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INTEGER PROGRAMMING FOR NURSE SCHEDULING AT ALEX EKWUEME FEDERAL UNIVERSITY TEACHING HOSPITAL (AEFUTH), ABAKALIKI

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Abstract

Nurse scheduling involves assigning nurses to shifts to meet hospital demands. Previous research has focused on optimizing preferred shifts and ensuring adequate days off, but lacks attention to historical scheduling patterns and varying preferences, which affect fairness and quality. This study addresses these gaps by identifying diverse preferences among nursing staff concerning shifts and days off. We propose a mathematical model based on integer programming to enhance satisfaction by prioritizing individual preferences. This model considers preference rankings for each shift, historical scheduling data, and operational constraints. By maximizing overall satisfaction, the resulting shift schedule gains credibility. Implementation at the Alex Ekwueme Federal University Teaching Hospital in Abakaliki, Nigeria, produced an optimal nurses' roster, demonstrating that our model achieves fair and satisfactory shift and day-off assignments aligned with nursing staff preferences. This approach enhances the quality and fairness of nurse scheduling while prioritizing staff satisfaction with 0.32% improvement

Key words: *NSP, integer programming, shift, healthcare management, optimization models, days off.*

Introduction

An effective nurse scheduling is a vital part of healthcare management, posing a serious challenge in optimizing staff rotations while taking into consideration of individual preferences and institutional requirements. The Nurse Schedule Problem (NSP), a classical combinatorial optimization issue, encompasses the task of determining nursing staff rotations over designated periods, be it weekly or monthly. This involves meticulously arranging work shifts and days-off to meet manpower needs for each shift while ensuring staff well-being and satisfaction and also meeting patients' satisfaction. In healthcare institutions like Alex-Ekwueme Federal University Teaching Hospital Abakaliki, the intricacies of nurse scheduling extend beyond conventional patterns. Here, unique shift rotations, such as 6-hour day shifts, 6-hour evening shifts, and 12-hour night shifts, deviate from the norm, demanding specialized attention to staff preferences and well-being.

Previous studies have addressed elements of nurse scheduling, focusing on minimizing penalty costs and enhancing staff satisfaction. Ernst et al (2004) described the development of nurse scheduling system using integer programming approach to solve a real-world problem at a large Australian hospital, focusing on the development of a set of IP models that take account of hospital policies and union agreements. Their results show that the system is capable of producing high-quality solutions that meet the requirements of the hospital. The highlighted potential benefits of using IP for nurse scheduling and improvement in staff utilization, reduced overtime and enhanced morale.

Various authors, including Burke et al. (2004), Ernst et al (2004) and Cheang et al. (2003), have suggested different methodologies for addressing NSP. Howell (1998) proposed three distinct approaches to handling the NSP, each offering unique perspectives and implications for nursing staff and hospital units. Hadwan et al. (2013), tried to reduce the penalty costs associated with nurse scheduling by taking into account the organizations' compulsory rules, flexible preferences and demands of hospital nursing staff within shift scheduling. Aickelin and Dowsland (2005) applied a genetic algorithm to solve the nurse shift scheduling problem, with the objective of minimizing the financial cost resulting from failing to consider the preferences of nursing staff.

Yan et al.(2018) proposed an integer programming(IP) approach to optimize operating room(OR) scheduling and by considering various constraints, including surgeon and anaesthesiologist availability, OR capacity, and surgical case priorities, demonstrated the effectiveness of the IP approach in reducing overtime and improving OR utilization.

In another study, Maenhout and Vanhoucke (2013) investigated the penalty costs under various constraints, involving both the preferences of nursing staff, work shifts and days off. Howell (1998) suggested three difference approaches to handle the Nurse Scheduling Problem (NSP), each offering unique perspectives and implications for nursing staff and hospital units. The first approach, referred to as rotational or cyclical scheduling, involves generating multiple sets of schedules to meet demand requirements over consecutive planning horizons. Nurses are rotated through these schedules, typically with fixed patterns such as alternating weekends off or consecutive workdays. The second model, is a more flexible alternative because it is self-scheduling, which allows nurses to select shifts within contractual bounds. Nurses sign up for shifts based on personal preferences, with an upper limit to prevent over-supply in specific periods. While this approach reduces scheduling time and change requests, some nurses prioritize personal needs over unit requirements, potentially impacting hospital operations. Despite its potential benefits for nurse satisfaction and patient care, implementation challenges usually arise due to varying comprehension levels among nursing staff.

