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Original Article

Nurse scheduling in a hospital emergency department: A case study at a Thai university hospital

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Abstract

Common problems of Thai nurses are low quality of life, working long hours, and a high turnover rate. The workload imbalance among nurses also worsens the turnover rate. With careful schedule planning, nurses do not have to work in consecutive shifts and can rest more. We interviewed and collected data from an emergency department at a hospital administered by a Thai university, related to objectives and constraints of monthly nurse scheduling, and actual monthly schedules. A multi-objective mathematical model was developed using the open source “OpenSolver” software in MS-Excel for nurse schedulers to freely use. We tested the model using actual data collected from the department and found that the schedules created by the model tended to provide more balanced workloads and more days off compared to the schedules created manually by a real scheduler. The model also suggested an easy policy to increase the number of nurses for future expansion.

Keywords: operations oanagement, healthcare management, goal programming, mathematical model, multi-objective optimization, nurse scheduling

1. Introduction

In Thailand and many countries, such as the USA, a high turnover rate and nurse shortages are major problems. It was found that 45.5% of Thai nurses had high stress from working long hours of more than 12 hours per day and a low quality of life, especially in young nurses. The stress was also a main cause of accidents such as sharp object induced injuries. These factors resulted in a high turnover rate. Therefore, researches to help improve health and quality of life of nurses should be promoted (ASTV manager online, 2015). According to Srisupan *et al.* (1998), frequent evening and night shifts caused a low quality of services, stress, and poor relationships with patients and their relatives. The irregular working schedules not only disturbed circadian rhythms but also affected families and their social life. A stressful working environment was physically and psychologically unhealthy to nurses. The factors influencing turnover of nurses in nursing divisions in hospitals were work conditions, lack of policy to meet nurse satisfaction, and lack of knowledge to improve nurse scheduling (Liao & Kao, 1997).

Due to a high shortage of nurses, retention of nurses by improving nurse schedules is one of the most important measures to create a better working environment for nurses. O’Connor (1992) showed that schedules that provided nurses with more autonomy and participation in determining their work schedules could significantly influence the nurse turnover rate. Typically in Thai hospitals, a nurse schedule planner, who is likely to be a head nurse or a senior nurse, manually creates monthly nurse schedules. Due to the complexity of scheduling, the schedule process can take up to several days or weeks and yet cannot meet the requests of the nurses for taking leaves, hospital regulations, and daily demands. Our research studied a nurse-scheduling problem in

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an emergency department. We developed a multi-objective mixed-integer mathematical model to create an optimal monthly schedule for nurses while trying to find a compromise of multiple objectives at the same time. The objectives were to satisfy leave requests, reduce overwork, and increase workload fairness. The model was developed such that it could be solved by an open source optimization software add-in to MS-Excel called "OpenSolver" for nurse schedule planners around the country to use widely and freely. As nurse scheduling problems are very complex, schedule planners typically need a decision tool to help. An integrated decision support system to help with scheduling was clearly needed in general public hospitals (Steyn, Coetzee, & van Dyk, 2015).

Many researchers used mathematical programming models such as mixed-integer linear programming models and heuristic algorithms as the main tools for scheduling. A mathematical programming problem is a linear program (LP) when an objective function is linear and constraints are only linear equations and inequalities. Mixed-integer programming (MIP) models are linear program (LP) models with some integer variables, and some variables not constrained to be integers (or continuous variables) (Johnson & Nemhauser, 1992).

However, mixed-integer programming models are based on a single objective function which might not be suitable for problems with conflicting objectives or multiple objective functions. Under these situations, a goal programming model is used to seek a compromise solution based on the relative importance of each objective (Taha, 2002).

Multi-objective mixed-integer and mixed-integer goal-programming models have wide applications. They are applied mostly in manufacturing settings. In the mid 1980s, multi-objective mixed-integer or mixed-integer goal-programming models with actual industrial applications started to be developed and implemented (El-Sayed, 1997). Vickery and Markland (1986) studied an integer linear goal programming model in a large pharmaceutical manufacturer. The large scale, multiple-capacity constrained model was successfully implemented by the company. Likewise, many other researchers, such as Gangan *et al.* (1987), Galbraith and Miller (1989), Saad (1990), and Dean *et al.* (1990), applied multi-objective mixed-integer or mixed-integer goal-programming models to manufacturing and production planning problems.

