shift periods and incorporate break assignments for extended shifts.

Fugener et al. [12] present a structured PRP model where each physician is assigned a single daily shift. Their model

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defines specific shift durations and requires at least one sub-senior or specialist for morning shifts and experienced personnel for evening shifts. To prevent overwork, they prohibit absences from any shift for more than four consecutive days and recommend at least one day off every two weeks.

Thielen [36] builds upon these ideas, presenting a PRP model for the Department of Orthopaedics and Trauma Surgery. This model introduces new features aimed at producing fair rosters for physicians. Key aspects include mandatory rostering of two compulsory shifts on Saturday weekends for each physician and providing an off day following night shifts. Additionally, the model accommodates individual physicians' preferences for shift requests, enhancing personalisation and potentially improving satisfaction.

Huang et al. [34] further refine the scheduling guidelines by distinguishing between morning and evening shifts. Their model specifies mandatory attendance for weekday morning shifts unless physicians have approved leave, and requires a team composed of junior and senior physicians for evening shifts.

Recent real-world PRP models, such as those by Wickert et al. [9] and Meister et al. [37], focus on limiting physicians to one shift per weekday and maintaining valid shift successions to prevent fatigue. Cappanera et al. [38] introduced an emergency department PRP model that incorporates alternating weekend work, supporting work-life balance and minimising burnout.

C. RECENT ADVANCEMENTS IN ARP

While PRP has been extensively studied, ARP presents unique challenges that require specialised attention. Anaesthetists often work across multiple locations during a shift, manage concurrent responsibilities, and have specific preferences that need to be considered.

Recent advancements in ARP research have significantly expanded the complexity and scope of scheduling models. Hsu et al. [18] applied job shop scheduling concepts to optimise anaesthetist availability for operating theatres. Sun et al. [19] introduced a data-driven framework for the academic anaesthetists from the Department of Anaesthesiology, incorporating demand uncertainty and using multiobjective mixed-integer programming to handle assignments. Kraul et al. [20] addressed resident anaesthetist programs, focusing on timely program completion while managing uncertainty in intervention numbers.

Abdullah et al. [21] developed a model specifically for on-call shift ARP at HCTM in Malaysia, tackling real-world challenges such as multi-location rostering, consecutive day assignments, and anaesthetist preferences. These studies represent significant progress in addressing the complex scheduling requirements of anaesthetists in both academic and clinical settings.

Despite these advancements, current models still do not fully address all the complex requirements of HCTM's ARP, particularly in terms of integrating both monthly and weekly rostering needs. This gap in the literature motivates our current study to develop a more comprehensive model tailored to HCTM's specific requirements.

Drawing from a comprehensive analysis of existing work on the PRP model for monthly and weekly rosters, we summarise key aspects in Table 1. This table provides a side-by-side comparison of monthly and weekly rostering practices, highlighting the primary focus, shift durations, rest rules, maximum shift allocations, assignment rules, physician preferences, and other critical considerations. It also emphasizes recent developments in ARP models, such as multi-location assignments and integration with teaching duties, which are not typically addressed in traditional PRP models. This summary not only encapsulates the current state of the art in physician and anaesthetist rostering but also underscores the gaps that our proposed model aims to address, particularly in managing the complex, multi-faceted requirements of real-world hospital environments like HCTM.

TABLE 1 SUMMARIZE EXISTING WORK.

Aspect	Monthly Roster	Weekly Roster
Primary Focus	On-call shifts.	Morning, evening, and office hour shifts
Shift Duration	Typically 24-hour shifts (e.g., 8:00 am to 8:00 am next day) [10].	Morning: 9 hours (e.g., 07:30-16:30) [12]; Evening: 11.15 hours (e.g., 10:00-21:15) [12]; Night: 15 hours (e.g., 17:00-08:00) [34].
Rest Rules	12-hour rest after an on-call shift [10]; 8-hour break after an on-call shift [32]; day off after an on-call shift [12].	16-hour break after night/evening shifts [32]; day off after night shift [36]; no consecutive shifts [34].
Maximum Shifts	One on-call per week [10]; one on-call every two consecutive weekends [33].	One shift per day [9, 33, 37]; limit of 60 hours per week [14].
Shift Assignment Rules	Separated by at least one day [10]; no consecutive days [12]; one on-call every two consecutive weekends [33].	No early/late shifts after nights [9, 37]; an absence is not allowed for four consecutive days [12].
Physician Preferences	Shift length, days-on/off patterns, preferred partners [13].	Shift preferences are considered [36]; avoid consecutive and holiday shifts [34].
Speciality Considerations	Qualification-based assignments [34].	Sub-senior or specialist required for morning shifts [12].
Workload Balance	Weekly cap on on-call hours [14].	Alternating weekend work [38].
Multi-location Assignments	Not typically addressed	Addressed in recent ARP models [21].

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Integration with Teaching Duties	Not typically addressed	Considered in academic department models [19].

III. PROBLEM DESCRIPTION AND MODELS

The proposed model, based on HCTM's ARP and incorporating concepts from previous studies, addresses both monthly and weekly rosters. The monthly roster manages on-call shifts (08:00-08:00 the next day), while the weekly roster covers morning (09:00-14:00), evening (14:00-17:00 or 19:00), and office hours (08:00-17:00) shifts.

This approach helps manage different types of surgeries and anaesthetist availability patterns. HCTM currently generates monthly and weekly rosters manually using Microsoft Excel [21]. This approach presents challenges due to its complexity, time-intensive nature, and tendency to produce suboptimal outcomes [37]. Crafting a high-quality roster considering fairness and satisfaction among anaesthetists proves challenging [12]. Hence, this study develops a mathematical model to address HCTM's ARP problem, aiming to minimise penalties related to soft constraints while meeting all mandatory ones [39, 40].

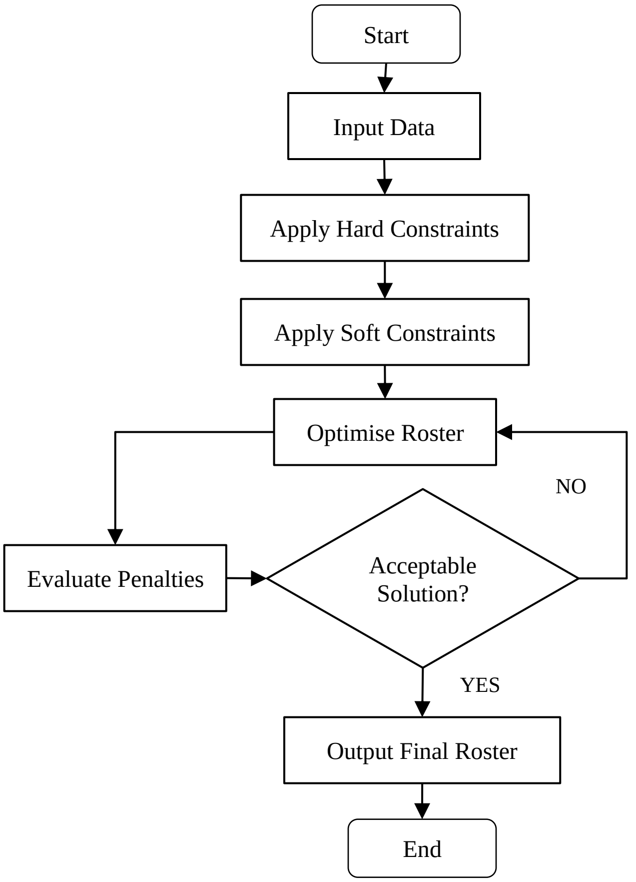

FIGURE 1 **ARP process flowchart.**

Assigning penalty weights for soft constraint violations is challenging due to the absence of standardised values, as constraints differ across hospitals [41, 42]. To resolve this, we consulted with HCTM personnel, who manually created the rosters. Their expertise guided us in assigning appropriate weights based on practical experience. Figure 1 presents the flowchart outlining the procedure for solving the ARP, providing an overview of the proposed solution approach.

The scheduling process starts by collecting necessary information and ends with the final roster output. It first satisfies hard constraints, such as legal requirements, and then addresses soft constraints like employee preferences. The system optimises the roster by minimising violations of soft constraints. If the roster meets the required standards, it outputs the final roster. Otherwise, it further refines the roster iteratively until it is acceptable.

A. BASIC MODEL

Table 2 shows the list of constraints based on the existing work of the monthly and weekly roster for the basic model. We have modified some of the constraints and the penalty value to make it applicable to the real-world ARP. As previous work in [12] denoted the places as the location, we make use of the terms of the location to represent the places for the ARP at HCTM.

TABLE 2 LIST OF HARD AND SOFT CONSTRAINTS FOR THE BASIC ARP MODEL BASED ON EXISTING WORK.