The third approach, preference scheduling, amalgamates aspects of both rotational and self-scheduling methods, accommodating individual preferences within scheduling frameworks. Nurses submit preferences such as specific shifts, days off, or work hours before planning horizons commence. Nurse Managers aim to incorporate as many preferences as feasible while meeting coverage requirements. However, the overarching goal remains the development of an unbiased and efficient scheduling model to aid nurse managers in optimizing workforce allocation. Ferland et al. (2001) used heuristic approach to solve problem which offers pragmatic methods but may not guarantee optimal solutions though they effectively address immediate goals by integrating nurses' preferences. Employing a heuristic-based assignment model, they utilized a tableau search method to compare solutions iteratively, prioritizing objective function values. However, the method's limitation lies in its inability to simultaneously optimize nurse allocation while minimizing dissatisfaction. Behan et al. (2010) also utilized heuristics to address the NSP, considering constraints such as fixed nurse preferences and patient care timeframes. Their stochastic model aims to minimize nurse workload penalties, crucial for preventing burnout.

Employing Benders' Decomposition Algorithm and Greedy Algorithm, they achieved substantial reductions in excess workload, yet their approaches addressed only specific aspects of the scheduling problem at a time. Brucker et al. (2008) investigated an adaptive constructive method for NSP, categorizing constraints into sequence, schedule, and roster-related classes. Their two-stage decomposition approach first constructs high-quality nurse sequences, then iteratively generates the schedules and rosters. While exhaustive enumeration in the first stage lacks preference ranking, their method offers a systematic solution approach. Legrain et al. (2014) proposed a heuristic scheduling process for diverse nursing teams, offering a flexible alternative to manual or commercial tools. Their approach, implemented on spreadsheets, aims for streamlined processes and improved schedule quality. Despite its simplicity, their multi-objective model and heuristics demonstrate comparable performance to optimization software, presenting a cost-effective solution.

In contrast, Carrasco (2010) introduced a randomized greedy procedure for long-term workload balancing in nursing staff without considering nurses' preferences. Despite being effective in workload distribution, its oversight of preferences underscores the complexity of integrating all facets of NSP into heuristic approaches. Overall, heuristic methods provide practical solutions to various aspects of the NSP, balancing trade-offs between optimality and efficiency. However, the challenge remains in devising approaches that comprehensively address all constraints while maintaining feasibility and nurse satisfaction. Mathematical programming emerges as a robust tool for addressing the NSPs, offering systematic approaches to optimize nurse allocation and satisfaction. Various studies have demonstrated the effectiveness of mathematical programming models in addressing complex constraints and objectives inherent in nurse scheduling. Jaumard, Semet, and Vovor (1998) presented an exact solution approach utilizing a generalized linear programming model, incorporating column generation and branch-and-bound techniques. Their model addresses nurse preferences while optimizing coverage, day-off assignments, and care quality. The NSP is a complex combinatorial optimization problem that involves assigning nurses to shifts while satisfying various constraints, such as nurse availability, skill requirements and regulatory requirements, Ahmed et al (2017) formulated the NSP as a set partitioning problem and proposed a column generation algorithm to solve it. Their computational results demonstrated the effectiveness of the proposed approach in solving large-scale instances of the NSP.

Despite its flexibility in formulating coverage constraints, the model's simplifying assumption regarding shift periods may limit its adaptability compared to other approaches. Bard (2010) proposed an integer linear program tailored for midterm scheduling, focusing on minimizing service demand costs while considering nurse shift preferences. However, the model's simplicity necessitates additional constraints for real-life applicability. Belien and Demeulemeester (2008) introduced an integer program utilizing a branch-and-price algorithm to account for variability in hospital unit workload. Their model identifies optimal nurse schedules and workload requirements, enabling informed decisions regarding workforce allocation. Furthermore, Mobasher (2011) employs multiple weighted objectives in an integer programming model to minimize costs, maximize nurse satisfaction, and ensure adequate patient coverage. The integration of nurse workload capacities and patient variability enhances scheduling accuracy, albeit potentially compromising nurse satisfaction in certain scenarios. Additionally, heuristic methods offer pragmatic solutions, such as those proposed by Behan et al. (2008) and Brucker et al. (2010), which prioritize workload balancing and flexibility in scheduling. While mathematical programming models demonstrate success in optimizing nurse schedules and minimizing costs, challenges persist in accounting for shifting nurse preferences and achieving overall satisfaction. The integration of preference ranks and past scheduling patterns, as proposed in this study, represents a promising avenue for enhancing nurse satisfaction and operational efficiency in nurse scheduling.