The goal programming and multi-objective programming models were also applied to many other areas. For example, in logistics, Baidya (2016) developed two multi-objective multi-stage models to obtain the optimal distribution of goods from different sources to different destinations with minimal total transportation cost and time.

Similarly, nurse scheduling problems were previously studied and solved using mixed–integer programming, multi-objective mixed-integer programming or mixed-integer goal-programming models. Warner and Prawda (1972) presented a mixed-integer quadratic programming model to calculate the number of nurses from a set of skill categories to work in each shift. Warner (1976) modified the previous formulation developed by Warner and Prawda (1972) by introducing weights or fairness levels. Bard and Purnomo (2005) studied short-term nurse scheduling in response to daily fluctuations in supply and demand. They aimed to adjust nurse schedules to match the demand that continuously changed within a 24-hour period. Grano *et al.* (2009) considered individual preferences of the nurses in nurse scheduling. They adopted a point system and asked nurses to bid via an auction. Then the inputs were processed using an optimization model. A search method was proposed to solve the model.

Tsai and Lee (2010) formulated a nurse-scheduling problem as a two-stage mathematical programming model. A nurse optimal vacation schedule was solved by a self-scheduling program while following government regulations, scheduling fairness, and hospital management requirements. Then, a genetic algorithm was used to determine the optimal schedule. Mobasher (2011) developed a mixed integer-programming model considering the types of patient workloads, duration, nurse preferences, and hospital regulations to assign nurses to different shifts. This model considered common constraints shared by many hospitals.

Burke *et al.* (2012) studied a Pareto-based search methodology for multi-objective nurse scheduling. An adaptive heuristic method and a simulated annealing method were proposed. Constantino *et al.* (2014) created a deterministic heuristic algorithm based on successive resolutions of an assignment problem. The algorithm was tested with published results using almost 250,000 instances. The algorithm was better in most large instances of the problems. Tontarski (2015) considered nurse scheduling in operating rooms using simulation and optimization. The objectives of the model were to maximize the percentage of nurse time in surgeries while maximizing nurse satisfaction at the same time.

Research studies of the scheduling problems in a Thai hospital environment are scarce. Our research collected real factors and constraints that nurse schedule planners in Thai hospitals considered when they constructed monthly schedules. Typically, in most Thai hospitals, the nurses are allowed to request days off each month so that nurses can plan and take care of their daily lives. This method provides more autonomy in their jobs. However, meeting the leave requests of the nurses, while satisfying changing daily demand and other constraints, creates problems for schedule planners. Also, the experiences of nurses are an important aspect in scheduling for Thai hospitals. Typically, in each shift, there are requirements to maintain a minimum number of nurses in each level of experience. For example, a head nurse might be required only in morning shifts, while senior nurses are required during all shifts. Also, policies to allow nurses to work in consecutive shifts are crucial, but they are also different among Thai hospitals. Previous research studies were typically conducted outside Thailand and did not consider all of the factors that are considered by Thai schedule planners in a single model. Thus, it is difficult for Thai hospitals to readily adopt a model. Our model was tailored to meet the constraints found in Thai hospitals. The model also recognizes nurses by their levels of experience. The model allows nurses with more experience to replace nurses with less experience, but nurses with less experience cannot replace nurses with more experience. Since the policies vary from hospital to hospital to allow consecutive shifts, the model should be easily adjusted. Also, the model was tested by using a data set of actual leave requests to show the effectiveness of the model. Then, the results were compared to the results of the schedule done manually.