Indices	Constraint Description	Type of Constraint	Penalty	Research
HC1	On each day, the number of anaesthetists required for each shift at each location of the shift must be met.	Hard	-	[10-14]
HC2	An anaesthetist who is absent must not be rostered for any location of the shift on that day.	Hard	-	[9-14, 36, 37]
HC3	For a certain location of the on-call shift, an anaesthetist must not be rostered continuously on weekdays (except on pairs of public holidays).	Hard	-	[10-12]
HC4	An anaesthetist must be assigned to an appropriate location based on their specialist and the location's requirements.	Hard	-	[10-14]
HC5	The total number of working days for each anaesthetist on each location of the shift for each week must be less than or equal to the	Hard	-	[10-14]

	maximum number of working days allowed.			
HC6	An anaesthetist must not be rostered on the next day after completing the certain location of the on-call shift.	Hard	-	[10-12]
SC1	Ensure that each anaesthetist gets appropriate rest before and after completing the on-call shift location.	Soft	$C^{SC1} = 10$	[10-14]
SC2	An anaesthetist's request for not working any on-call shifts on that day should be honoured.	Soft	$C^{SC2} = 5$	[12]
SC3	Any anaesthetist requesting a morning or evening shift on a day should be accommodated.	Soft	$C^{SC3} = 30$	[12]

We adopt several hard constraints (HC) from the literature to suit the real-world ARP at HCTM. HC1, derived from Brunner et al. [10, 11]; Fugener et al. [12] and Schoenfelder & Pfefferlen [14] focuses on meeting the demand for anaesthetists at each location daily. HC2, commonly discussed by authors such as Wickert et al. [9], Thielen [36] and Meister et al.[37], ensures that shift allocations align with operational needs. We also adapt HC3, which governs on-call shifts, for weekdays in the ARP at HCTM, excluding public holiday pairs, as discussed by Brunner et al. [10, 11] and Fugener et al. [12]. Constraints HC4 and HC5, also from Brunner et al. [10, 11], and others, have been updated to align with the specific needs of HCTM. These adaptations ensure the model's relevance and applicability to the real-world challenges faced in anaesthetist rostering.

Our model introduces modifications to soft constraints (SC) to enhance fairness and flexibility in anaesthetist rostering. SC1, as discussed by Fugener et al. [12] and Schoenfelder and Pfefferlein [14], typically involves a day of rest after an on-call shift. We build on this by mandating a compulsory day off after specific on-call shifts, ensuring no scheduling during this rest period. Additionally, a three-day break is required before the next on-call shift, with penalties for any violations. During this break, anaesthetists can manage weekly shifts, prioritising morning or evening shifts on the first day. This adjustment strikes a balance between workload and rest, improving shift management in high-pressure environments.

For shift requests (SC2), we diverge from Fugener et al. [12], who apply a reward system for fulfilled requests. Instead, we implement a penalty-based approach where unfulfilled shift requests incur demerits. This method ensures fairness by penalising unmet requests, and compelling rosters to more carefully consider shift preferences. It offers a more practical solution for balancing operational demands with individual preferences in real-world scheduling scenarios.

We address two key preferences in ARP: avoiding on-call shifts and securing preferred weekly shifts, treating them as separate soft constraints (SC2 and SC3). In practice, weekly shift preferences take precedence over avoiding on-call shifts, reflecting real-world healthcare needs. Unlike previous models that treated these as hard constraints, we use soft constraints with penalties, providing more flexibility in scheduling while still accounting for individual preferences.

B. EXTENDED MODEL

The new ARP model distributes shifts fairly among anaesthetists for both monthly and weekly rosters while incorporating HCTM's real-world requirements. Table 3 shows the list of the constraints that we extended to improve the basic model and make it applicable to the real-world ARP.

TABLE 3 LIST OF HARD AND SOFT CONSTRAINTS FOR REAL ARP MODEL AT HCTM (EXTENDED MODEL).

Indices	Constraint Description	Type of Constraint	Penalty
HC7	The location of the shift that must be rostered together for the same anaesthetist on the pair days of the weekends or pair days of public holidays must be fulfilled.	Hard	-
HC8	The anaesthetist must be rostered to at least one location of the shift or no more than the total number of permissible locations of the shift.	Hard	-
HC9	Invalid location combinations must not be permitted.	Hard	-
HC10	Shift succession for certain shifts must not be allowed.	Hard	-
HC11	Some pair combinations of the location must be fulfilled during the pair days of the weekends or public holidays.	Hard	-
SC4	Some pair combinations of the location for specific shifts that can be rostered together for the same anaesthetist should be met except on the pair days of the weekends or pair days of public holidays.	Soft	$C^{SC4} = 8$
SC5	All anaesthetists should be rostered fairly for each location of the shifts during the planning period.	Soft	$C^{SC5} = 10$
SC6	All anaesthetists should be rostered fairly for each location of the shifts on weekends and public holidays.	Soft	$C^{SC6} = 10$
SC7	All anaesthetists should be rostered fairly for each location of the shifts on pre-holiday (the days before the public holidays or weekends).	Soft	$C^{SC7} = 3$
SC8	An anaesthetist should be rostered monthly and weekly based on their preferences.	Soft	$C^{SC8} = 8$

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SC9	An anaesthetist who needs to be rostered based on the pair of consecutive days for the specific location of the on-call shift should be fulfilled.	Soft	$C^{SC9} = 8$
SC10	An anaesthetist with undesired combinations of locations should be avoided.	Soft	$C^{SC10} = 8$

C. EXAMPLE OF THE MONTHLY AND WEEKLY ROSTER

Table 4 outlines the locations and shift types for both monthly and weekly rosters, specifying categories, abbreviations, and shift names. The roster includes passive, active, and private on-call shifts. Passive and private on-call shifts, running from 08:00 to 08:00 the following day, require attendance only if necessary, except at specialist locations like SICU and SCT, which require presence from 08:00 to 17:00. In contrast, active on-call shifts mandate a 24-hour hospital stay. Weekly shifts cover office hours (08:00 to 17:00), morning shifts (09:00 to 14:00), and evening shifts (14:00 to 17:00, except for EU2, which ends at 19:00). Locations are classified as major or minor, with major categories carrying a heavier workload, potentially equivalent to two minor locations.

TABLE 4 LIST OF LOCATIONS OF THE SHIFT FOR MONTHLY AND WEEKLY ROSTER.

Location	Name	Shift	Category
CGOT	Consultant General Operating Theatre	Passive on-call	Minor
CICU	Consultant Incentive Care Unit	Passive on-call	Minor
SICU	Specialist Incentive Care Unit	Passive on-call	Major
CCT	Consultant Cardiothoracic	Passive on-call	Minor
SCT	Specialist Cardiothoracic	Passive on-call	Major
SGOT	Specialist General Operating Theatre	Active on-call	Major
PWOT	Private Ward Operating Theatre	Private on-call	Major
OHMAU	Office Hours Major Universal	Office hours	Major
OHMIU	Office Hours Minor Universal	Office hours	Minor
MMAU	Morning Major Universal	Morning	Major
MMIU	Morning Minor Universal	Morning	Minor
MCT	Morning Cardiothoracic	Morning	Major
MPWOT	Morning Private Ward Operating Theatre	Morning	Major
MPMIS	Morning Paediatric	Morning	Major
EU1	Evening Universal 1	Evening	Major
EPWOT	Evening Private Ward Operating Theatre	Evening	Major
EU2	Evening Universal 2	Evening	Major

Table 5 provides details on the qualified anaesthetists and their location preferences, based on one month of ARP data from HCTM. The data includes 12 junior anaesthetists (JU) and 10 senior anaesthetists (SE). Each anaesthetist has preferences for specific monthly and weekly roster locations. For instance, while all junior anaesthetists meet the requirements for SGOT locations, JU12 prefers not to be rostered there. Assigning JU12 to SGOT would incur a penalty in the model, emphasising the importance of aligning assignments with individual preferences.

TABLE 5 LIST OF ANESTHETISES THAT QUALIFY WITH THE PREFERENCE FOR THE LOCATION.

Location	List anaesthetists qualify for the location	List anaesthetists qualify but are less preferred for the location
CGOT	SE1, SE2, SE3, SE4, SE5, SE6, SE7	None
CICU	SE2, SE9, SE10	None
SICU	JU3, JU4, JU5, JU8, JU10, JU11, SE2, SE9	None
CCT	SE8	None
SCT	JU12	None
SGOT	JU1, JU2, JU3, JU4, JU5, JU6, JU7, JU8, JU9, JU10, JU11	JU12
PWOT	JU6, JU7, JU9, SE3, SE5, SE7, SE8	None
OHMAU	Except for SE9	SE9
OHMIU	Except for SE9	SE9
MMAU	Except for SE9	SE9
MMIU	Except for SE9	SE9
MCT	JU12, SE8	None
MWK	JU2, JU6, JU7, JU9, SE1, SE2, SE3, SE5, SE7, SE8, SE10	None
MPMIS	JU1, JU7, SE6	None
EU1	Except for SE9	SE9
EWK	JU2, JU6, JU7, JU9, SE1, SE2, SE3, SE5, SE7, SE8, SE10	None
EU2	Except for SE9	SE9

Figure 2 exhibits a comprehensive example of the ARP roster at HCTM, covering both monthly and weekly rosters across seven days. The first column outlines the shift locations for both rosters, with rows indicating the rostered anaesthetists. Throughout these rosters, some anaesthetists cover multiple locations on their working days. For instance, JU6 manages SGOT and PWOT in the monthly roster, while MMIU and MWK are handled in the weekly roster. Locations carry individual weights based on their category (major or minor). Notably, there's a discrepancy in the daily anaesthetist requirement for servicing weekly and monthly locations. For example, OHMIU necessitates one anaesthetist on Mondays, fulfilled by SE4, representing a demand that must be fulfilled (refer to HC1).

