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Nurses Scheduling by Considering the Qualification using Integer Linear Programming

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Abstract

One of problems that frequently occurs in hospital management is nurses scheduling problem. A suitable schedule is needed in order to avoid fatigue, both physically and psychologically, which subsequently may deteriorate their performance. Nurse scheduling is commonly designed by the head of nurse manually. In this research, nurse scheduling problem is modeled by considering the qualification of the nurses and the model has the form of integer linear programming. The objective of the model is to maximize the number of nurse's day-offs. Then optimization problem is implemented to nurses scheduling in the High Care Unit and the Emergency room of Rumah Sehat Terpadu Dompet Dhuafa Parung Bogor.

Keywords*: Integer Linear Programming, nurse scheduling, nurse qualification*

1. Introduction

Scheduling is a classic problem which commonly occurs in many corporations, such as in university, Abbaszadeh et al. have applied Memetic Algorithm to solve university courses scheduling problem [1]; in transportation, Xiaoni et al. have solved the optimal headway and bus scheduling combination of a bus lane line [2]; and in hospital, Agyei et al. have developed nurse scheduling problem using goal programming [3].

A hospital as one of health facilities that serves people has a major role in providing health care services. Normally a hospital would have several services, such as emergency, outpatient, inpatient, surgery, and intensive care unit. Some of research that has been done in hospital includes doctors scheduling [4], operation room scheduling [5], and nurse scheduling [6]. Each service unit will be administered by medical professionals. The facility would operate 24 hours a day, seven days a week.

A nurse is one of the important medical professionals in a hospital. Nurses scheduling is a common problem in hospitals. Good schedule would avoid nurses from overtired physically and psychologically, in order they can deliver an optimum service. To achieve this, it requires a precise and efficient nurse scheduling that abides by hospital's rules and fulfill the number of nurses required in each of the service unit. Each nurse is expected to have skills required to deliver minimum standard services. All nurses in the emergency unit should have Basic Life Support (BLS) or Emergency First Aid (EFA) or General Emergency Life Support (GELS) or Advance Life Support (ALS) certificates [7]. Each nurse who works in High Care Unit (HCU) should be certified with BLS, has skills in using monitor, and has experience in an ICU training [8]. Thus, nurses can not be assigned to any unit, because the nurse might not have the minimum requirement for the unit.

Generally, there are two types of scheduling that normally used that are cyclic and non-cyclic schedulings. Millar and Kiragu have solved cyclic and non-cyclic nurses scheduling using network programming [9], and Jenal et al. have developed a cyclical nurse schedule using goal programming [10]. This approach is aimed to design a cyclic nurse scheduling by using the integer linear programming with consideration on nurse's specific expertise required in several units in a hospital.

In this research, nurses scheduling problem is modeled by considering the qualification of the nurses and is formulated using Integer Linear Progromming technique. The model will be implemented for the case at Rumah Sehat Terpadu Dompet Dhuafa Parung, Bogor. The objective of the model is to maximize the number of nurse's day-offs.

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2. The Model

2.1. Problem Description

The designed scheduling is a cyclic scheduling for 18 nurses with two qualifications to be assigned in two units, High Care Unit (HCU) and Emergency Room (ER). Each nurse can only be assigned in a certain units according to his or her qualification. Nurses with index value of 1-9 have qualification 1 and can be assigned in either HCU or ER. Nurses with index value of 10-18 have qualification 2 and can only be assigned in ER.

Each unit is covered by three working shifts: morning shift (7 am – 2 pm) for 7 working hours, evening shift (2 pm – 9 pm) for 7 working hours, and night shift (9 pm – 7 am) for 10 working hours. There are two types of day-off. First, nurses are provided with a full day-off, in example 24 hours a day. Second, we call it free time where the nurse can get it when he or she has already spent a night shift in the day before. The set of all rules is given as follows:

1. Each nurse works only one shift a day
2. The minimum number of nurses are fulfilled for each shift each day. The number of required for each shift is at leat 2 nurses.
3. Each nurse cannot work in two consecutive night shifts
4. Each nurse cannot be assigned in a night shift followed by a morning shift or an evening shift in the next day
5. Each nurse cannot be assigned in an evening shift followed by a morning shift in the next day
6. Each nurse cannot be assigned in a morning shift or an evening shift or a day off followed by a free time in the next day
7. After having a night shift, each nurse is granted a free time, not a day off
8. Each nurse gets a day off after having a free time
9. Each nurse gets at least one day off within seven working days
10. Each nurse gets a day off at most five days in 30 days
11. Each nurse cannot be assigned off-on-off pattern
12. Each nurse works between 170 to 176 hours in 30 days
13. Each nurse gets morning, evening, and night shifts between 6 to 9 days in 30 days.