Our first contribution was to create a single model considering all factors, such as multiple levels of nurse experience, leave requests, and fairness considerations, which are important in a Thai hospital environment. The second contribution was for the model to be coded and tested with the open source "OpenSolver" add-in software in MS-Excel to allow Thai hospitals to use it freely. With the limited capability of the software in terms of heavy computation, the model must be made easy so that the software can solve practical size problems. The third contribution was that our numerical results from actual data provided an easy rule of thumb to increase the number of nurses to match the increasing demand of nurses in the future.

2. Model

2.1 Background and assumptions

We interviewed schedule planners at several hospitals in Thailand. We aimed to understand the requirements (what a schedule must satisfy) and the preferences of schedules (what qualifies a schedule as a good schedule) in order to develop a mathematical model. The planning requirements of Thai hospitals were adapted to fit the Thai working environments which are different from the planning requirements found in the literature. For example, in the emergency departments of Thailand, nurses can specify which shifts and which days they prefer to work or not to work. Some Thai hospitals allow nurses to work two consecutive shifts and some do not. The planning model must be flexible. Some Thai hospitals limit the number of night shifts. Therefore, it is important to understand the requirements of the working environment of Thai emergency departments. The requirements are converted to hard constraints that schedules must satisfy and the preferences (measures preferred to have) as soft constraints that the optimization model tries to maximize. There were four preferences of the schedule.

1. The schedule satisfies leave requests of each nurse.
2. The maximum number of working days per month among all nurses is minimized.
3. The maximum number of all shifts assigned per month among all nurses is minimized.
4. The maximum number of night shifts assigned per month among all nurses is minimized.

Each preference was converted to be an objective of the model which was to minimize each of these objectives (Equation 1).

1. The weighted sum of the number of shift assignments which are different from the leave requests of the nurses
2. The weighted sum of the maximum number of working days per month among all nurses
3. The weighted sum of the maximum number of all shifts assigned per month among all nurses
4. The weighted sum of the maximum number of night shifts assigned per month among all nurses

The requirements were set as constraints.

1. The schedule must satisfy the minimum number of nurses required for each job level. However, a position of a lower-level less experienced nurse can be done by a higher-level more experienced nurse, but the position of a higher-level nurse cannot be done by a lower-level nurse due to lack of experience (Equation 2).
2. For each shift, the total number of nurses assigned to work must be the same as the number of nurses required from all nurse levels (Equation 3).
3. The nurses cannot work two consecutive shifts from afternoon shift to night shift and from night shift to morning shift (Equation 4 and 5, respectively).
4. The number of working hours per week cannot exceed the maximum number of hours allowed (Equation 6).
5. The maximum number of consecutive working days must not exceed the maximum limit (Equation 7).
6. The number of working days per week must not exceed the maximum limit (Equation 8).
7. The number of working days per month must not exceed the maximum limit (Equation 9).
8. The number of all shifts assigned per month must not exceed the maximum limit (Equation 10).
9. The number of all night shifts assigned per month must not exceed the maximum limit (Equation 11).

Based on the nine constraints listed and assumptions explained for each nurse, the mathematical model that was developed attempts to assign "0" or "1" to all shifts of all days in the planning period in the planning table. "1" indicated that a particular nurse is assigned to work in that shift of the day and "0" indicated otherwise. Figure 1 illustrates the planning table. However, the mathematical model will assign "0" or "1", such that all constraints from number 1 to 9 are satisfied for all nurses and all days. The related performance measures are then calculated.

	Day 1			Day 2			...	Last Day		
Nurse Name	Morning	Afternoon	Night	Morning	Afternoon	Night	...	Morning	Afternoon	Night
A	1	1	0	1	1	0	...	1	1	0
B	1	0	0	1	0	0	...	1	0	0
C	0	1	0	0	1	0	...	0	1	0