ARP at HCTM follows specific rules:

i. SGOT shifts have limits on consecutive weekdays worked. After SGOT, no work is allowed the next day.

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ii. Only certain anaesthetists qualify for CCT and SCT.
iii. Unavailable anaesthetists can't be rostered.
iv. Preferred anaesthetists may work multiple locations per day.
v. MCT, MWK, or EWK shifts exclude other work that week.
vi. CICU requires 2-3 day shifts.

Roster	Workstation	Mon	Tue	Wed	Thu	Fri	Sat	Sun
MONTHLY	**CGOT**	SE2	SE3	SE1	SE4	SE5	SE5	SE5
	CICU	SE2	SE2	SE9	SE9	SE10	SE10	SE10
	SICU	JU5 & SE2	JU8	SE9	SE9 & JU11	SE9 & JU4	JU2	JU2
	CCT	SE8	SE8	SE8	SE8	SE8	SE8	SE8
	SCT	JU12	JU12	JU12				
	SGOT	JU6	JU8	JU5	JU3	JU11	JU2	JU2
	PWOT	JU6	SE3	SE8	JU7	JU6	SE5	JU9
WEEKLY	**OHMAU**	SE5	JU8	JU6, JU12	SE1, SE6	SE8, JU10	JU2	JU2
	OHMIU	SE4	PUBLIC HOLIDAY	**SE1***, SE2	**JU9***	JU7	WEEKEND	
	DISSERTATION			SE3	SE2	SE5		
	EXAMINATION							
	TEACHING	SE3			SE2			
	MMAU	JU1, JU4, **SE1***, **SE6***		**JU3***, **JU4***, **SE2***, SE6	JU1, SE4	JU1, JU7, SE1, SE5, **SE6***		
	MMIU	JU6, JU12		**JU5***	JU3, SE4	**JU11***		
	MCT	JU12			SE8			
	MWK	JU9		SE8	JU7	JU6, SE10		
	MPMIS			JU7, SE6				
	EU1	JU10		JU11	JU8, SE7	SE4		
	EWK	SE3		SE7	JU6	JU2, SE2		
	EU2			JU10				

Note: * refer to anaesthetist work for more than one place in that location.

FIGURE 2 Example of ARP Roster that Combines Between Monthly and Weekly Roster For 7 Days

D. MATHEMATICAL MODEL

Table 6 presents the notation used in our mathematical model, which optimises monthly and weekly rosters for anaesthetists. The model aims to minimise penalties from soft constraint violations while ensuring all hard constraints are met, enhancing fairness and satisfaction.

TABLE 6 MATHEMATICAL MODEL NOTATION.

Set and Indices	
A	Set of anaesthetists.
W	Set of locations.
W^{MO}	Subset locations for the monthly roster.
W^{WK}	Subset locations for the weekly roster.
K	Set of shifts.
D	Set of days in the planning period (e.g., 28 days).
G	Set of days within a week (7 days).
E	Set of weeks in a planning period (Week 1, ..., Week 4).
D^{WH}	Subset of days that are weekends or public holidays.
D^{PH}	Subset of days that are pre-holidays.
H	Set of pairs of weekend/public holiday days, where $(d_1, d_2) \in H$.
L^M	Set of pairs of locations that must be rostered together with the same anaesthetist, where $(w_1, w_2) \in L^M$.
L^S	Set of pairs of locations that should be rostered together with the same anaesthetist, where $(w_1, w_2) \in L^S$.
L^U	Set of pairs of locations that are undesired to be rostered together with the same anaesthetist, where $(w_1, w_2) \in L^U$.
V^{2D}	Set of pairs of two consecutive days, where $(d_1, d_2) \in V^{2D}$.
V^{3D}	Set of pairs of three consecutive days, where $(d_1, d_2, d_3) \in V^{3D}$.
Parameters	
$b_{(w,d)}$	Number of anaesthetists required for location w on day d.
$r^{EX}_{(a,d)}$	0 if anaesthetist a requests an examination on day d; 1 otherwise.
$r^{DS}_{(a,d)}$	0 if anaesthetist a requests a dissertation on day d; 1 otherwise.
$r^{MS}_{(a,d)}$	0 if anaesthetist a requests a morning shift on day d; 1 otherwise.
$r^{ES}_{(a,d)}$	0 if anaesthetist a requests an evening shift on day d; 1 otherwise.
$r^{CT}_{(a,d)}$	0 if anaesthetist a requests the cardiothoracic task on day d; 1 otherwise.
$r^{NOC}_{(a,d)}$	0 if anaesthetist a requests not to receive on-call on day d; 1 otherwise.
$r^{TT}_{(a,d)}$	0 if anaesthetist a requests teaching on day d; 1 otherwise.
$r^{NA}_{(a,d)}$	0 if anaesthetist a requests absence on day d; 1 otherwise.
$p^{MR}_{(a,w)}$	1 if anaesthetist a meets the requirement for location w; 0 otherwise.
$p^{LP}_{(a,w)}$	1 if anaesthetist a meets the requirement for the location w but with less preference; 0 otherwise.
z^{MWK}	Maximum number of working days in a week.
z^{MD}	Maximum weight of locations of the shift that is allowed to be rostered for each anaesthetist in a day.
z^{WT}_w	Weight for the location w.
j^{RD}	Number of rest days for the anaesthetist after completing the on-call shift.
$z^{AD}_{(a,w)}$	Total number of working days of anaesthetist a in location w for all days in the previous roster.
$z^{WH}_{(a,w)}$	Total number of working days of anaesthetist a in location w for weekends and public holidays in the previous roster.
$z^{PH}_{(a,w)}$	Total number of working days of anaesthetist a in location w for pre-holiday in the previous roster.
$C^{SC1}, \ldots, C^{SC10}$	Penalty weight for soft constraint SC1 to SC10.
Decision Variables	
$x^{MO}_{(a,w,k,d,e)}$	1 if anaesthetist a is rostered for the monthly roster of location w on shift k for day d in week e; 0 otherwise.
$x^{WK}_{(a,w,k,g,e)}$	1 if anaesthetist a is rostered for the weekly roster of location w on shift k for day g in week e; 0 otherwise.
o_a	1 if anaesthetist a did not get enough rest after completing the monthly and weekly roster; 0 otherwise.
$u^{NOC}_{(a,d)}$	1 if the request of anaesthetist a on day d to not receive an on-call shift is not fulfilled; 0 otherwise.
$u^{SF}_{(a,d)}$	1 if the request of anaesthetist a on day d for a morning or evening shift is not fulfilled; 0 otherwise.
n_a	1 if anaesthetist a is not rostered together for all locations in the combination of pairs that should be rostered together.
m^{MXD}_w	Maximum number of working days for location w in the planning period based on the total working days distribution.
m^{MID}_w	Minimum number of working days for location w in the planning period based on the total working days distribution.

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m_w^{MXWH}	Maximum number of working days for location w in the planning period based on the total working days on weekends and public holidays distribution.
m_w^{MIWH}	Minimum number of working days for location w in the planning period based on the total working days on weekends and public holidays distribution.
m_w^{MXPH}	Maximum number of working days for location w in the planning period based on the total working days on pre-holiday distribution.
m_w^{MIPH}	Minimum number of working days for location w in the planning period based on the total working days on pre-holiday distribution.
$q_{(a,w)}$	1 if anaesthetist a with less preference is rostered on location w; 0 otherwise.
s_a	1 if the anaesthetist a not rostered on consecutive days; 0 otherwise.
$t_{(a,d)}$	1 if anaesthetist a is rostered for all locations in the combination of undesired pairs on day d; 0 otherwise.

We have separate objective functions for monthly and weekly rosters:

$$Minimise\ f^{MO}(x) = SC1 + SC2 + SC3 + SC4 + SC5 + SC6 + SC7 + SC8 + SC9 + SC10 \quad (1)$$

$$Minimise\ f^{WK}(x) = SC1 + SC3 + SC4 + SC5 + SC7 + SC8 + SC10 \quad (2)$$

Where SC1 to SC10 represent penalties for violating different soft constraints, each weighted by a corresponding penalty factor C^{SC1} to C^{SC10}.

$$SC1 = \left[\sum_{a\in A} o_a \times C^{SC1}\right]$$

$$SC2 = \left[\sum_{a\in A}\sum_{d\in D} u_{(a,d)}^{NOC} \times C^{SC2}\right]$$

$$SC3 = \left[\sum_{a\in A}\sum_{d\in D} u_{(a,d)}^{SF} \times C^{SC3}\right]$$

$$SC4 = \left[\sum_{a\in A} n_a \times C^{SC4}\right]$$

$$SC5 = \left[\sum_{w\in W} m_w^{MXD} - \sum_{w\in W} m_w^{MID}\right] \times C^{SC5}$$

$$SC6 = \left[\sum_{w\in W} m_w^{MXWH} - \sum_{w\in W} m_w^{MIWH}\right] \times C^{SC6}$$

$$SC7 = \left[\sum_{w\in W} m_w^{MXPH} - \sum_{w\in W} m_w^{MIPH}\right] \times C^{SC7}$$

$$SC8 = \left[\sum_{a\in A}\sum_{w\in W} q_{(a,w)} \times C^{SC8}\right]$$

$$SC9 = \left[\sum_{a\in A} s_a \times C^{SC9}\right]$$

$$SC10 = \left[\sum_{a\in A}\sum_{d\in D} t_{(a,d)} \times C^{SC10}\right]$$

Our evaluation function differs significantly from those found in the existing ARP literature, offering several key improvements. While previous models, such as those by Brunner et al. [11, 43] and Fugener et al. [12], primarily focused on minimising the total number of shifts or maximising preference satisfaction, our approach provides a more comprehensive and nuanced assessment of roster quality. Our model incorporates a wider range of soft constraints (SC1-SC10) compared to previous studies.