2.2. Notations and Decision Variables

Sets

V = set of nurses, $V = 1,2,\dots,18$
W = set of nurse qualifications, $W = 1,2$
X = set of units, $X = 1,2$
Y = set of days, $Y = 1,2,\dots,30$

Index

i = index of nurses, $i \in V$
j = index of nurse qualifications, $j \in W$
k = index of units, $k \in X$
l = index of days, $l \in Y$

Parameter

A_{kl} = number of nurses required on morning shift at unit k on day l
B_{kl} = number of nurses required on evening shift at unit k on day l
C_{kl} = number of nurses required on night shift at unit k on day l
r_{ij} = $\begin{cases}1, & \text{if the nurse } i \text{ has qualification } j\\ 0, & \text{otherwise}\end{cases}$

Decision Variable

M_{ijkl} = $\begin{cases}1, & \text{if the nurse } i \text{ with qualification } j \text{ is assigned a morning shift at unit } k \text{ on day } l\\ 0, & \text{otherwise}\end{cases}$
E_{ijkl} = $\begin{cases}1, & \text{if the nurse } i \text{ with qualification } j \text{ is assigned a evening shift at unit } k \text{ on day } l\\ 0, & \text{otherwise}\end{cases}$
N_{ijkl} = $\begin{cases}1, & \text{if the nurse } i \text{ with qualification } j \text{ is assigned a night shift at unit } k \text{ on day } l\\ 0, & \text{otherwise}\end{cases}$

$F_{ijl} = \begin{cases} 1, & \text{if the nurse } i \text{ with qualification } j \text{ is assigned a free time on day } l \\ 0, & \text{otherwise} \end{cases}$

$D_{ijl} = \begin{cases} 1, & \text{if the nurse } i \text{ with qualification } j \text{ is assigned a day off on day } l \\ 0, & \text{otherwise} \end{cases}$

2.3. Objective function

The objective function is to maximize the total amount of days off z.

$$\text{Max } z = \sum_{i=1}^{18} \sum_{j=1}^{2} \sum_{l=1}^{30} D_{ijl}$$

2.4. Constraints

The following constraints will be imposed:

1. Each nurse works only one shift a day.

$$\text{If } r_{ij} = 1 \text{ then } \sum_{k=1}^{2} M_{ijkl} + E_{ijkl} + N_{ijkl} + F_{ijl} + D_{ijl} = 1$$
$$i = 1,2,\dots,18$$
$$j = 1,2$$
$$l = 1,2,\dots,30$$
$$\text{If } r_{ij} \neq 1 \text{ then } M_{ijkl} = 0, E_{ijkl} = 0, N_{ijkl} = 0, F_{ijl} = 0, D_{ijl} = 0$$
$$i = 1,2,\dots,18$$
$$j = 1,2$$
$$k = 1,2$$
$$l = 1,2,\dots,30$$

2. The minimum number of nurses are fulfilled for each shift each day.

$$\sum_{i=1}^{18} \sum_{j=1}^{2} M_{ijkl} \geq A_{kl}$$
$$\sum_{i=1}^{18} \sum_{j=1}^{2} E_{ijkl} \geq B_{kl}$$
$$\sum_{i=1}^{18} \sum_{j=1}^{2} N_{ijkl} \geq C_{kl}$$
$$k = 1,2$$
$$l = 1,2,\dots,30$$

3. Each nurse cannot work in two consecutive night shifts.

$$\sum_{j=1}^{2} \sum_{k=1}^{2} N_{ijkl} + N_{ijk,l+1} - \left(F_{ij,l+1} + F_{ij,l+2}\right) \leq 1$$
$$i = 1,2,\dots,18$$
$$l = 1,2,\dots,28$$

4. Each nurse cannot be assigned in a night shift followed by a morning shift or an evening shift in the next day.

$$\sum_{j=1}^{2} \sum_{k=1}^{2} N_{ijkl} + M_{ijk,l+1} \leq 1$$
$$\sum_{j=1}^{2} \sum_{k=1}^{2} N_{ijkl} + E_{ijk,l+1} \leq 1$$
$$i = 1,2,\dots,18$$
$$l = 1,2,\dots,29$$