Figure 1. Planning table to meet the constraints listed

While satisfying all nine constraints, the model attempts to find a compromise of all goals: 1) the weighted sum of the number of shift assignments are different from the leave requests of the nurses, 2) the weighted sum of the maximum number of working days per month, 3) the weighted sum of the maximum number of all shifts assigned per month, 4) and the weighted sum of the maximum number of night shifts assigned per month. Warner and Prawda (1972) considered a nurse scheduling problem with similar features: nurses with multiple skills, nurse personality capacity constraints, minimum staffing requirements, and substitution of tasks allowed among the nursing skill classes. However, the constraints in the model did not address many requirements of Thai schedule planners, such as leave request considerations or consecutive shift limitations. Similarly, Mobasher (2011) considered multi-grade nurses as well. The grade of a nurse reflected the skill set the nurse had. Mobahser (2011) also included in the model the consecutive shift limitation, nurse working hours, and minimum nurse assignments per shift. However, Mobasher (2011) only considered the preferences of shifts in general but it did not recognize the preference of shifts in each day. Tsai and Lee (2010) considered leave requests in their model. However, the model lacked many requirements such as the multiple skill levels of the nurses, substitution of nurses, and consecutive shifts and days. As a result, the models reported in the literature did not completely incorporate the requirements of Thai nurse schedule planners.

2.2 Indexes, parameters and decision variables

2.2.1 Notations

1) Indexes

$d \in D$ *where* $D = \{1, \ldots d_{max}\}$ *and d indicates day in a planning period.*

$s \in S$ *where* $S = \{1, \ldots, s_{max}\}$ *and s indicates shift in a day.*

$i \in I$ *where* $I = \{1, \ldots i_{max}\}$ *and i indicates nurse.*

$l \in$ *where* $L = \{1, \ldots l_{max}\}$ and i *indicates the level of nurse's skill.*

2) Parameters

d_{max} = *maximum number of days in planning period*

i_{max} = *total number of nurses to schedule*

P_i = *weight of objective i*

$po_{ids} = 1$ *if nurse i prefers to have day on in shift s of day d*; 0 *otherwise*

n_{lds} = *minimum number of level − l nurses required for shift s of day d*

$level_{li} = 1$ *if job level of nurse i is l*; 0 *otherwise*

h_{max} = *maximum number of working hours per week*

$mwdw$ = *maximum number of working days per week*

mwd = *maximum number of working days per month*

mns = *maximum number of night shifst per month*

mas = *maximum number of all shifts per month*

$\overline{mcwd}$ = *maximum number of consecutive working days allowed*

w_{ids} = *weight of days off requested by nurse i for shift s of day d*

w_{mwdl} = *weight of maximum number of working days per month for level l nurses*

w_{masl} = *weight of maximum number of all shifts assigned per month for level l nurses*

w_{mnsl} = *weight of maximum number of night shifts assigned per month for level l nurses*

3) Decision variables:

$x_{ids} = 1$ *if nurse i works on day d in shift s*; 0 *otherwise*

$o_{id} = 1$ *if nurse i works on day d*; 0 *otherwise*

mwd_l = *maximum number of working days for level l nurse*

mns_l = *maximum number of night shifts for level l nurse*

mas_l = *maximum number of all shifts for level l nurse*

$mcwd_i$ = *maximum number of consecutive working days for nurse i*

$dx^{+}_{ids} = 1$ *if nurse i requests to work in shift s of day d, but the request is not satisfied*; 0 *otherwise*

$dx^{-}_{ids} = 1$ *if nurse i requests not to work in shift s of day d, but the request is not satisfied*; 0 *otherwise*

2.3 Mixed integer goal-programming model

The mixed integer goal-programming (non-preemptive) model of the problem was constructed.

Objective:

$$Minimize\ z = P_1\sum_{s=1}^{s_{max}}\sum_{d=1}^{d_{max}}\sum_{i=1}^{i_{max}}(w_{ids}dx^{-}_{ids}) + P_2\sum_{l=1}^{l_{max}}\left(w_{mwdl}mwd_l + w_{mnsl}mns_l + w_{masl}mas_l\right) \quad (1)$$

