Chapter 2
A Mathematical Model for Nurse Scheduling with Different Preference Ranks

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Abstract On nurse shift schedules, it is common that the nursing staff have diverse preferences about shift rotations and days off. We propose a nurse scheduling model based upon integer programming under the constraints of the schedule, different preference ranks towards each shift and the historical data of previous schedule periods so that the nursing staff's preference satisfaction about the shift schedule is maximized. The main difference of the proposed model from the previous works is to consider that the nursing staff's satisfaction level is affected by preference ranks and their priority ordering to be scheduled, so that the quality of shift schedule is more reasonable.

Keywords Nurse shift schedules · Integer programming · Preference ranks

2.1 Introduction

This paper is concerned with the nurse schedule, which aims at determining the rotating shifts of the nursing staff over a schedule period [4]. In general, the work shifts and days off of the nursing staff should be consider in a nurse schedule. In order to ensure a feasible schedule, when the manager plans the nurse schedule, all the combinations of shifts and days off have to meet the manpower requirement of each shift, and simultaneously, the number of basic days off of each staff member should be fulfilled [3]. In addition, there are a lot of types of the work shifts and days off in the schedule. The nursing staff usually has different preferences for work

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shifts and days off, because diverse personal lifestyles and different degrees of physical tolerance for continuous working days.

The preference satisfaction of the nursing staff for work shifts and days off enables them to take the proper rest to increase the quality of medical service and reduce medical cost of the hospital and risks of occupational hazard [2, 5]. Therefore, it has drawn a lot of attention in the recent works to consider the nursing staff's preferences in planning the schedule of work shifts and days off, and apply maximization of satisfaction and minimization of penalty cost to evaluate the quality of shift schedule with preferences [1, 5–7].

For example, Hadwan et al. [4] investigated how to minimize the penalty cost of a nurse schedule. Aickelin and Dowsland [1] applied a genetic algorithm to solve the nurse shift schedule problem in hospitals with the aim to minimize the penalty cost for not fulfilling the preferences of the nursing staff. Maenhout and Vanhoucke [6] studied the penalty costs with multiple constraints (including the nursing staff's preferences and some certain combinations of work shifts and days off). Topaloglu and Selim [7] considered a variety of uncertain factors in nurse schedule to propose a fuzzy multi-objective integer programming model which takes into consideration the fuzziness of the objective and the nursing staff's preferences.

From the previous works, it can be found that many studies do not explore the preference ranks of the nursing staff towards each shift rotation or day off. In addition, the preferred shift and day off are not given any priority ordering. Based on this, this paper proposes a mathematical programming model for the nurse scheduling problem. Our model takes into account constraints of the schedule, different preference ranks towards each shift and the historical data of previous schedule periods to maximize the nursing staff's preference satisfaction about the shift schedule.

The main contributions of this paper are listed as follows.

- The work shift and day off preferences of the nursing staff are categorized into different levels, and are then integrated to be solved.
- A priority ordering mechanism of the nursing staff when planning their shift schedule is applied to solve the contradictory situations among their preferences.

The rest of this paper is organized as follows. Section 2.2 describes our concerned problem. Section 2.3 proposes the mathematical model. Finally, a conclusion is made in Sect. 2.4.

2.2 Problem Description

We consider a shift schedule for a 2-week work in which the shifts of a day start at midnight, and the hospital runs on a 3-shift rotation: a day shift, an evening shift, and a night shift. Note that only regular days off are planned in the schedule. The nursing staff are asked to rank their preferences for each shift and day off, which are called *preference ranks*. The preference ranks for each shift are classified into 3 types: “good,” “normal,” and “bad” shifts. The preference ranks of days off are classified into “good” and “bad” days off based on the “preferred” and “not preferred” days off, respectively.

In order to ensure the nurse schedule available, some schedule constraints assumed are listed as follows.

The planned schedule has some constraints on shift rotations:

- Each nursing staff member is only assigned to a fixed type of shift within each schedule period.
- The number of nursing staff members required for each shift is fixed.
- Each person should have at least an 8-h rest before continuing on to the next shift.