5. Each nurse cannot be assigned in an evening shift followed by a morning shift in the next day.

$$\sum_{j=1}^{2}\sum_{k=1}^{2} E_{ijkl} + M_{ijk,l+1} \leq 1$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,29$

6. Each nurse cannot be assigned in a morning shift or an evening shift or a day off followed by a free time in the next day.

$$\sum_{j=1}^{2}\sum_{k=1}^{2} M_{ijkl} + F_{ij,l+1} \leq 1$$
$$\sum_{j=1}^{2}\sum_{k=1}^{2} E_{ijkl} + F_{ij,l+1} \leq 1$$
$$\sum_{j=1}^{2} D_{ijl} + F_{ij,l+1} \leq 1$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,29$

7. After having a night shift, each nurse is granted a free time, not a day off.

$$\sum_{j=1}^{2}\sum_{k=1}^{2} N_{ijkl} + D_{ij,l+1} \leq 1$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,29$

8. Each nurse gets a day off after having a free time.

$$\sum_{j=1}^{2} F_{ijkl} + D_{ij,l+1} \leq 0$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,29$

9. Each nurse gets at least one day off within seven working days.

$$\sum_{j=1}^{2} D_{ijl} + D_{ij,l+1} + D_{ij,l+2} + D_{ij,l+3} + D_{ij,l+4} + D_{ij,l+5} + D_{ij,l+6} \geq 1$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,24$

10. Each nurse gets a day off at most five days in 30 days.

$$\sum_{j=1}^{2}\sum_{l=1}^{30} D_{ijl} \leq 5$$
$i = 1,2,\ldots,18$

11. Each nurse cannot be assigned off-on-off pattern.

$$\sum_{j=1}^{2} D_{ijl} + \left(\sum_{k=1}^{2} M_{ijk,l+1} + E_{ijk,l+1} + N_{ijk,l+1}\right) + D_{ij,l+2} \leq 2$$
$i = 1,2,\ldots,18$
$l = 1,2,\ldots,28$

12. Each nurse works between 170 to 176 hours in 30 days.

$$170 \leq \sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{l=1}^{30} 7M_{ijkl} + 7E_{ijkl} + 10N_{ijkl} \leq 176$$

$i = 1,2,\dots,18$

13. Each nurse gets morning, evening, and night shifts between 6 to 9 days in 30 days.

$$6 \leq \sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{l=1}^{30} M_{ijkl} \leq 9$$
$$6 \leq \sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{l=1}^{30} E_{ijkl} \leq 9$$
$$6 \leq \sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{l=1}^{30} N_{ijkl} \leq 9$$
$$i = 1,2,\dots,18$$

14. The nurse who lacks the required qualification can not be assigned to the certain unit.

$$M_{ijkl} = E_{ijkl} = N_{ijkl} = 0$$
$$i = 1,2,\dots,18$$
$$j = p,\ k \notin X_p, p \in W$$
$$l = 1,2,\dots,30$$

15. The variables $M_{ijkl}, E_{ijkl}, N_{ijkl}, F_{ijl}$ and D_{ijl} are binary.

$$M_{ijkl}, E_{ijkl}, N_{ijkl}, F_{ijl}, D_{ijl} \in \{0,1\}$$
$$i = 1,2,\dots,18$$
$$j = 1,2$$
$$k = 1,2$$
$$l = 1,2,\dots,30$$

3. Results and Analysis

The cyclical nurse scheduling model in Rumah Sehat Terpadu Dompet Dhuafa Parung, Bogor was modeled and solved using Integer Linear Programming technique. A few model has been developed in order to get a good solution. The model presented here is the best model for the nurse scheduling. Table 1, Table 2, and Table 3 summaries the result of the model using Integer Linear Programming technique.

Table 1 shows the patterns of the shift of the working day, a free time, and a day off for 30 days scheduling period developed by using the Integer Linear Programming technique. The schedule satisfied all the constraints. There is no night shift followed by a morning shift or an evening shift the next day, and also there is no evening shift followed by a morning shift the next day is assigned to each schedule's pattern.

Table 2 shows the summary for the number of shifts, free time, and day off for each schedule's pattern. In 30 days of scheduling period, all nurses have the same 5 days of total number of night shift per the 30 days period. And also they have between 6 to 9 working days, 3-4 days of free time, and also 170-176 working hours.

Table 3 shows the summary for the number of shift for each day. It can be seen that in HCU, there are 2-3 nurses is assigned in morning shift, whereas there are only two nurses is assigned in other shifts. In ER, there are 2-4 nurses in each shift every day. It shows that the number of nurses required on each shift in every unit can be satisfied as expected and the nurse in each unit works according to the requisite qualifications.