Subject to:

$$\sum_{i=1}^{i_{max}}\sum_{l=1}^{k} level_{li}x_{ids} \le \sum_{l=1}^{k} n_{lds},\ \forall\ k \in L, d \in D\ and\ s \in S \quad (2)$$

$$\sum_{i=1}^{i_{max}}\sum_{l=1}^{l_{max}} level_{li}x_{ids} = \sum_{l=1}^{l_{max}} n_{lds},\ \forall d \in D\ and\ s \in S \quad (3)$$

$$x_{id2} + x_{id3} \le 1,\ \forall\ i \in I\ and\ d \in D$$
$$x_{id3} + x_{i,(d+1),1} \le 1,\ \forall\ i \in I\ and\ d \in \{1,2,...,(d_{max}-1)\} \quad (4)\text{-}(5)$$

$$\sum_{d=w+1}^{w+7}\sum_{s=1}^{s_{max}} 8 \times x_{ids} \le h_{max},\ \forall i \in I\ and\ w \in \{0, 7, 14, 21\} \quad (6)$$

$$\sum_{d=k}^{k+\overline{mcwd}} o_{id} \le mcwd_i \le \overline{mcwd},\ \forall i \in I\ and\ k \in \{1, 2, ..., (d_{max} - \overline{mcwd})\} \quad (7)$$

$$\sum_{d=w+1}^{w+7} o_{id} \le mwdw,\ \forall\ i\ and\ w \in \{0, 7, 14, 21\} \quad (8)$$

$$\sum_{d=1}^{31} o_{id} \le mwd_l \le mwd,\ \forall\ i\ with\ level\ l\ and\ l \in L \quad (9)$$

$$\sum_{d=1}^{d_{max}}\sum_{s=1}^{s_{max}} x_{ids} \le mas_l \le mas,\ \forall i \in I\ and\ \forall l \in L \quad (10)$$

$$\sum_{d=1}^{d_{max}} x_{id3} \le mns_l \le mns, \forall i\ with\ level\ l\ and\ l \in L \quad (11)$$

$$po_{ids} - x_{ids} = dx^{+}_{ids} - dx^{-}_{ids}, \forall i \in I, d \in D, and\ s \in S \quad (12)$$

$$o_{id} \le \sum_{s=1}^{M} x_{ids} \le s_{max} \times o_{id}, \forall i \in I \text{ and } d \in D \quad (13)$$

$$x_{ids}, dx^{+}_{ids}, dx^{-}_{ids} \in \{0,1\} \; \forall i \in I, d \in D, s \in S$$
$$o_{id} \in \{0,1\}, \forall i \in I, d \in D$$
$$mwd_l, mns_l, mas_l \ge 0, \forall l \in L$$
$$mcwd_i \ge 0, \forall i \in I \quad (14)\text{-}(17)$$

Equation (1) determines the objective function. Equations (2)-(11) ensure that the nine requirements were met. Equation (12) calculates the deviation from leave requests. Equation (13) sets up a relationship between the shift assignment and day assignment. Equations (14)-(17) define the decision variables. The model was then constructed in MS-Excel and the optimization model was solved using OpenSolver in MS-Excel.

3. Numerical Experiments and Discussion

After interviewing several Thai hospitals, we selected one Thai hospital to analyze in detail. We interviewed the schedule planner at the selected Thai university hospital in July 2012 and collected actual leave requests and an actual monthly schedule. The hospital was administrated by a well-known Thai public university with approximately 540 beds in the hospital and 15 beds in the emergency room. There were a total of 31 full-time nurses in the emergency department. The levels of nurses were categorized into 5 levels from 1 to 5. Higher level indicates more experience or skills. The department operated 24 hour a day in 3 shifts: morning, afternoon, and night. After the interview, the actual leave requests were coded in MS-Excel as input. The model was then solved using OpenSolver (version 2.1) add-in software in MS-Excel. A notebook computer with an Intel Core™ i5-4250U CPU (1.90 GHz clock speed) and 8 GB of RAM was used to solve the model. The maximum computation time was within 15 min. The actual nurse preferences of shifts and actual leave requests were collected and put into the model. A sample of nurse preferences of shifts and days off of the first seven days is shown in Table 1. In each day, there were 3 shifts: morning, afternoon, and night. There were 5 levels of nurses who ranked from 1 to 5. A higher level indicates more experience or skill levels of the nurses. “1” in the table represents the shift preferred on a given day, and “0” means the shift is not preferred by a nurse. Three “0” in the same day indicate a day off request. In addition, the parameters in Table 2 were set. The minimum number of nurses in each level in a shift is provided in Table 3.