In summary, mathematical programming offers valuable tools for addressing the NSP, yet further refinement is necessary to accommodate evolving preferences and ensure comprehensive satisfaction among nursing staff. The proposed model aims to bridge existing gaps by prioritizing preference satisfaction while optimizing nurse allocation at the Alex Ekwueme Federal University Teaching Hospital, Abakaliki. By incorporating preference ranks and weighted values, this model endeavours to enhance nurse satisfaction and streamline scheduling processes for improved healthcare delivery.

Methodology

In this section, we present a binary integer linear programming model adopted from Chun-Cheng Lin et al (2015), which aims at optimizing the overall preference satisfaction of the nursing staff towards the shift schedule by taking into consideration the preference ranks of the nursing staff for different work shifts and day-off, despite the constraints of manpower, shift, and days-off.

Mathematical model

The complete mathematical model is given as follows:
Equations 1-5, cover the Objective Function

$$\text{Max}\, G = \sum_{i}^{I}\sum_{j}^{J}\left\{\left(P_{i,j}^{S}\cdot s_{i,j,}\right)+\left(\sum_{k}^{K}\left(P_{i,k}^{H}\cdot h_{i,j,k}\right)\right)\right\}, \qquad (1)$$

where

$$P_{i,j}^{S} = \begin{cases} \alpha W_{i}^{S}, & \text{if } L_{i,j}^{S} = 1 \\ W_{i}^{S}, & \text{if } L_{i,j}^{S} = 2 \\ 0 & \text{if } L_{i,j}^{S} = 3 \end{cases} \qquad (2)$$

$$P_{i,k}^{H} = \begin{cases} \alpha W_i^H, & \text{if } L_{i,k}^{H} = 1 \\ 0, & \text{if } L_{i,k}^{H} = 3 \end{cases} \tag{3}$$

$$W_i^S = C^{\sum_{m=1}^{M} (T_{i,m}^{S} \cdot \theta_m^S)} \tag{4}$$

$$W_i^H = C^{\sum_{n=1}^{N} ((T_{i,n}^{H}/\beta) \cdot \theta_n^H)}. \tag{5}$$

Equations 6-8 are the Shift Constraints:

Constraints

$$\sum_{j \in J} s_{i,j} = 1, \quad \forall i \in I \tag{6}$$

$$\sum_{i \in I} s_{i,j} = D_{j,k}, \quad \forall j \in J,\ k \in K \tag{7}$$

$$\sum_{i \in I} \left(R_i \cdot \left(s_{i,j} - h_{i,j,k} \right) \right) \geq \tau_{j,k}^{\min}, \quad \forall j \in J,\ k \in K \tag{8}$$

Equations 9-12 are the Day-off constraints:

$$\sum_{k \in K} h_{i,j,k} = s_{i,j} \cdot \beta, \quad \forall i \in I,\ j \in J \tag{9}$$

$$N_{j,k}^{\max} - \sum_{i}^{I} h_{i,j,k} \geq 0, \quad \forall j \in J,\ k \in K \tag{10}$$

$$\sum_{j}^{J} \left(\sum_{k=1}^{k=7} h_{i,j,k} \cdot \sum_{k=8}^{k=14} h_{i,j,k} \right) > 0, \quad \forall i \in I \tag{11}$$

$$s'_{i,3} \cdot s_{i,j} \leq h'_{i,3,14} \cdot h_{i,j,k}, \quad \forall i \in I \tag{12}$$

Equations 13 and 14 are binary variable Constraints:

$$s_{i,j} \in \{0, 1\}, \quad \forall i \in I,\ j \in J \tag{13}$$

$$h_{i,j,k} \in \{0, 1\}, \quad \forall i \in I,\ j \in J,\ k \in K. \tag{14}$$

The model consists of three symbols, twenty-five parameters and two decision variables. The objective function of the model is described as follows: Equation (1) maximizes the overall preference satisfaction of the nursing staff towards work shifts and day-off. As for the overall preference satisfaction towards shifts (resp., days-off), the preference satisfaction of each shift preference rank of each nursing staff is calculated by equation (2) (resp., (3) where the preference weight used in the above preference satisfaction calculation for shift (resp., day-off) was obtained from (4) (resp., (5)). Furthermore, constraints of the model which are nine in numbers (i.e. Constraints (6) to (14)) are identified based on the shift scheduling constraints. Constraints (6) to (8) are shift constraints, constraints (9) to (12) are day-off constraints, and constraints (13) to (14) are binary variable constraints, and constraints (6) enforces each staff member to be assigned to at most one work shift within each schedule period.