Table 4 shows the manual schedule prepared by the head nurse in one unit. The schedule produced manually has shown that there is an inconsistency in the total number of working hours for the nurses. The distribution of night shift is also unbalance. There is one nurse who has been assigned in a night shift 5 days in 30 days.

Table 1. Nurses scheduling developed using Integer Linear Programming technique

Day	Nurses																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	M	E	N	E	M	E	D	F	N	N	E	M	E	M	F	E	N	D
2	M	D	N	N	E	E	M	D	F	N	E	M	E	E	D	N	F	M
3	E	M	F	N	N	E	M	M	D	F	E	N	D	E	M	N	D	M
4	N	M	D	F	N	E	M	M	E	D	E	N	M	E	N	F	M	E
5	N	M	E	D	F	D	N	M	E	M	E	F	E	D	N	D	M	N
6	F	M	E	M	D	N	N	E	E	N	D	D	E	M	F	M	E	N
7	D	M	E	M	M	N	F	E	N	N	N	E	N	M	D	M	E	F
8	E	M	N	M	E	F	D	D	N	F	N	E	N	M	M	E	D	D
9	E	D	N	E	N	D	M	M	F	D	F	E	F	N	M	N	E	M
10	N	E	F	D	N	M	E	M	D	M	D	N	D	N	M	N	E	E
11	N	E	D	E	F	M	N	N	M	M	M	N	M	F	N	F	E	E
12	F	N	M	E	D	E	N	N	M	M	M	F	E	D	N	D	N	D
13	D	N	M	E	M	E	F	F	N	N	M	D	E	M	F	E	N	M
14	M	F	E	N	M	E	D	D	N	N	E	M	D	E	D	N	F	M
15	M	D	E	N	M	D	N	E	F	F	E	E	M	N	E	N	D	M
16	M	N	D	F	E	M	N	E	D	D	E	N	M	N	E	F	M	M
17	M	N	M	D	E	E	F	N	M	E	D	N	N	F	E	D	M	M
18	E	F	M	E	D	N	D	N	M	E	M	F	N	D	N	M	E	D
19	E	D	E	N	M	N	M	F	D	E	M	D	F	M	N	E	N	E
20	D	M	N	N	E	F	E	D	M	E	M	M	D	M	F	N	N	E
21	M	E	N	F	N	D	E	E	M	E	N	M	M	M	D	N	F	N
22	E	N	F	D	N	M	E	E	M	D	N	M	E	N	M	F	D	N
23	E	N	D	M	F	M	E	E	N	M	F	E	N	N	M	D	M	F
24	N	F	M	M	D	M	E	E	N	E	D	E	N	F	E	M	N	D
25	N	D	M	M	E	N	D	E	F	E	M	D	F	D	N	M	N	E
26	F	E	E	M	N	N	M	D	D	E	M	N	D	E	N	M	F	E
27	D	E	N	M	N	F	M	M	E	E	N	N	M	E	F	E	D	E
28	M	E	N	E	F	D	N	M	E	D	N	F	M	E	D	D	M	N
29	M	E	F	D	D	M	N	N	E	M	F	D	E	D	N	M	E	N
30	D	E	D	M	M	E	F	N	N	M	D	M	E	M	N	E	N	F

Description:

M: morning shift; E: evening shift; N: night shift; F: free time; D: day off

: assigned in HCU

: assigned in ER

Table 2. Summary of the number of shifts, free time, day off, and working hours

Nurse	Working Time			Free Time	Days Off	Working Hours
	Morning	Evening	Night			
1	9	7	6	3	5	172
2	7	9	6	3	5	172
3	6	7	8	4	5	171
4	9	7	6	3	5	172
5	7	6	8	4	5	171
6	7	9	6	3	5	172
7	7	6	8	4	5	171
8	7	9	6	3	5	172
9	7	6	8	4	5	171
10	7	9	6	3	5	172
11	8	8	6	3	5	172
12	7	6	8	4	5	171
13	7	9	6	3	5	172
14	9	7	6	3	5	172
15	7	6	8	4	5	171
16	7	6	8	4	5	171
17	6	7	8	4	5	171
18	8	8	6	3	5	172