Table 1. Preferences of shifts.

	Day	1			2			3			4			5			6			7		
	Shift	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N	M	A	N
Name	Level																					
Nurse 1	5	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 2	4	0	0	0	1	1	0	1	1	0	1	0	0	1	0	0	1	0	0	0	1	0
Nurse 3	5	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 4	5	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 5	5	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 6	3	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	0	1
Nurse 7	1	0	1	0	1	0	0	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0
Nurse 8	2	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Nurse 9	4	1	0	1	0	1	0	0	0	1	0	0	0	1	1	0	1	0	1	0	0	1
Nurse 10	3	1	0	1	0	1	0	0	0	0	1	1	0	0	0	1	0	1	0	0	0	0
Nurse 11	4	1	0	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1	0
Nurse 12	3	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0
Nurse 13	4	1	0	1	0	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Nurse 14	3	0	1	0	1	0	1	0	0	1	0	0	0	1	0	1	0	1	0	1	0	1
Nurse 15	4	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0
Nurse 16	4	0	0	0	1	1	0	1	1	0	0	1	0	1	1	0	1	0	0	0	0	0
Nurse 17	3	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	0	0	0	0	0	0
Nurse 18	3	1	0	1	0	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	0	1
Nurse 19	4	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 20	4	0	0	0	1	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0
Nurse 21	3	1	1	0	0	0	0	1	0	1	0	1	0	0	1	0	1	0	1	0	0	0
Nurse 22	3	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0
Nurse 23	2	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	1	1	0
Nurse 24	2	1	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	1
Nurse 25	2	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	1	0	0	1	1	0
Nurse 26	1	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	1	0	0	0
Nurse 27	1	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
Nurse 28	1	1	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	1	1	0
Nurse 29	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0
Nurse 30	1	0	1	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0
Nurse 31	1	1	1	0	1	0	0	1	0	1	0	0	1	0	0	0	0	1	0	1	0	1

Table 2. Parameters of the model.

Parameters	Values
Maximum number of working hours per week	150 hours
Maximum number of working days per week	6 days
Maximum number of consecutive working days	7 days
Maximum number of shifts allowed	30 shifts per month
Maximum number of nights shift allowed	9 shifts per month
Maximum number of working days per month	31 days per month

Table 3. Minimum number of nurses at each level in each shift.

Level	Morning Shift	Afternoon Shift	Night Shift
1	4	4	2
2	4	2	2
3	2	2	2
4	1	1	0
5	4	0	0

Tables 4 and 5 show the key performance measures of a real solution from manual planning and from the optimal plan using the model. Both methods satisfy the minimum requirement for the number of nurses in each shift for the whole month but they differed in terms of details. The model could produce a higher number of consecutive days off (2.81 days vs. 2.74 days) (Tables 4 and 5). The average days off per nurse from the model was 10.26 days which was considerably higher than the 8.87 days from the manual solution collected from the hospital. The model provided almost 1.5 more days of rest. The maximum number of days working consecutively reduced from 5.42 days to 5.13 days on average by using the model. However, the model asked nurses to do consecutive shifts more often as the maximum number of consecutive days with double shifts increased from 0.97 days to 1.10 days. The number of working days marginally increased (20.74 days vs. 20.42 days) using the model, but the number of shifts to work in a month decreased from 26.35 shifts to 25.16 shifts which was almost a one-shift reduction. The model also moved nurses to work more afternoon shifts and reduced the number of morning shifts.

Overall, the results of the model showed that nurses had more time to rest which was almost 1.5 more days of rest time. Also, the standard deviation of performance measures (indicating the variability of workload assignments for each nurse or unfairness in workload assignments) of the actual solution was higher than those of the solution from the model in most measures. As a result, the solution from the model provided more balanced workloads, especially on the key measures such as the number of working days, the number of days off, the number of consecutive working days, the number of night shifts, number of all shifts, and more fairness to the nurses. The results from the model indicated a greater likelihood that the nurses would have less burnout and less fatigue that should result in less turnover.