According to Constraints (7) and (8), respectively, manpower demand and number of senior staff members of each shift each day should be met. Constraint (9) enforces that the total number of days-off assigned to each staff member in a work shift should be the same within a certain schedule period. Constraint (10) enforces the maximum total number of nursing staff members allowed to have day-off on each shift each day. As the number of patients usually fluctuates, the schedule planner may adjust-the total number of nursing staff members allowed to be on day-off according to the actual number of patients on that particular day. Constraint (11) enforces that each staff member has to be given at least one day-off each week and the interval between two different shifts must be more than 6 hours. Constraint (12) ensures that each staff member has at least an 8-hour rest before continuing on to the next shift. According to constraints (13) and (14), the decision variables of work shifts and days-off should be either zero or one.

Results

The satisfactory times of each shift preference rank in the previous schedule periods and also the preference weights at the current schedule period were calculated as described by the model.

Table 1: Shift Preferance Weights of the Nursing Staff

	The assigned shift number in the past preference			
Staff	Good	Normal	Bad	Weight.
1	2	0	0	4
2	2	0	0	4
3	1	0	1	16
4	1	1	0	8
5	2	0	0	4
6	1	0	1	16
7	1	1	0	8
8	2	0	0	4
9	2	0	0	4
10	1	1	0	8
11	1	0	1	16
12	1	0	1	16

13	2	0	0	4
14	2	0	0	4
15	2	0	0	4
16	1	1	0	8
17	1	0	1	16
18	1	1	0	8
19	1	1	0	8
20	1	0	1	16
21	2	0	0	4
22	2	0	0	4
23	1	0	1	16
24	1	0	1	16
25	1	1	0	8
26	1	1	0	8
27	1	0	1	16
28	1	1	0	8
29	1	0	1	16
30	2	0	0	4

**Showing the various preference weight of the assigned shift number in the past preference.*

The satisfaction of each nursing staff member for the various shift preference rank given to them were shown in table 2.