A key innovation in our model is the distinction between monthly (on-call) and weekly rosters with separate objective functions (1) and (2). This allows for more targeted optimisation of different roster types, addressing the unique challenges of each. Furthermore, our model explicitly incorporates fairness metrics (SC5, SC6, SC7) for overall workload, weekend/holiday work, and pre-holiday work. This is a significant improvement over models like those of Brunner et al. [11, 43], which did not directly address fairness in their objective functions. Our approach ensures a more equitable distribution of workload across all anaesthetists.

Our model also offers greater preference granularity. While previous models often used a single preference score, we distinguish between different types of preferences (e.g., SC2 for on-call preferences, and SC3 for shift requests), allowing for more nuanced preference satisfaction. Additionally, we include location-specific constraints (e.g., SC4, SC10) that are particularly relevant to the multi-location nature of modern hospital environments. This addresses a gap in many existing models that do not account for the complexity of anaesthetists working across multiple locations.

Finally, the use of separate penalty weights (C^{SC1} to C^{SC10}) for each soft constraint allows for adaptive prioritisation of different aspects of roster quality. This flexibility is not present in many existing models, which often use fixed weights or prioritisation schemes. By incorporating these elements, our evaluation function provides a more comprehensive and flexible approach to assessing roster quality. It balances multiple competing objectives, including fairness, preference satisfaction, and operational efficiency, in a way that is more aligned with the complex realities of modern hospital environments.

The model enhances the ARP evaluation function by incorporating a wider range of soft constraints (SC1-SC10) and tailoring solutions for both monthly and weekly rosters to ensure fair workload distribution. It addresses gaps in previous models by offering more precise preference handling and incorporating location-specific constraints. By using flexible penalty weights, the model adapts to balance

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fairness, preferences, and operational efficiency, optimizing roster quality in complex hospital settings.

A. *Hard Constraints (HC1-HC11)*

- *HC1: Meeting the required number of anaesthetists.*
  Equations (3) and (4) ensure that the required number of anaesthetists are assigned to each shift and location daily. This is crucial for maintaining adequate staffing levels across all hospital areas.

$$\sum_{a\in A} x^{MO}_{(a,w,k,d,e)} = b_{(w,d)}, \forall w \in W^{MO}, k \in K, d \in D, e \in E \tag{3}$$

$$\sum_{a\in A} x^{WK}_{(a,w,k,g,e)} = b_{(w,d)}, \forall w \in W^{WK}, k \in K, g \in G, e \in E, \{G = D\} \tag{4}$$

- *HC2: Ensuring unavailable anaesthetists are not rostered.*
  Equations (5) and (6) prevent the assignment of shifts to anaesthetists who are unavailable, including those with exam duties. This constraint respects anaesthetists' commitments outside of their regular duties.

$$\begin{aligned} &x^{MO}_{(a,w,k,d,e)} \cdot r^{EX}_{(a,d)} = 0 \; where \; r^{EX}_{(a,d)} = 0, \forall a \in A, w \in W^{MO}, k \in K, D \in D, e \in E \\ &x^{MO}_{(a,w,k,d,e)} \cdot r^{NA}_{(a,d)} = 0 \; where \; r^{NA}_{(a,d)} = 0, \forall a \in A, w \in W^{MO}, k \in K, D \in D, e \in E \end{aligned} \tag{5}$$

$$\begin{aligned} &x^{WK}_{(a,w,k,g,e)} \cdot r^{EX}_{(a,d)} = 0 \; where \; r^{EX}_{(a,d)} = 0, \forall a \in A, w \in W^{WK}, k \in K, g \in G, e \in E, \{G = D\} \\ &x^{WK}_{(a,w,k,g,e)} \cdot r^{NA}_{(a,d)} = 0 \; where \; r^{na}_{(a,d)} = 0, \forall a \in A, w \in W^{WK}, k \in K, g \in G, e \in E, \{G = D\} \end{aligned} \tag{6}$$

- *HC3: Preventing continuous rostering for specific locations.*
  Equations (7) and (8) limit continuous weekday rostering for on-call shifts, except during consecutive public holidays. This constraint helps prevent burnout by ensuring anaesthetists have breaks between demanding shifts.

$$\sum_{d_1 \in \{d | d_2 \le d \le d_2+1 \; and \; d \in D-H\}} x^{MO}_{(a,w,k,d_1,e)} \le 1 \;, \forall a \in A, w \in \{SGOT\}, k \in K, d_2 \in D - H, e \in E \tag{7}$$

$$\sum_{d_3 \in \{d | d_4 \le d \le d_5 \; and \; d \in D\}} x^{MO}_{(a,w,k,d_3,e)} \le 2 \;, \forall a \in A, w \in \{SGOT\}, k \in K, (d_1, d_2) \in H, d_4 = d_1 - 1, d_5 = d_2 + 1, e \in E \tag{8}$$

- *HC4: Assigning anaesthetists to appropriate locations based on speciality.*
  Equations (9)-(12) match anaesthetists to locations based on their specialities and qualifications. This ensures that each location is staffed with appropriately skilled personnel.

$$x^{MO}_{(a,w,k,d,e)} \cdot p^{MR}_{(a,w)} = 0 \; where \; p^{MR}_{(a,w)} = 0, \forall a \in A, w \in \{SICU\}, k \in K, D \in D - D^{WH}, e \in E \tag{9}$$

$$x^{MO}_{(a,w,k,e,d)} \cdot p^{MR}_{(a,w)} = 0 \; where \; p^{MR}_{(a,w)} = 0, \forall a \in A, w \in \{W - SICU\}, k \in K, d \in D, e \in E \tag{10}$$

$$x^{WK}_{(a,w,k,g,e)} \cdot p^{MR}_{(a,w)} = 0 \; where \; p^{MR}_{(a,w)} = 0, \forall a \in A, w \in \{W - OHMAU\}, k \in K, g \in G - D^{WH}, e \in E \tag{11}$$

$$x^{WK}_{(a,w,k,g,e)} \cdot p^{MR}_{(a,w)} = 0 \; where \; p^{MR}_{(a,w)} = 0, \forall a \in A, w \in \{OHMAU\}, k \in K, g \in G, e \in E \tag{12}$$

- *HC5: Limiting the total number of working days per week.*
  Equation (13) caps each anaesthetist's weekly working days per location. This constraint helps maintain work-life balance and comply with labour regulations.

$$\sum_{d\in D} x^{MO}_{(a,w,k,d,e)} \le z^{MWK}, \forall a \in A, w \in \{CGOT, SGOT, PWOT, SICU\}, k \in K, e \in E \tag{13}$$

- *HC6: Ensuring break assignment after specific on-call shifts.*
  Equations (14)-(21) prevent anaesthetists from working the day after certain on-call shifts, particularly after SGOT. This constraint ensures adequate rest periods between demanding shifts.

$$x^{MO}_{(a,w_1,k,d_1,e)} + x^{MO}_{(a,w_2,k,d_2,e)} \le 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in W^{MO} - \{SGOT\}, k \in K, d_1 \in D - D^{WH}, d_2 = d_1 + 1, e \in E \tag{14}$$

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$$x^{MO}_{(a,w_1,k,d_2,e)} + x^{MO}_{(a,w_2,k,d_3,e)} \leq 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in W^{MO} - \{SGOT\}, k \in K, (d_1,d_2) \in H, d_3 \in d_2 + 1, e \in E \quad (15)$$

$$x^{MO}_{(a,w_1,k,d_1,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in W^{WK}, k \in K, d_1 \in D - D^{WH}, g = d_1 + 1, e \in E \quad (16)$$

$$x^{MO}_{(a,w_1,k,d_2,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in W^{WK}, k \in K, (d_1,d_2) \in H, g = d_2 + 1, e \in E \quad (17)$$

$$\begin{aligned} &x^{MO}_{(a,w,k,d_1,e)} \cdot r^{EX}_{(a,d_2)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D - D^{WH}, d_2 \in d_1 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_1,e)} \cdot r^{DS}_{(a,d_2)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D - D^{WH}, d_2 \in d_1 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_1,e)} \cdot r^{TT}_{(a,d_2)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D - D^{WH}, d_2 \in d_1 + 1, e \in E \end{aligned} \quad (18)$$

$$x^{WK}_{(a,w,k,g,e-1)} + x^{MO}_{(a,w,k,d,s)} \leq 1, \forall a \in A, w \in \{SGOT\}, k \in K, g \in G, d = g + 1, e \in E \quad (19)$$

$$\begin{aligned} &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{EX}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, (d_1,d_2) \in H, d_3 \in d_2 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{DS}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, (d_1,d_2) \in H, d_3 \in d_2 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{TT}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, (d_1,d_2) \in H, d_3 \in d_2 + 1, e \in E \end{aligned} \quad (20)$$

$$\begin{aligned} &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{CT}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_2 \in \{28\}, d_3 = d_2 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{EX}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_2 \in \{28\}, d_3 = d_2 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{DS}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_2 \in \{28\}, d_3 = d_2 + 1, e \in E \\ &x^{MO}_{(a,w,k,d_2,e)} \cdot r^{TT}_{(a,d_3)} = 0, \forall a \in A, w \in \{SGOT\}, k \in K, d_2 \in \{28\}, d_3 = d_2 + 1, e \in E \end{aligned} \quad (21)$$