Table 4. Key performance measures of both planning methods.

		Maximum Number of Consecutive Days Off	Maximum Number of Consecutive Days On	Maximum Consecutive Night Shifts	Number of Days Off	Number of Consecutive Morning-Afternoon Shifts	Number of Consecutive Afternoon-Night Shifts	Number of Consecutive Night-Morning Shifts	Maximum Number of Consecutive Days with Consecutive Shifts
Manual Method (Actual Solution)	Mean	2.74	5.42	1.52	8.87	2.42	0.00	0.00	0.97
	SD	1.26	1.36	0.93	1.28	1.91	0.00	0.00	0.60
Model	Mean	2.81	5.13	1.52	10.26	2.32	0.00	0.00	1.10
	SD	0.87	0.81	0.89	0.68	1.66	0.00	0.00	0.70

Table 5. Key performance measures of both planning methods (continued).

		Number of Working Days	Number of Morning Shifts	Number of Afternoon Shifts	Number of Night Shifts	Number of All Shifts
Manual Method (Actual Solution)	Mean	20.42	13.03	7.52	5.81	26.35
	SD	1.31	4.62	3.78	4.00	3.53
Model	Mean	20.74	10.65	8.71	5.81	25.16
	SD	0.68	5.52	4.18	3.62	1.90

Next, we tested the robustness of model and explored the proper workforce planning policy as workloads increase. According to Table 6, in one step of change, we added one more level-1 nurse requirement to each shift (all three shifts). That means we needed 3 more level-1 nurses per day. We experimented by adding 3 more level-1 nurses to the pool of available nurses. (Similarly, if we adjusted two steps, we added 2 level-1 nurses to the requirement of every shift and added 6 more level-1 nurses to the pool of available nurses, and so on.) Following this method, the increased demand and increased supply of nurses are simulated (Table 6).

Table 6. Key performance measures as the workload and supply of nurses increased.

Number of Steps Increased	Total Nurses in All Shifts Needed	Total Nurses Available	Statistics	Maximum Number of Consecutive Days Off	Maximum Number of Consecutive Days On	Maximum Consecutive Night Shifts	Number of Days Off	Number of Working Days	Number of Night Shifts	Number of All Shifts
-2	600	25	Mean	3.48	3.48	1.12	15.68	15.32	4.80	24.00
			SD	0.87	0.96	0.44	0.85	0.85	1.00	1.08
-1	690	28	Mean	3.46	2.96	1.36	16.46	14.54	5.36	24.64
			SD	0.84	0.79	0.49	0.51	0.51	0.49	0.83
0	780	31	Mean	3.19	3.23	1.35	16.13	14.87	5.81	25.16
			SD	0.95	0.80	0.61	0.34	0.34	0.40	0.73
1	870	34	Mean	3.00	3.68	1.68	14.74	16.26	6.18	25.59
			SD	0.74	0.77	0.68	0.90	0.90	0.67	0.74
2	960	37	Mean	2.78	2.92	1.59	15.38	15.62	6.49	25.95
			SD	0.75	0.68	0.50	0.83	0.83	0.69	1.18
3	1050	40	Mean	3.10	3.15	1.53	15.10	15.90	6.75	26.25
			SD	0.81	0.80	0.60	0.38	0.38	0.49	0.78
4	1140	43	Mean	2.58	3.30	1.67	13.84	17.16	6.98	26.51
			SD	0.85	0.86	0.47	1.13	1.13	0.56	1.18
5	1230	46	Mean	2.61	3.59	1.72	14.07	16.93	7.17	26.74
			SD	0.86	0.93	0.83	1.08	1.08	0.74	0.57
6	1320	49	Mean	2.73	3.41	1.80	14.14	16.86	7.35	26.94
			SD	0.73	0.89	0.64	0.35	0.35	0.56	0.24
7	1410	52	Mean	2.48	3.37	1.77	13.25	17.50	7.50	27.12
			SD	0.83	1.01	0.58	2.17	1.09	0.70	1.32
8	1500	55	Mean	2.09	3.07	1.65	12.85	17.18	7.64	27.27
			SD	0.89	1.15	0.64	3.96	1.61	0.59	1.64
9	1590	58	Mean	2.07	3.50	1.90	12.07	17.24	7.76	27.41
			SD	1.02	1.11	0.58	4.69	1.43	0.76	1.64
Average increase of mean (%) per one step of requirement				-4.3%	0.7%	5.4%	-2.2%	1.2%	4.5%	1.2%