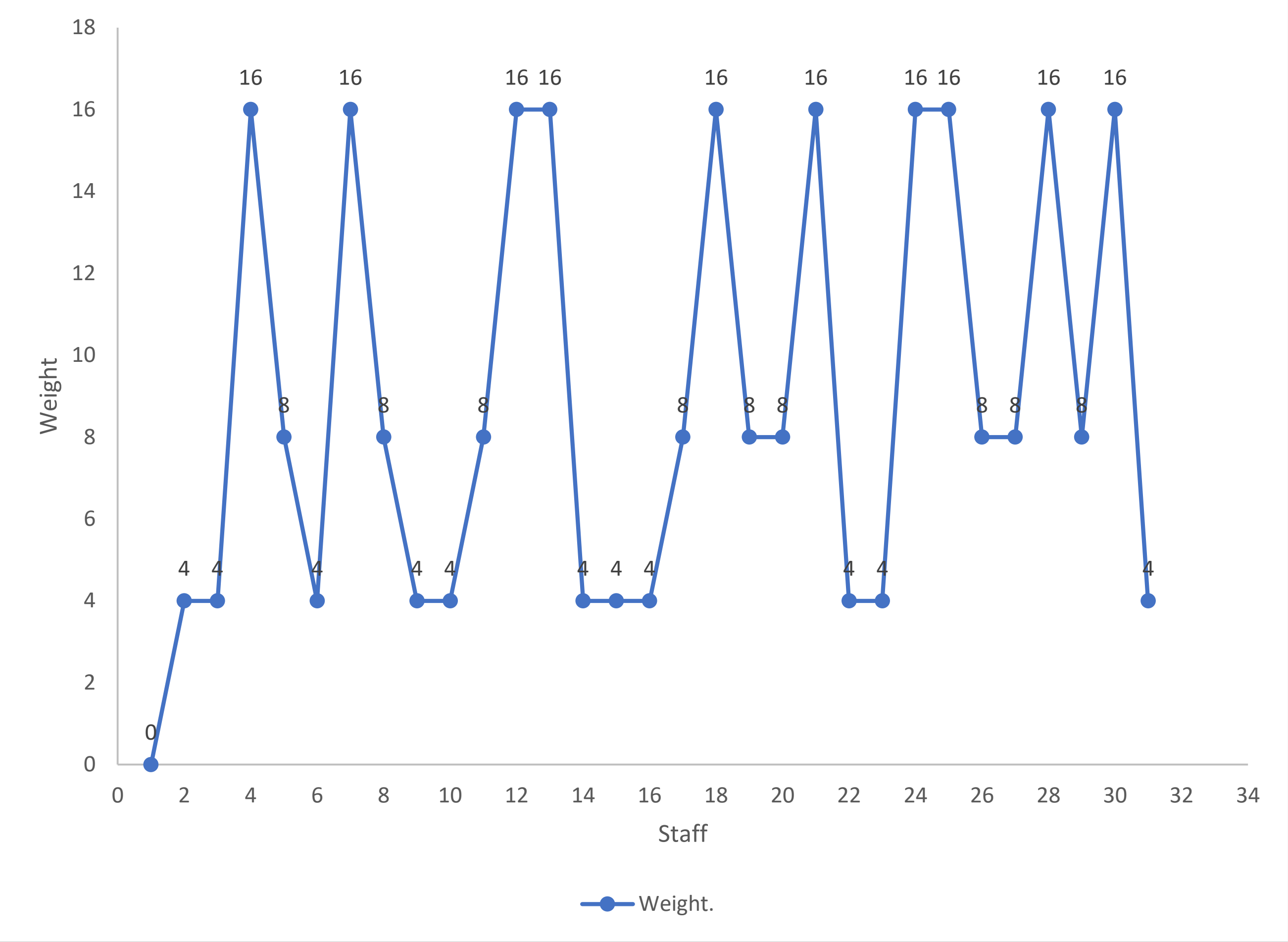

Figure 1: Shift Preference Weights of the Nursing Staff

Table 2: Shift Preference Rank and Prefernce Satisfaction of Nursing Staff.

	DAY SHIFT		EVENING SHIFT		NIGHT SHIFT	
STAFF	PREFERENCE RANK	PREF. SATISFACTION	PREF. RANK	PREF SATISFY	PREF. RANK	PREF.SATISF
1	1	8	2	4	3	0
2	2	4	1	8	3	0
3	1	32	2	16	3	0
4	1	16	2	8	3	0
5	2	4	1	8	3	0
6	1	32	2	16	3	0
7	2	8	1	16	3	0
8	1	8	2	4	3	0
9	2	4	1	8	3	0
10	1	16	2	8	3	0
11	1	32	2	16	3	0
12	1	32	2	16	3	0

13	2	4	1	8	3	0
14	1	8	2	4	3	0
15	1	8	2	4	3	0
16	1	16	2	8	3	0
17	2	16	1	32	3	0
18	1	16	2	8	3	0
19	2	8	1	16	3	0
20	1	32	2	16	3	0
21	2	4	1	8	3	0
22	1	8	2	4	3	0
23	2	16	1	32	3	0
24	1	32	2	16	3	0
25	1	16	2	8	3	0
26	1	16	2	8	3	0
27	1	32	2	16	3	0
28	1	16	2	8	3	0
29	2	16	3	0	3	0
30	1	8	2	4	1	8

*****_Showing the various shift preference rank in each shift with their satisfaction status of each nursing staff member_