The planned schedule has some constraints on days off:

- The total number of days off of each nursing staff member within the schedule period is the same.
- Each nursing staff member is entitled to at least one day off each week.
- The maximum number of the nursing staff members allowed to be on day off, and the number of senior staff members working in each shift each day are known and flexible.

2.3 Methodology

In this subsection, a binary integer linear programming model is constructed, which aims to maximize 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 days off, despite the constraints of manpower, shifts, and days off.

- Symbols

Subscript:

i Index of a nursing staff member

j Index of a shift type

k Index of date

Parameters:

I Set of the nursing staff (i.e., $i \in I$)

J Set of shift types (i.e., $j \in J$; note that $J = \{1$ (day shift), 2 (evening shift), 3 (night shift)$\}$ in this paper)

K Set of days off (i.e., $k \in K$; note that $|K| = 14$ in this paper)

M Set of preference ranks for shifts, $M = \{1$ (good), 2 (normal), 3 (bad)$\}$

N	Set of preference ranks for days off, $N = \{1 \text{ (good)}, 3 \text{ (bad)}\}$
P	Number of considered past schedule periods
α	Coefficient of the most preferred shift, $\alpha > 1$
β	Total number of days off of each staff member within the schedule period, $\beta > 1$
R_i	The variable to identify whether staff member i is senior, $R_i = \{0 \text{ (junior)}, 1 \text{ (senior)}\}$
W_i^S	The preference weight of each nursing staff member for work shift
W_i^H	The preference weight of each nursing staff member for day off
C	The base of preference weight ($C = 2$ in this paper)
$P_{i,j}^S$	Shift preference satisfaction of staff member i in work shift j
$P_{i,k}^H$	Day off preference satisfaction of staff member i in taking day k off
$L_{i,j}^S$	Preference rank of staff member i for shift j within the schedule period, $L_{i,j}^S \in \{1(\text{good}), 2(\text{normal}), 3(\text{bad})\}$
$L_{i,k}^H$	Preference rank of staff member i for taking day k off within the schedule period, $L_{i,k}^H \in \{1(\text{good}), 3(\text{bad})\}$
$T_{i,m}^S$	In the recent P periods, the number of times staff i is assigned to the shift of preference rank m, $0 \le T_{i,m}^S \le P$
$T_{i,n}^H$	In the recent P periods, the number of times staff i is assigned to the day off of preference rank n, $0 \le T_{i,n}^H \le (P \cdot \beta)$
θ_m^S	Preference score for being assigned to the shift of preference rank m, $\theta_{m=1}^S = 1 < \theta_{m=2}^S = 2 < \theta_{m=3}^S = 3$
θ_n^H	Preference score for being assigned to the day off of preference rank n, $\theta_{n=1}^H = 1 < \theta_{n=2}^H = 3$
$D_{j,k}$	Manpower demand in shift j on day k off
$\tau_{j,k}^{\min}$	Lower bound of the required number of senior staff members in shift j on day k off
$N_{j,k}^{\max}$	The maximum number of staff members allowed to have day off in shift j on day k
$s_{i,j}^{'}$	Whether staff member i worked shift j in the previous schedule period $s_{i,j}^{'} \in \{0 \text{ (off shift)}, 1 \text{ (on shift)}\}$
$h_{i,j,k}^{'}$	Whether staff member i had day off in shift j on day k in the previous schedule period, $h_{i,j,k}^{'} \in \{0 \text{ (off shift)}, 1 \text{ (on shift)}\}$

Decision variable:

$s_{i,j}$	Whether staff i is scheduled for shift j, $s_{i,j} \in \{0 \text{ (off shift)}, 1 \text{ (on shift)}\}$.
$h_{i,j,k}$	Whether staff i is scheduled for day off j on day k, $h_{i,j,k} \in \{0 \text{ (off shift)}, 1 \text{ (on shift)}\}$

- Mathematical model

The complete mathematical model is constructed as follows.