- *HC7: Rostering the same anaesthetist for specific location pairs on weekends/holidays.*
  Equations (22) and (23) ensure that certain locations are staffed by the same anaesthetist on a weekend or public holiday pairs. This promotes continuity of care during these periods.

$$x^{MO}_{(a,w,k,d_1,e)} = x^{MO}_{(a,w,k,d_2,e)}, \forall a \in A, w \in \{CGOT, SGOT, SICU\}, k \in K, (d_1,d_2) \in H, e \in E \quad (22)$$

$$x^{WK}_{(a,w,k,g_1,e)} = x^{WK}_{(a,w,k,g_2,e)}, \forall a \in A, w \in \{OHMAU\}, k \in K, (d_1,d_2) \in H, g_1 \in d_1, g_2 \in d_2, e \in E \quad (23)$$

- *HC8: Limiting the total number of locations per day.*
  Equation (24) sets boundaries on the number of locations an anaesthetist can be assigned to in a day. This prevents overloading and ensures efficient distribution of workload.

$$\left[\sum_{d \in D - D^{WH}} x^{MO}_{(a,w_1,k,d,e)} \times z^{WT}_{w_1}\right] + \left[\sum_{g \in G - D^{WH}} x^{WK}_{(a,w_2,k,g,e)} \times z^{WT}_{w_2}\right] \leq z^{MD}, \forall a \in A, w_1 \in W^{MO}, w_2 \in W^{WK}, k \in K, e \in E \quad (24)$$

- *HC9: Preventing invalid location combinations.*
  Equations (25)-(32) prohibit certain combinations of location assignments that are operationally unfeasible or undesirable.

$$x^{MO}_{(a,w_1,k,d,e)} + x^{MO}_{(a,w_2,k,d,e)} \leq 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in \{SICU\}, k \in K, d \in D - D^{WH}, e \in E \quad (25)$$

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$$x^{MO}_{(a,w_1,k,d,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{SGOT\}, w_2 \in \{MMAU\}, k \in K, d \in D - D^{WH}, g \in G, e \in E \quad (26)$$

$$x^{MO}_{(a,w_1,k,d,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{CCT\}, w_2 \in \{MMAU\}, k \in K, d \in D - D^{WH}, g \in G, e \in E \quad (27)$$

$$x^{MO}_{(a,w_1,k,d,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{CICU, SICU\}, w_2 \in W^{WK}, k \in K, d \in D - D^{WH}, g \in G, e \in E \quad (28)$$

$$x^{WK}_{(a,w_1,k,g,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{MWK\}, w_2 \in W^{WK} - \{MWK\}, k \in K, g \in G - D^{WH}, e \in E \quad (29)$$

$$x^{WK}_{(a,w_1,k,g,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{MCT\}, w_2 \in W^{WK} - \{MCT\}, k \in K, g \in G - D^{WH}, e \in E \quad (30)$$

$$x^{WK}_{(a,w_1,k,g,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{EWK\}, w_2 \in \{EU1, EU2\}, k \in K, g \in G - D^{WH}, e \in E \quad (31)$$

$$x^{WK}_{(a,w_1,k,g,e)} + x^{WK}_{(a,w_2,k,g,e)} \leq 1, \forall a \in A, w_1 \in \{OHMAU\}, w_2 \in \{OHMIU\}, k \in K, g \in G - D^{WH}, e \in E \quad (32)$$

- *HC10: Preventing certain shift successions.*
  Equations (33)-(36) avoid undesirable shift sequences in both monthly and weekly rosters, promoting better work patterns and rest periods.

$$x^{MO}_{(a,w_1,k_1,d,e)} + x^{WK}_{(a,w_2,k_2,g,e)} \leq 1, \forall a \in A, w_1 \in W^{MO}, w_2 \in W^{WK}, k_1 \in K, k_2 \in \{Evening, Late\ Evening\}, d \in D - H, g \in G, e \in E, \{G = D\} \quad (33)$$

$$x^{WK}_{(a,w,k_1,g,e)} + x^{WK}_{(a,w,k_2,g,e)} \leq 1, \forall a \in A, w \in W^{WK}, k_1 \in \{Evening\}, k_2 \in \{Late\ Evening\}, g \in G - H, e \in E \quad (34)$$

$$x^{WK}_{(a,w,k_1,g,e)} + x^{WK}_{(a,w,k_2,g,e)} \leq 1, \forall a \in A, w \in W^{WK}, k_1 \in \{Morning, Evening, Late\ Evening\}, k_2 \in \{Office\ Hours\}, g \in G - H, e \in E \quad (35)$$

$$x^{WK}_{(a,w,k_1,g,e)} + x^{WK}_{(a,w,k_2,g,e)} \leq 1, \forall a \in A, w \in W^{WK}, k_1 \in \{Morning\}, k_2 \in \{Evening, Late\ Evening\}, \mathrm{g} \in \mathrm{G} - \mathrm{H}, e \in E \quad (36)$$

- *HC11: Ensuring specific location combinations on weekends/holidays.*
  Equations (37) and (38) mandate certain location combinations during a weekend or public holiday pairs, ensuring appropriate coverage during these periods.

$$x^{MO}_{(a,w_1,k,d_1,e)} = x^{MO}_{(a,w_2,k,d_1,e)}\ and\ x^{MO}_{(a,w_1,k,d_2,e)} = x^{MO}_{(a,w_2,k,d_2,e)}, \forall a \in A, (w_1, w_2) \in L^M, k \in K, (d_1, d_2) \in H, e \in E \quad (37)$$

$$x^{MO}_{(a,w_1,k,d_1,e)} = x^{WK}_{(a,w_2,k,g_1,e)}\ and\ x^{MO}_{(a,w_1,k,d_2,e)} = x^{WK}_{(a,w_2,k,g_2,e)}, \forall a \in A, (w_1, w_2) \in L^M, k \in K, (d_1, d_2) \in H, g_1 \in d_1, g_2 \in d_2, e \in E \quad (38)$$

B. Soft Constraints (SC1-SC10)

- *SC1: Ensuring adequate rest for anaesthetists.*
  Equations (39)-(46) govern rest periods for anaesthetists before and after various shifts. While not always possible to fully satisfy, this constraint aims to promote better work-life balance and prevent fatigue.

$$if \sum_{d_3 \in \{d_1 - j^{RD} \leq d_3 \leq d_2 + j^{RD}\}} x^{MO}_{(a,w,k,d_3,e)} \geq 3, then\ o_a = 1\ otherwise\ o_a = 0, \forall a \in A, w \in \{CGOT, SGOT, SICU\}, k \in K, (d_1, d_2) \in H, e \in E \quad (39)$$

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$$if \sum_{d_1 \in \{D-H: d_1 \geq d_2 \leq d_2 + j^{RD}\}} x^{MO}_{(a,w,k,d_1,e)} \geq 2,$$
$$then\ o_a = 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{CGOT, SGOT, SICU\},$$
$$k \in K, d_2 \in D - H, e \in E \quad (40)$$

$$if \sum_{d_1 \in \{d_1 \leq d_1 \leq d_2 + j^{RD}\}} x^{MO}_{(a,w,k,d_1,e)} \geq 2,$$
$$then\ o_a = 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{PWOT\}, k \in K, d_2 \in D - H,$$
$$e \in E \quad (41)$$

$$if\ x^{MO}_{(a,w,k,d_1,e_1)} + x^{MO}_{(a,w,k,d_2,e_2)} \geq 2,$$
$$then\ o_a = 1, otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{CICU\}, k \in K, d_3 \in D/E,$$
$$d_1 = \{d_3 = 7\}, d_2 = \{d_3 = 1\},$$
$$e_1 \in E, e_2 \in e_1 + 1 \quad (42)$$

$$if x^{MO}_{(a,w,k,d_3,e)} \cdot r^{EX}_{(a,d_2)} = 1, then\ o_a = 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D,$$
$$d_2 \in \{d_1 + 2\}, d_3 \in \{d_1 - 1\}, e \in E$$
$$if x^{MO}_{(a,w,k,d_3,e)} \cdot r^{DS}_{(a,d_2)} = 1, then\ o_a = 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D,$$
$$d_2 \in \{d_1 + 2\}, d_3 \in \{d_1 - 1\}, e \in E$$
$$if x^{MO}_{(a,w,k,d_3,e)} \cdot r^{TT}_{(a,d_2)} = 1, then\ o_a = 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D,$$
$$d_2 \in \{d_1 + 2\}, d_3 \in \{d_1 - 1\}, e \in E \quad (43)$$

$$if \sum_{d_3 \in \{d_1 - j^{RD} \leq d_3 \leq d_2 + (j^{RD} - 1)\}} x^{MO}_{(a,w,k,d_3,e)} \geq 3,\ then\ o_a$$
$$= 1\ otherwise\ o_a = 0,$$
$$\forall a \in A, w \in \{CGOT, SGOT, PWOT, SICU\},$$
$$k \in K, d_1 = \{27\}, d_2 = \{1\}, e \in E \quad (44)$$

$$if\ x^{MO}_{(a,w_1,k_1,d,e)} = 1 \text{ and } x^{WK}_{(a,w_2,k_2,g,e)} = 1,$$
$$then\ o_a = 1, otherwise\ o_a = 0,$$
$$\forall a \in A, w_1 \in \{SGOT\}, w_2 \in W^{WK},$$
$$k_1 \in K, k_2 \in \{Office\ Hours\}, \mathrm{d} \in \mathrm{D} - 1,$$
$$\mathrm{g} \in \mathrm{G} + 2, e \in E, \{G = D\} \quad (45)$$

$$if\ x^{MO}_{(a,w_1,k_1,d_1,e)} = 1 \text{ and } x^{WK}_{(a,w_2,k_2,g,e)} = 1,$$
$$then\ o_a = 1, otherwise\ o_a = 0,$$
$$\forall a \in A, w_1 \in \{CGOT, SGOT\}, w_2 \in W^{WK},$$
$$k_1 \in K, k_2 \in \{Office\ Hours\},$$
$$d_1 = \{28\}, g = \{2\}, e \in E \quad (46)$$