Table 3. summary for the number of shift for each day

Qualifications	Nurses											
	Morning				Evening				Night			
	HCU		ER		HCU		ER		HCU		ER	
Days	1	2	1	2	1	2	1	2	1	2	1	2
1	2	-	-	2	2	-	1	3	2	-	-	2
2	2	-	-	2	2	-	-	3	2	-	-	2
3	2	-	1	2	2	-	-	2	2	-	-	2
4	2	-	1	2	2	-	-	3	2	-	-	2
5	2	-	-	2	2	-	-	2	2	-	-	2
6	2	-	-	2	2	-	1	2	2	-	-	2
7	3	-	-	2	2	-	-	2	2	-	-	3
8	2	-	-	2	2	-	-	2	2	-	-	2
9	2	-	-	2	2	-	-	2	2	-	-	2
10	2	-	-	2	2	-	-	2	2	-	-	3
11	2	-	-	4	2	-	-	2	2	-	1	1
12	2	-	-	2	2	-	-	2	2	-	1	1
13	2	-	-	3	2	-	-	3	2	-	-	3
14	2	-	-	2	2	-	-	2	2	-	-	3
15	2	-	-	2	2	-	-	3	2	-	-	3
16	2	-	-	3	2	-	-	2	2	-	-	2
17	2	-	1	2	2	-	-	2	2	-	-	2
18	2	-	-	2	2	-	-	2	2	-	-	2
19	2	-	-	2	2	-	-	3	2	-	-	2
20	2	-	-	3	2	-	-	2	2	-	-	2
21	2	-	-	3	2	-	1	1	2	-	-	3
22	2	-	-	2	2	-	1	1	2	-	-	3
23	2	-	-	3	2	-	1	1	2	-	-	2
24	2	-	1	1	2	-	-	3	2	-	-	2
25	2	-	-	2	2	-	-	2	2	-	-	2
26	2	-	-	2	2	-	-	3	2	-	-	2
27	2	-	1	1	2	-	-	4	2	-	-	2
28	2	-	-	2	2	-	1	1	2	-	-	2
29	2	-	-	2	2	-	-	2	2	-	-	2
30	2	-	-	3	2	-	-	2	2	-	-	2

Table 4. Manual Nurses Scheduling prepared by the head nurse in one unit

Days	Nurses								
	1	2	3	4	5	6	7	8	9
1	D	M	E	E	N	N	D	N	M
2	M	E	N	D	N	F	M	F	E
3	M	E	N	N	F	D	M	D	E
4	E	N	F	N	D	M	E	M	E
5	E	N	D	F	M	E	E	M	N
6	N	F	M	D	M	E	N	E	N
7	N	D	M	M	E	E	N	N	F
8	F	M	E	M	E	N	F	N	D
9	D	D	E	E	N	N	D	F	M
10	M	E	N	E	N	F	M	D	D
11	M	E	N	N	F	D	D	M	E
12	E	N	F	N	D	M	E	M	E
13	E	N	D	F	M	E	E	D	N
14	N	F	M	D	M	E	N	E	N
15	N	D	M	M	E	N	N	E	F
16	F	M	E	M	E	N	F	N	D
17	D	M	E	E	N	F	D	N	M
18	D	E	N	E	N	D	M	F	M
19	M	E	N	N	F	M	M	D	E
20	E	N	F	N	D	D	E	M	E
21	E	N	D	F	M	E	E	M	N
22	N	F	M	D	D	E	N	E	N
23	N	D	M	M	E	N	N	E	F
24	F	M	E	M	E	N	F	D	D
25	D	M	E	E	N	F	D	N	M
26	M	E	N	E	N	D	M	N	M
27	M	E	E	N	F	M	E	F	N
28	M	N	F	N	D	M	E	E	N
29	N	N	D	F	M	E	N	E	F
30	N	F	D	D	M	E	N	E	D
Morning	8	6	6	6	7	5	6	6	6
Evening	6	8	8	7	6	9	8	8	7
Night	8	8	7	8	8	7	8	7	8
Free time	3	4	4	4	4	4	3	4	4
Days off	5	4	5	5	5	5	5	5	5
Working hours	178	178	168	171	171	168	178	168	171

4. Conclusion

In this research, we had solved a nurse scheduling problem by considering the nurse qualification in Rumah Sehat Terpadu Dompet Dhuafa Parung Bogor. It is formulated using integer linear programming technique. The resulted scheduling was an effective scheduling because it obeyed all of the hospital's rules. This research can be further improved for scheduling that involves more units, such as in a polyclinic since it has a different set of rules from the ones we used in this research. Moreover, this research can also be enhanced to solve a scheduling problem involving a higher number of nurses.

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