We found that the model could be solved up to 58 nurses and optimal solutions were still found within 15 min. Also, we found that as the demand of nurses increased by 3X nurses per day (X nurses per shift), hiring at least 3X more nurses (where X is an integer number from 1 to 9) is a good rule of thumb in a hiring policy and planning workforce. The key measures in Table 6 changed marginally for each step of change. The two most important measures of the number of working days and number of all shifts increased at the rate of 1.2% per one step of change. The nurses tended to work incrementally harder following this policy. However, in this experiment, the number of total nurses in all shifts (or demand of nurses) increased 2.65 times (or 165%) from 600 (at Step -2) to 1590 nurses (at Step 9), but the number of all shifts per nurse increased only 1.14 times (14%). The standard deviations of the measures among all nurses in Table 6 were also relatively stable. The same result was also applied when the workload decreased one or two more steps. The changes in the measures were marginal. As a result, this shows that the suggested hiring policy performed very well to match the supply and demand of nurses. Also, the varying range of supply of nurses from 25 nurses to 58 nurses in this experiment was very extreme in practice. A workforce of 58 nurses almost doubled the current workforce of 31 nurses. It would take many years or a substantial change in the organization before this could actually occurs. Therefore, the hospital should adopt the suggested rule of thumb to cope with the increased demand of services in the future.

The main reason that might explain the marginal increase of workloads (for example, the increase in the number of all shifts) was due to the fact that the demand or requirements of nurses increases everyday (all 28 days) at all shifts, but the added work of the nurses was only about 15-17 days a month on average. Therefore, the supply of nurses did not match perfectly with the increased demand.

However, there are some concerns from the experiment, such as the worse performance measures related to night shifts (average increase per one step of change in maximum consecutive night shifts and the number of night shifts) and the larger standard deviation of the number of days off. Even though the worst case (at Step 9) is still acceptable with a maximum consecutive night shifts of 1.9 days and the number of night shifts of 7.76 shifts, these numbers should be re-evaluated by hospital managers for acceptability. As stated in the hiring policy, the suggested number from 3X is only a minimum number of nurses to be hired. Hiring more nurses than the workforce size, calculated from the rule of thumb, should always be considered. The developed model can help plan the workforce in more detail for Thai hospitals.

4. Conclusions

We studied a nurse-scheduling problem in a hospital emergency department in Thailand. We interviewed the schedule planners at several Thai hospitals to collect information and factors affecting the planning. The planning requirements of a workforce at an emergency department in Thailand differ from the planning requirements found in the literature. The models previously studied did not consider all factors in a single model as needed by Thai hospitals. Using the information collected, we developed a mixed-integer goal-programming model to help schedule planners develop a monthly schedule using the open source "OpenSolver" add-in optimization software in MS-Excel. The results showed that the model worked well and could provide the optimal solution within approximately 15 min using a typical notebook computer. The model suggested a better solution in terms of the number of days off for the nurses compared to the actual solution developed manually by a Thai schedule planner which was the main goal of this research. We showed that proper planning can help lower the number of shifts to work with more days off in a month. This helps lower nurse burnout and increases the quality of life of nurses. We also explored and suggested a good rule of thumb for planning a future workforce as the demand of nurses per shift increases. Importantly, the model can also lower the variability in the workload assignments and increase the fairness among nurses in terms of the number of days off or the number of night shifts assigned. In future research, we will test the model further with actual data and make the model and MS-Excel file available for schedule planners to freely use.

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