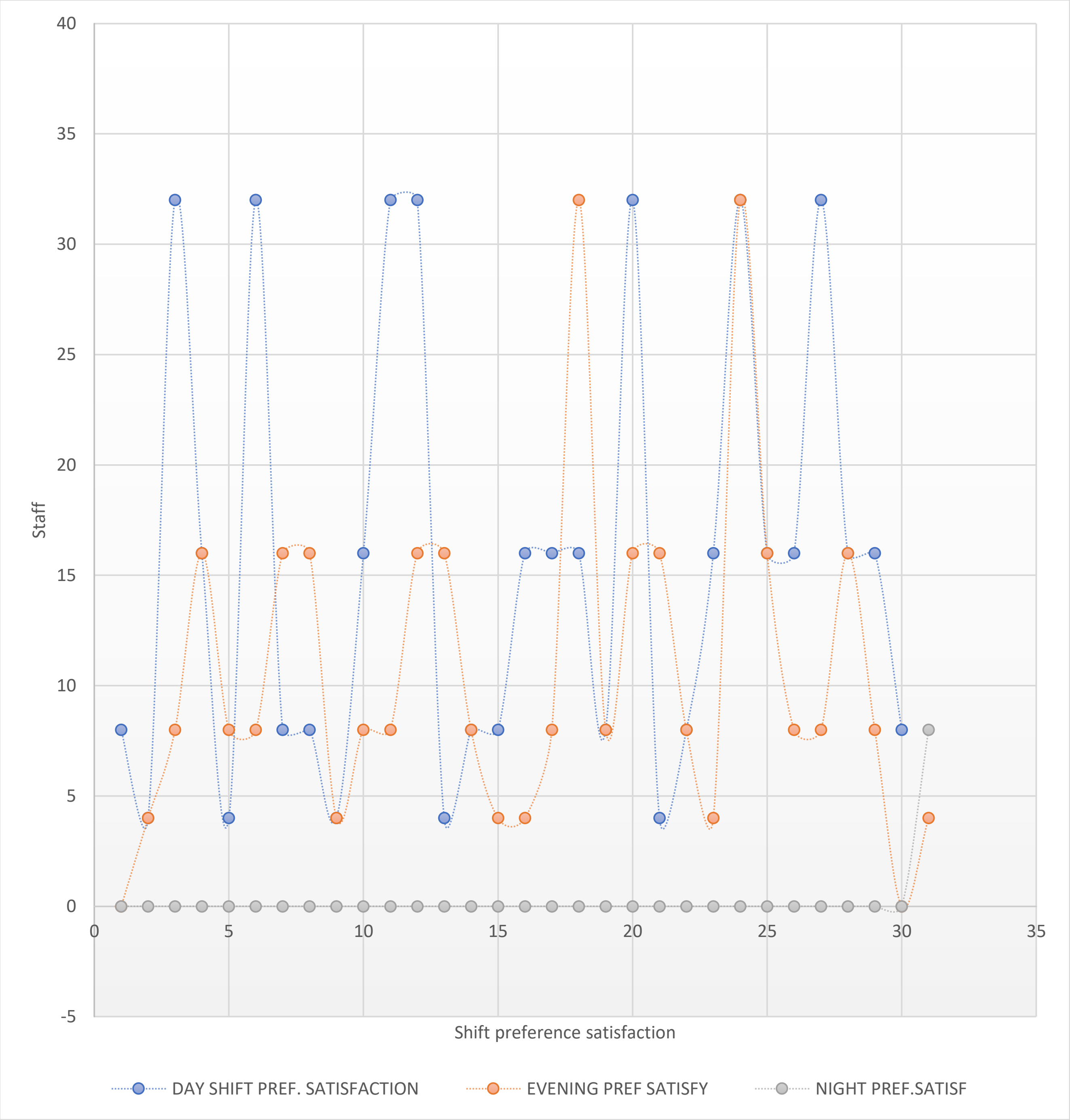

Figure 2: Scatter plot showing shift preference rank and preference satisfaction of nursing staff

The satisfactory times of the day-off preference rank in the past schedule periods and current weighted preference are shown in the table 3.

TABLE 3: DAY-OFF PREFERENCE WEIGHTS OF THE NURSING STAFF

	The Assigned Number With Past		Preference Weight
Staff	Good	Bad	
1	8	0	4
2	7	1	5.6569 (≈5.7)
3	5	3	11.3137(≈ 11)
4	8	0	4
5	7	1	5.6569(≈ 5.7)
6	6	2	8
7	8	0	4
8	8	0	4
9	8	0	4
10	7	1	5.656(≈ 5.7)
11	6	2	8
12	3	5	22.6274(≈ 23)
13	7	1	5.6569(≈ 5.7)
14	7	1	5.6569(≈ 5.7)
15	7	1	5.6569(≈ 5.7)
16	7	1	5.6569(≈ 5.7)
17	8	0	4
18	8	0	4
19	7	1	5.6569(≈ 5.7)
20	8	0	4
21	8	0	4
21	7	1	45.6569(≈ 5.7)
22	8	0	4
23	7	1	5.6569
24	8	0	4
25	6	2	8
26	3	5	22.6274(≈ 23)
27	8	0	4
28	3	5	22.6274(≈ 23)
29	8	0	4
30	8	0	4

**The above shows the various day-off preference e weight of the assigned number in the past preference*

The day-off preference and preference satisfaction of each nursing staff member is placed according to the assigned days.
past preference