- *SC2: Honoring requests for no on-call shifts.*
  Equation (47) tries to accommodate anaesthetists' requests to avoid on-call shifts on specific days. This helps improve job satisfaction and respect personal commitments.

$$if\ x^{MO}_{(a,w,k,d,e)} \cdot r^{NOC}_{(a,d)} = 1\ where\ r^{NOC}_{(a,d)} = 1,$$
$$then\ u^{NOC}_{(a,d)} = 1, otherwise\ u^{NOC}_{(a,d)} = 0,$$
$$\forall a \in A, w \in W^{MO}, k \in K, d \in D, e \in E \quad (47)$$

- *SC3: Satisfying shift requests.*
  Equations (48)-(51) attempt to fulfil anaesthetists' requests for specific morning or evening shifts. This constraint balances operational needs with individual preferences.

$$if\ x^{MO}_{(a,w,k,d,e)} \cdot r^{MS}_{(a,d)} = 1\ where\ r^{MS}_{(a,d)} = 1,$$
$$then\ u^{SF}_{(a,d)} = 1, otherwise\ u^{SF}_{a,d} = 0,$$
$$\forall a \in A, w \in W^{MO}, k \in K, d \in D, e \in E \quad (48)$$

$$if\ x^{MO}_{(a,w,k,d,e)} \cdot r^{ES}_{(a,d)} = 1\ where\ r^{ES}_{(a,d)} = 1,$$
$$then\ u^{SF}_{(a,d)} = 1, otherwise\ u^{SF}_{(a,d)} = 0,$$
$$\forall a \in A, w \in W^{MO}, k \in K, d \in D, e \in E \quad (49)$$

$$if\ x^{MO}_{(a,w,k,d_1,e)} \cdot r^{MS}_{(a,d_1)} = 1\ where\ r^{ES}_{(a,d_2)} = 1,$$
$$then\ u^{SF}_{(a,d_1)} = 1, otherwise\ u^{SF}_{(a,d_1)} = 0,$$
$$\forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D,$$
$$d_2 \in d_1 + 1, e \in E \quad (50)$$

$$if\ x^{MO}_{(a,w,k,d_1,e)} \cdot r^{ES}_{(a,d_2)} = 1\ where\ r^{MS}_{(a,d_1)} = 1,$$
$$then\ u^{SF}_{(a,d_1)} = 1, otherwise\ u^{SF}_{(a,d_1)} = 0,$$
$$\forall a \in A, w \in \{SGOT\}, k \in K, d_1 \in D,$$
$$d_2 \in d_1 - 1, e \in E \quad (51)$$

- *SC4: Rostering location pairs together.*
  Equations (52) and (53) aim to roster certain location pairs together for the same anaesthetist, except on weekends or public holidays. This promotes efficiency and continuity in care delivery.

$$if\ x^{MO}_{(a,w_1,k,d,e)} = 1\ and\ x^{MO}_{(a,w_2,k,d,e)} = 0, \quad then\ n_a = 1, otherwise\ n_a = 0, \quad \forall a \in A, (w_1, w_2) \in L^S, k \in K, d \in D, e \in E \tag{52}$$

$$if\ x^{WK}_{(a,w_1,k,g,e)} = 1\ and\ x^{WK}_{(a,w_2,k,g,e)} = 0, \quad then\ n_a = 1, otherwise\ n_a = 0, \quad \forall a \in A, (w_1, w_2) \in L^S, k \in K, g \in G, e \in E \tag{53}$$

- *SC5: Fair distribution of workload.*
  Equations (54)-(57) strive for a fair distribution of working days across all anaesthetists for each location. This constraint promotes equity in workload allocation.

$$m^{MID}_w \leq \sum_{d \in D} x^{MO}_{(a,w,k,d,e)} + z^{AD}_{(a,w)}, \forall a \in A, w \in W^{MO}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{54}$$

$$\sum_{d \in D} x^{MO}_{(a,w,k,d,e)} + z^{AD}_{(a,w)} \leq m^{MXD}_w, \forall a \in A, w \in W^{MO}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{55}$$

$$m^{MID}_w \leq \sum_{g \in G} x^{WK}_{(a,w,k,g,e)} + z^{AD}_{(a,w)}, \forall a \in A, w \in W^{WK}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{56}$$

$$\sum_{g \in G} x^{WK}_{(a,w,k,g,e)} + z^{AD}_{(a,w)} \leq m^{MXD}_w, \forall a \in A, w \in W^{WK}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{57}$$

- *SC6: Fair distribution of weekend and holiday work.*
  Equations (58)-(61) aim for equitable distribution of weekend and public holiday shifts. This ensures that these often less desirable shifts are shared fairly among staff.

$$m^{MIWH}_w \leq \sum_{d \in D \cap D^{WH}} x^{MO}_{(a,w,k,d,e)} + z^{WH}_{(a,w)}, \forall a \in A, w \in W^{MO} - \{SICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{58}$$

$$\sum_{d \in D \cap D^{WH}} x^{MO}_{(a,w,k,d,e)} + z^{WH}_{(a,w)} \leq m^{MXWH}_w, \forall a \in A, w \in W^{MO} - \{SICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{59}$$

$$m^{MIWH}_w \leq \sum_{d \in D - H} x^{MO}_{(a,w,k,d,e)} + z^{WH}_{(a,w)}, \forall a \in A, w \in \{SICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{60}$$

$$\sum_{d \in D - H} x^{MO}_{(a,w,k,d,e)} + z^{WH}_{(a,w)} \leq m^{MXWH}_w, \forall a \in A, w \in \{SICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{61}$$

- *SC7: Fair distribution of pre-holiday work.*
  Equations (62)-(65) seek to distribute pre-holiday shifts fairly. This constraint recognizes the importance of equitable allocation for shifts immediately preceding holidays. The $\mathrm{m}^{\mathrm{MXPH}}_{\mathrm{w}}$ is the upper bound of pre-holidays, while $\mathrm{m}^{\mathrm{MIPH}}_{\mathrm{w}}$ is the lower bound. For example, with four pre-holidays, $\mathrm{m}^{\mathrm{MXPH}}_{\mathrm{w}}$ is four, and $\mathrm{m}^{\mathrm{MIPH}}_{\mathrm{w}}$ is zero. Thus, one anaesthetist could be assigned to all four pre-holidays. In the HCTM case study, these values are not fixed due to anaesthetists' involvement in various tasks. It is usually hard to have the same number of available anaesthetists each week during the planning horizon. Instead, $\mathrm{m}^{\mathrm{MXPH}}_{\mathrm{w}}$ and $\mathrm{m}^{\mathrm{MIPH}}_{\mathrm{w}}$ are decision variables that the solver adjusts to minimise the range of total working days on pre-holidays.

$$m^{MIPH}_w \leq \sum_{d \in D \cap D^{PH}} x^{MO}_{(a,w,k,d,e)} + z^{PH}_{(a,w)}, \forall a \in A, w \in W^{MO} - \{CICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{62}$$

$$\sum_{d \in D \cap D^{PH}} x^{MO}_{(a,w,k,d,e)} + z^{PH}_{(a,w)} \leq m^{MXPH}_w, \forall a \in A, w \in W^{MO} - \{CICU\}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{63}$$

$$m^{MIPH}_w \leq \sum_{g \in G \cap D^{PH}} x^{WK}_{(a,w,k,g,e)} + z^{PH}_{(a,w)}, \forall a \in A, w \in W^{WK}, k \in K, e \in E, p^{MR}_{(a,w)} = 1$$

(64)

$$\sum_{g \in G \cap D^{PH}} x^{WK}_{(a,w,k,g,e)} + z^{PH}_{(a,w)} \leq m^{MXPH}_{w}, \forall a \in A, \quad w \in W^{WK}, k \in K, e \in E, p^{MR}_{(a,w)} = 1 \tag{65}$$

- *SC8: Respecting anaesthetist preferences.*
  Equations (66)-(69) attempt to roster anaesthetists based on their stated preferences for both monthly and weekly rosters. This constraint aims to improve job satisfaction and accommodate individual needs where possible.