Objective:

$$\text{Max } G = \sum_{i}^{I}\sum_{j}^{J}\left\{\left(P_{i,j}^{S}\cdot s_{i,j,}\right)+\left(\sum_{k}^{K}\left(P_{i,k}^{H}\cdot h_{i,j,k}\right)\right)\right\} \tag{2.1}$$

where

$$P_{i,j,m}^{S}=\begin{cases}\alpha W_i^S, & \text{if } L_{i,j}^{S}=1\\ W_i^S, & \text{if } L_{i,j}^{S}=2\\ 0, & \text{if } L_{i,j}^{S}=3\end{cases} \tag{2.2}$$

$$P_{i,k,n}^{H}=\begin{cases}\alpha W_i^H, & \text{if } L_{i,k}^{H}=1\\ 0, & \text{if } L_{i,k}^{H}=3\end{cases} \tag{2.3}$$

$$W_i^S = C^{\sum_{m=1}^{M}(T_{i,m}^{S}\cdot\ \theta_m^S)} \tag{2.4}$$

$$W_i^H = C^{\sum_{n=1}^{N}(\frac{T_{i,n}^{H}}{\beta}\cdot\ \theta_n^H)} \tag{2.5}$$

Constraints:

$$\sum_{j\in J} s_{i,j}=1,\quad \forall i\in I \tag{2.6}$$

$$\sum_{i\in I} s_{i,j}=D_{j,k},\quad \forall j\in J,k\in K \tag{2.7}$$

$$\sum_{i\in I}(R_i\cdot(s_{i,j}-h_{i,j,k}))\geq\tau_{j,k}^{\min},\quad \forall j\in J,k\in K \tag{2.8}$$

$$\sum_{k\in K} h_{i,j,k}=s_{i,j}\cdot\beta,\quad \forall i\in I,j\in J \tag{2.9}$$

$$N_{j,k}^{\max} - \sum_{i}^{I} h_{i,j,k} \geq 0, \quad \forall j \in J, k \in K \tag{2.10}$$

$$\sum_{j}^{J} \left(\sum_{k=1}^{k=7} h_{i,j,k} \cdot \sum_{k=8}^{k=14} h_{i,j,k} \right) > 0, \quad \forall i \in I \tag{2.11}$$

$$s'_{i,3} \cdot s_{i,j} \leq h'_{i,3,14} \cdot h_{i,j,k}, \quad \forall i \in I \tag{2.12}$$

$$s_{i,j} \in \{0, 1\}, \quad \forall i \in I, j \in J \tag{2.13}$$

$$h_{i,j,k} \in \{0, 1\}, \quad \forall i \in I, j \in J, k \in K \tag{2.14}$$

First, the objective function of the model is explained as follows. Equation (2.1) maximizes the overall preference satisfaction of the nursing staff towards work shifts and days off. The preference satisfaction of each shift preference rank of each nursing staff is calculated by Eq. (2.2) [resp., Eq. (2.3)]. The preference satisfaction calculation for shift (resp., day off) is obtained from Eq. (2.4) [resp., Eq. (2.5)].

We continue to look at the constraints of the model. Constraint (2.6) enforces each nursing staff member to be assigned to at most one work shift within each schedule period. According to Constraints (2.7) and (2.8) respectively, manpower demand and number of senior nursing staff members of each shift each day should be met. Constraint (2.9) 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 (2.10) 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 patient on that particular day. Constraint (2.11) enforces that each staff member has to be given at least 1 day off each week, and the interval between two different shifts must be more than 8 h. According to Constraints (2.13) and (2.14), the decision variables of work shifts and days off should be either zero or one.

2.4 Conclusion

In hospital, it is specific and significant to investigate the problem of scheduling devise types of work shifts and days off for nurse staff members preferred. This paper proposes a mathematical programming model that integrates both the shift and day off into the analysis model. Not only are the shift and day off constraints taken into consideration, but also the historical records and individual preferences. Scheduling is performed on a fair and objective basis.

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