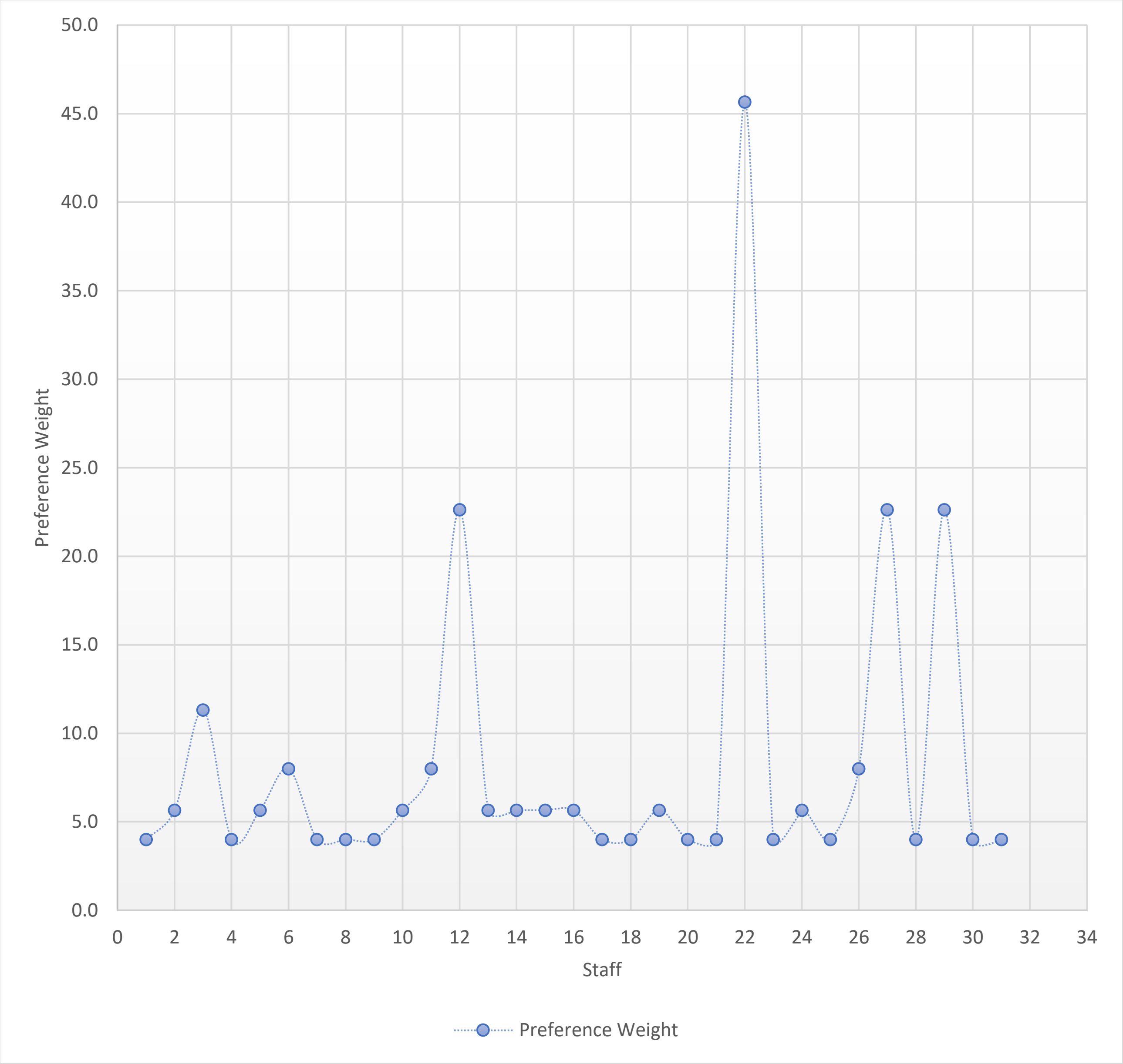

Figure 3: Day-Off Preference Weights of the Nursing Staff

Table 4: Day-off preference and preference satisfaction of the nursing staff.

Staff	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1			4	4						4	4			
2			5.7	5.7						5.7	5.7			
3								11	11	11			11	
4	4	4	4	4										
5			5.7	5.7						5.7	5.7			
6		8	8				8	8						
7					4	4					4	4		
8			4	4						4	4			

9	4	4	4	4										
10		5.7						5.7	5.7					5.7
11			8	8						8	8			
12		23	23					23	23					
13		5.7	5.7					5.7	5.7					
14					5.7	5.7	5.7							
15				5.7	5.7	5.7	5.7							
16						5.7	5.7	5.7	5.7					
17	4	4	4											
18	4	4	4											
19		5.7						5.7				5.7		
20					4	4								4
21			4							4	4			4
22	4	4	4											
23	5.7	5.7						5.7	5.7					
24	4	4	4											
25						8	8					8	8	
26	23				23					23	23			
27			4	4	4					4	4			
28		23	23	23	23									
29	4	4	4	4										
30	4	4			4				4					

**This shows the placement of day-off preference and its satisfaction for each nursing staff in their various assigned days.*

Presented in this **table 5** is the resultant schedule of shifts being assigned to the 30 nursing staff members of their various work shifts.

Table 5: The resultant schedule for shifts.