$$q_{(a,w)} = \sum_{d \in D} x^{MO}_{(a,w,k,d,e)}, \forall a \in A, w \in W^{MO} - \{SICU\}, \quad k \in K, e \in E, p^{LP}_{(a,w)} = 1 \tag{66}$$

$$q_{(a,w)} = \sum_{d \in D - D^{WH}} x^{MO}_{(a,w,k,d,e)}, \forall a \in A, w \in \{SICU\}, k \in K, \quad e \in E, p^{LP}_{(a,w)} = 1 \tag{67}$$

$$q_{(a,w)} = \sum_{g \in G} x^{WK}_{(a,w,k,g,e)}, \forall a \in A, w \in W^{WK} - \{OHMAU\}, \quad k \in K, e \in E, p^{LP}_{(a,w)} = 1 \tag{68}$$

$$q_{(a,w)} = \sum_{g \in G - D^{WH}} x^{WK}_{(a,w,k,g,e)}, \forall a \in A, w \in \{OHMAU\}, k \in K, \quad e \in E, p^{LP}_{(a,w)} = 1 \tag{69}$$

- *SC9: Consecutive day assignments for specific locations.*
  Equations (70) and (71) try to roster consecutive days for certain locations, particularly CICU. This promotes continuity of care in critical areas.

$$if\, x^{MO}_{(a,w,k,d_1,e)} \neq x^{MO}_{(a,w,k,d_2,e)}, then\ s_a = 1, otherwise\ s_a = 0, \quad \forall a \in A, w \in \{CICU\}, k \in K, (d_1, d_2) \in V^{2D}, \quad e \in E \tag{70}$$

$$if\, x^{MO}_{(a,w,k,d_1,e)} \neq x^{MO}_{(a,w,k,d_2,e)} or\ x^{MO}_{(a,w,k,d_1,e)} \neq x^{MO}_{(a,w,k,d_3,e)}, \quad then\ s_a = 1, otherwise\ s_a = 0, \forall a \in A, \quad w \in \{CICU\}, k \in K, (d_1, d_2, d_3) \in V^{3D}, e \in E \tag{71}$$

- *SC10: Avoiding undesired location combinations.*
  Equations (72)-(74) attempt to avoid assigning anaesthetists to undesired combinations of locations or slots. This constraint aims to create more agreeable work patterns for staff.

$$if\ x^{MO}_{(a,w,k,d,e)} = 1\ and\ \left(r^{EX}_{(a,d)} = 1\ or\ r^{DS}_{(a,d)} = 1\right), \quad then\ t_{(a,d)} = 1, otherwise\ t_{(a,d)} = 0, \quad \forall a \in A, \quad w \in \{CGOT, SGOT, PWOT, CICU, SICU\}, \quad k \in K, d \in D, e \in E \tag{72}$$

$$if\ x^{WK}_{(a,w,k,g,e)} = 1\ and\ \left(r^{EX}_{(a,d)} = 1\ or\ r^{DS}_{(a,d)} = 1\right), \quad then\ t_{(a,d)} = 1, otherwise\ t_{(a,d)} = 0, \quad \forall a \in A, w \in W^{WK} - \{OHMIU, MMIU\}, \quad k \in K, d \in D, g \in G, e \in E, \{G = D\} \tag{73}$$

$$if\ x^{MO}_{(a,w_1,k,d,e)} = 1\ and\ x^{WK}_{(a,w_2,k,g,e)} = 1, \quad then\ t_{(a,d)} = 1, otherwise\ t_{(a,d)} = 0, \quad \forall a \in A, (w_1, w_2) \in L^U, k \in K, d \in D, g \in G, \quad e \in E, \{G = D\} \tag{74}$$

IV. CASE STUDY

To test how well our model works for both monthly and weekly rosters, we conducted a case study using three months of data (31 December 2018 to 24 March 2019) from HCTM's Department of Anaesthesiology and Intensive Care. The model was solved using IBM ILOG CPLEX Optimization Studio. We compare our model's output (MODEL) against the manual approach (HCTM), calculating the percentage difference in overall penalty values as per Fugener et al.[12]: (MODEL - HCTM + HCTM x 100).

A. METHODOLOGY

The total penalty for the HCTM solution is calculated based on the manually produced roster by the human scheduler. Each month consists of 28 days, while each week has 7 days. The input data for both monthly and weekly rosters includes essential factors such as the number of anaesthetists, locations, requests, and location-specific anaesthetist demands.

To ensure continuity in the planning process and prevent constraint violations, our model incorporates the previous roster arrangements when building a new one. For monthly rosters, we account for the last three days of the previous month (Friday, Saturday, and Sunday) and the first two days of the upcoming month (Monday and Tuesday) to prevent violations. If an anaesthetist worked on Friday or both days of the last weekend, we ensure they receive adequate rest, as required by HC6 and HC10, ensuring a smooth transition between monthly and weekly rosters. The weekly roster excludes total working hours and future requests, as these are primarily managed by the monthly roster, which also handles rest days for locations like SGOT.

We used two primary metrics to evaluate the model's performance:

i. Effectiveness: The MODEL's solution is considered effective when the overall penalty for soft constraints is less than HCTM's manual solution.

ii. Fairness: Defined as a decrease in the differentiation percentage of the total penalty of SC5, SC6, and SC7 for the MODEL compared to HCTM.

B. RESULTS AND ANALYSIS

The findings of our case study for the monthly roster are shown in Table 7, while the weekly roster results are presented in Table 8. Figure 3 illustrates the analysis of the total penalty of all soft constraints for the monthly roster, and Figure 4 shows the same for the weekly roster.

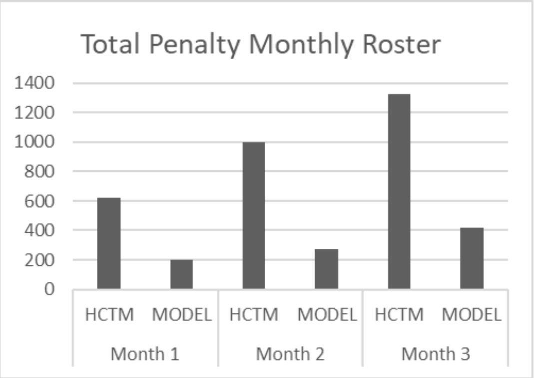

FIGURE 3 Analysis of the total penalty of all the soft constraints for the monthly roster between HCTM and MODEL

To provide a more rigorous evaluation of the MODEL's performance, we conducted statistical analyses of the results, summarised in Tables 9 and 10 for monthly and weekly rosters, respectively.

For the monthly roster, Table 9 shows a mean improvement of 52.33% across all constraints, with a standard deviation of 43.45%. Although the Wilcoxon signed-rank test ($W = 0$, $p = 0.109$) did not reach statistical significance due to the small sample size ($n=3$), the W-statistic of 0 indicates the MODEL consistently outperformed HCTM (manual roster) across all three months, suggesting practical significance. Significant improvements were seen in SC5 (fairness in workload distribution) and SC10 (avoiding undesired combinations), with mean improvements of 89.33% and 93.33%, respectively.

For the weekly roster, Table 10 shows a consistent performance improvement with a mean of 67.20% and a standard deviation of 10.45%. The highest improvements were seen in SC3 (shift requests) and SC10 (avoiding undesired combinations), with mean improvements of 85.83% and 84.75%. A paired t-test ($t = 22.37$, $p = 1.43e-10$) confirmed that the MODEL significantly outperforms HCTM (manual roster) in weekly rostering.

These statistical analyses provide strong evidence of the MODEL's effectiveness in improving both monthly and weekly rosters, with particularly consistent and significant gains in weekly scheduling. The results demonstrate that the MODEL is more efficient and capable of providing higher-quality solutions than HCTM's manual roster, especially in areas of fairness, shift request satisfaction, and avoiding undesired combinations.

Overall, the results indicate that the MODEL reduces the total penalty sum for soft constraint violations by an average of 69.57% over three months compared to HCTM's manual monthly roster. Over twelve weeks, the model reduces penalties by an average of 64.37%.

TABLE 7 STATISTICAL ANALYSIS OF MONTHLY ROSTER RESULTS.

	Mean Improvement (%)	Standard Deviation (%)
SC1.	-77.33	9.29
SC2.	+16.67	75.06
SC3.	-55.67	51.07
SC4.	-38.67	9.81
SC5.	-89.33	3.51
SC6.	-27.33	24.34
SC7.	-58.33	12.50
SC8.	-50.00	62.92
SC9.	-50.00	86.60
SC10.	-93.33	11.55
Overall	-52.33	43.45

TABLE 8 STATISTICAL ANALYSIS OF WEEKLY ROSTER RESULTS.

	Mean Improvement (%)	Standard Deviation (%)
SC1.	-75.00	43.30
SC3.	-85.83	34.23
SC4.	-63.33	32.84
SC5.	-63.25	14.56
SC7.	-48.25	11.55
SC8.	-50.00	70.71
SC10.	-84.75	19.86
Overall	-67.20	10.46

C. LIMITATIONS AND PRACTICAL IMPLICATIONS

Despite these positive outcomes, our model does have several limitations that warrant discussion:

i. Processing Time: The model requires longer processing times for monthly rosters due to increased complexity and the larger set of constraints to consider. This could pose challenges in environments where rapid roster generation is necessary.

ii. Exceptional Circumstances: During periods with numerous public holidays or absences, the model may need to relax certain constraints to generate feasible rosters, potentially leading to suboptimal solutions.

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TABLE 9 DIFFERENTIATION RESULT OF PENALTY VALUE FOR THE CASE STUDY OF THE HCTM AND MODEL FOR THE MONTHLY ROSTER (MONTH 1, MONTH 2 AND MONTH 3).

	Month 1			Month 2			Month 3		
	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)
SC1.	130	20	**-85**	150	30	**-80**	150	50	**-67**
SC2.	20	10	**-50**	10	10	±0	10	20	+100
SC3.	90	30	**-67**	30	0	**-100**	30	30	±0
SC4.	32	16	**-50**	24	16	**-33**	24	16	**-33**
SC5.	180	20	**-89**	430	60	**-86**	730	50	**-93**
SC6.	100	90	**-10**	220	100	**-55**	230	190	**-17**
SC7.	27	15	**-44**	45	15	**-67**	66	24	**-64**
SC8.	8	0	**-100**	32	40	+25	32	8	**-75**
SC9.	16	0	**-100**	16	0	**-100**	16	24	+50
SC10.	16	0	**-100**	40	0	**-100**	40	8	**-80**

TABLE 10 DIFFERENTIATION RESULT OF PENALTY VALUE FOR THE CASE STUDY OF THE HCTM AND MODEL FOR WEEKLY ROSTER (WEEK 1 TO WEEK 12).

	Week 1			Week 2			Week 3			Week 4		
	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)
SC1.	10	0	**-100**	20	0	**-100**	20	0	**-100**	10	10	±0
SC3.	30	0	**-100**	120	60	**-50**	30	30	±0	150	30	**-80**
SC4.	16	0	**-100**	40	24	**-40**	40	24	**-60**	32	8	**-75**
SC5.	190	140	**-26**	280	110	**-61**	280	110	**-58**	490	220	**-55**
SC7.	45	33	**-27**	54	33	**-39**	54	33	**-45**	78	42	**-46**
SC8.	0	0	±0	8	0	**-100**	8	0	±0	8	8	±0
SC10.	32	0	**-100**	24	8	**-67**	24	8	**-100**	32	0	**-100**

	Week 5			Week 6 (Relaxed HC11)			Week 7 (Relaxed HC11)			Week 8		
	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)
SC1.	0	10	+100	20	0	**-100**	10	0	**-100**	20	0	**-100**
SC3.	30	0	**-100**	120	0	**-100**	30	0	**-100**	150	0	**-100**
SC4.	16	16	±0	40	16	**-60**	40	0	**-100**	32	8	**-75**
SC5.	600	250	**-58**	750	290	**-61**	880	340	**-61**	980	290	**-70**
SC7.	78	51	**-35**	102	63	**-38**	144	63	**-56**	156	66	**-58**
SC8.	0	0	±0	8	0	**-100**	0	8	+100	8	0	**-100**
SC10.	32	8	**-75**	24	0	**-100**	16	8	**-50**	32	0	**-100**

	Week 9			Week 10			Week 11 (Relaxed HC11)			Week 12		
	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)	HCTM	MODEL	DIFF (%)
SC1.	10	10	±0	20	0	**-100**	10	0	**-100**	10	0	**-100**
SC3.	30	0	**-100**	120	0	**-100**	30	0	**-100**	150	0	**-100**
SC4.	16	16	±0	40	16	**-60**	40	0	**-100**	32	8	**-75**
SC5.	1180	330	**-72**	1290	320	**-75**	1390	370	**-73**	1510	330	**-78**
SC7.	162	69	**-57**	171	66	**-61**	171	69	**-60**	183	78	**-57**
SC8.	0	0	±0	8	0	**-100**	0	8	+100	8	0	**-100**
SC10.	32	8	**-75**	24	0	**-100**	16	8	**-50**	32	0	**-100**

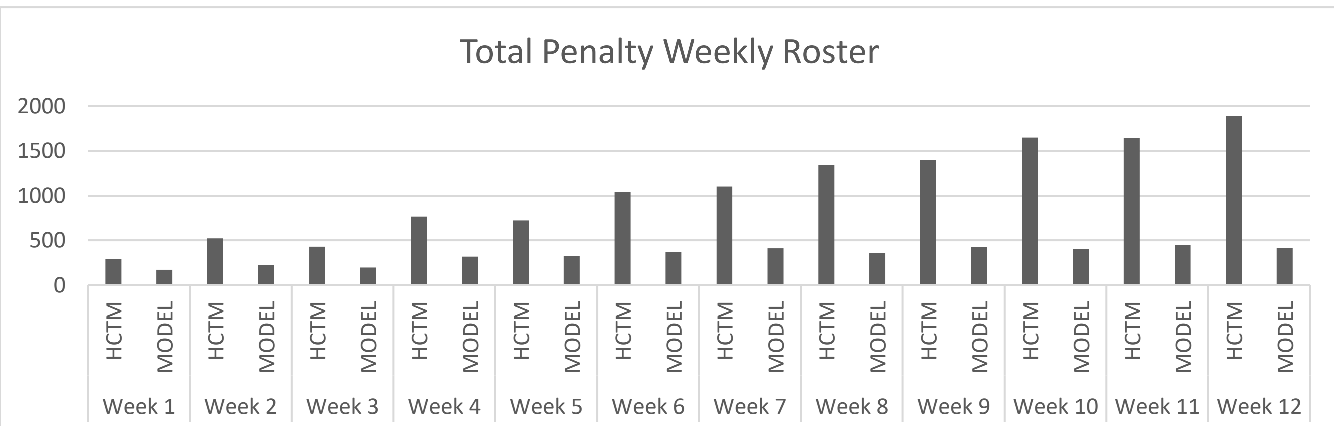

FIGURE 4 **Analysis of the total penalty of all the soft constraints for the weekly roster between HCTM and MODEL**

iii. Specificity: The current model is tailored to HCTM's specific requirements, which may limit its direct applicability to other hospitals without modifications.
iv. Data Dependency: The model's effectiveness is heavily dependent on the quality and completeness of input data.
v. Flexibility: The model may not be as flexible as human schedulers in adapting to last-minute changes or emergencies, which are common in hospital environments.

The practical implications and challenges of implementing a new rostering system are significant:

i. User Interface: A user-friendly interface is essential to make the model accessible to non-technical staff, requiring development efforts.
ii. Training and Adoption: Staff training would be necessary, and there could be resistance from personnel accustomed to manual rostering methods.
iii. Real-time Adjustments: The model must handle real-time updates and last-minute adjustments, which are common in hospital environments.
iv. Balancing Fairness and Efficiency: Strict adherence to fairness might sometimes impact operational efficiency, requiring careful balance.
v. Regulatory Compliance: The model must ensure compliance with local labour laws and regulations, which vary across regions and countries.
vi. Exceptional Circumstances: Flexibility is crucial, particularly in exceptional circumstances such as pandemics or natural disasters that demand rapid adjustments to standard rostering practices.
vii. System Integration: Technical challenges may arise when integrating the system with other hospital platforms like payroll and electronic health records. However, successful integration would streamline processes and enhance overall efficiency.

D. FUTURE WORK

Future research should focus on addressing these limitations and challenges. Key areas for development include:

i. Enhancing model flexibility to accommodate varying hospital policies and speciality-specific requirements.
ii. Developing user-friendly interfaces for non-technical staff.
iii. Improving real-time adjustment capabilities for last-minute changes.
iv. Integrating the model with existing hospital management systems.
v. Exploring machine learning techniques to adapt to changing circumstances and predict staffing needs.
vi. Conducting broader trials across diverse healthcare settings to refine the model's generalisability.

Additionally, future work should focus on reducing solution generation time, particularly for monthly rosters. This could involve exploring heuristics or matheuristics as suggested by Silver [26]. To handle uncertainty, such as last-minute anaesthetist absences, the model should incorporate re-rostering capabilities.

To mitigate increased penalties in certain soft constraints, we propose introducing adaptive weighting mechanisms that dynamically adjust constraint importance based on current demand and availability. This approach aims to balance competing requirements and minimise penalties more uniformly across all constraints.

V. CONCLUSION

The study answers the question of generating a high-quality roster by developing a mixed-integer linear programming model tailored to HCTM's specific needs. The model significantly improves fairness and efficiency in scheduling, reducing penalties by 69.57% for monthly rosters and 64.37% for weekly rosters compared to manual scheduling. While the weekly results were statistically significant, the monthly results showed consistent improvements but lacked statistical significance due to a small sample size.

Our model improves both fairness and efficiency by considering multiple factors, such as multi-location assignments, shift preferences, and workload distribution, while optimizing both monthly and weekly rosters. By minimizing soft constraint violations and ensuring balanced scheduling, the model significantly improves fairness in workload distribution and reduces unfavourable scheduling patterns. This approach effectively addresses HCTM's multifaceted requirements, providing a practical solution to the Anaesthetist Rostering Problem.

This research helps connect academic theories with practical hospital needs. However, challenges such as processing times, user integration, and generalization to other healthcare environments remain. Future research should focus on enhancing flexibility, reducing solution times, and expanding trials across diverse healthcare settings. Despite these challenges, the model offers promising potential for improving resource allocation and staff satisfaction in healthcare workforce management.

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