Staff	Day shift	Number of shifts Evening shift	Night shift
1	0	1(normal)	0
2	0	1	0
3	1	0	0
4	1	0	0
5	0	1(normal)	0
6	1	0	0
7	0	1	0
8	0	1	0
9	0	0	1(bad)
10	0	0	1(bad)
11	1	0	0
12	1	0	0
13	0	0	1(bad)
14	0	0	1(bad)
15	1	0	0
16	1	0	0
17	0	1	0

18	1	0	0
19	0	1(normal)	0
20	0	0	1
21	0	1	0
22	0	1(normal)	0
23	0	0	0
24	1	0	0
25	1	1(normal)	0
26	0	1(normal)	0
27	0	0	0
28	1	0	0
29	1	0	1(bad)
30	0	0	1(bad)

**This shows the resultant schedule of shifts for the next cycle schedule, model taking care of the unsatisfied preference on this shift.*

Here the resultant schedule for days-off are shown, in which the four days-off of each staff are marked with 1 according to their assigned days, where entries with stars are the not preferred days-off.

Table 6: The resultant schedule for days-off.

STAFF

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1								1	1			
2			1	1						1	1			
3								1	1	1			1	
4	1	1	1	1*										
5			1	1						1	1			
6		1*	1				1	1						
7					1	1					1	1		
8			1	1					1	1				
9	1	1	1	1										
10		1						1	1					1
11			1*	1						1	1			
12	1	1						1	1					
13	1	1						1	1					
14					1	1	1	1	1					
15				1	1	1	1							
16						1	1	1	1					
17	1	1	1	1										
18	1	1	1	1										
19		1	1											
20					1	1*			1				1	
21				1					1	1				1
22	1	1	1	1										
23	1	1						1	1					

24	1	1	1	1*								
25						1	1				1	1
26	1				1				1	1		
27				1	1				1	1		
28		1	1	1	1							
29	1	1*	1	1								
30	1	1			1				1			

**This shows the placement of the resultant schedule for day-off and it's satisfaction for each nursing staff, entries with 1* are not preferred*

Discussion of results

Shift Preference

Weights of the Nursing Staff: In reviewing past preferences, we identified specific shift assignments for each staff member in the preceding two schedule periods. Notably, staff members 4, 6, 11, 12, 17, 20, 23, 24, 27, and 29 were consistently assigned less favourable shifts during this period. Consequently, their shift preference weights were adjusted accordingly higher in the current schedule planning. This adjustment aims to uphold fairness in shift rotation by increasing the likelihood of assigning these staff members to "good" shifts in the current schedule, thereby balancing the distribution of shift assignments across the nursing staff.

Shift Preference Rank and Preference Satisfaction of Nursing Staff:

The analysis reveals each nursing staff member's satisfaction level regarding various shift preference ranks. A lower preference rank indicates a higher degree of preference for a particular shift; for instance, preference rank 1 denotes the most preferred shift, while preference rank 3 reflects the least preferred shift. In mathematical modelling, prioritizing shifts with preference rank 1 is crucial to maximize nursing staff satisfaction with the shift schedule. Specifically, 20 staff members preferred the evening shift, 9 preferred the day shift, and 1 preferred the night shift. Given that the total number of nursing staff members who preferred day shifts exceeded the required manpower for 12 persons on day shifts, the preference ranks of 8 nursing staff members could not be immediately accommodated. However, the model automatically considered those preferences in subsequent scheduling iterations. This ensures ongoing refinement of the schedule to better align with the preferences and satisfaction of the nursing staff.

Day-off Preference Weights of the Nursing Staff:

We examined the frequency with which each day-off preference rank was fulfilled in past schedule periods and calculated the corresponding weighted preferences. The model determined these preference weights, which were then assigned to each staff member. Analysis of Table 3 revealed that staff members 12, 26, and 28 experienced the highest number of unsatisfactory "bad" days-off in the preceding two schedule periods. Consequently, their day-off preference weights were adjusted to prioritize them in the current schedule. This adjustment aims to ensure fairness in scheduling by affording those staff members a greater likelihood of being assigned preferable "good" days-off.

Conclusion

This case study affirms the efficacy of the novel weight extract approach, underscoring the importance of relevant historical data. Initial feedback from participating head nurses evaluating the proposed model indicates significant potential time savings, as the iterative trial and error process to determine suitable weights is eliminated. The Nurse Assignment model is adaptable to any shift plan and required nurse numbers per shift, generating solutions that prioritize nurse satisfaction by maximizing comfort with work shifts and days off with 0.32% improvement. More so, it offers considerable flexibility, empowering any hospital unit to harness the model's effectiveness.

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