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An Optimization Model for Scheduling Additional Medical Personnel During a Pandemic

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Abstract **– The most severe and pervasive problems in modern healthcare systems occur during epidemics and pandemics. One of these problems is the reassignment and the rescheduling of the medical staff during the days of the critical weeks with a high number of infected patients, which, at the same time, amplifies the need for hiring additional medical staff. In this paper we are addressing the problem of the number of additional nurses that must be hired as part time workers, with the following objective: to satisfy the minimum number of nurses needed during the days of the critical weeks, while keeping the hospital costs as low as possible. The solution of this problem is obtained by a schedule of the additional personal based on four, partially overlapping shifts, which gave a reduction of the initial costs. It can be applied in any organization that is in need for additional staff, regardless of the reason.**

Keywords **– Scheduling, medical personnel, linear programming, COVID-19 pandemic.**

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1. Introduction

Throughout the history of mankind there have been many pandemics that were overcome with difficulties.

The last one that affected the whole world was the pandemic of the COVID-19 virus. North Macedonia was no exception. On the contrary, the pandemic was gaining momentum in this country as well. This brought many problems, difficulties, and changes in all professions, but most of all in the healthcare system. Healthcare workers were most exposed to infection, overburdened, exhausted both mentally and physically, most criticized. The pandemic amplified the need for additional engagements of doctors and nurses and the urgent need for new employments as well. The frequent changes in the number of hospitalized patients resulted with changes in the distribution of the medical staff, reorganization of those dealing with sick patients and, consequently, the reorganization of those dealing the rest of the patients, creation of new schedules of the shifts, etc.

In order to detect the issues that affect the healthcare workers, especially the nurses, the authors have conducted an integrative review of papers and studies published (in English) around the world that were available to them in 2020, following the outbreak of COVID-19 [1]. As expected, their results show that nurses faced problems that fall into two main categories. The first category included individual problems: depression, anxiety, high risks of injuries, fear for their own health, fear of transmitting the virus to their families and to the other patients, and exhaustion. The second category included the lack of personal protective equipment, medical supplies, and resources. Based on their findings, the authors emphasized that an appropriate disaster plan for pandemics must be created and that investing in nurses must be a priority since they make up the largest healthcare group.

In order to identify risk factors for the health impact associated with COVID-19, in [11] the authors conducted a scoping review of the literature available on PubMed and Google Scholar. Based on their findings, they emphasized that, in order to reduce the morbidity and mortality among healthcare workers, proper strategies for reduction of the chances of infections, schedules with shorter shift lengths, and mechanisms for mental health support must be developed and implemented during the epidemic or pandemic crises.

Several studies on staff scheduling have been established to cater scheduling problems during a pandemic outbreak. Considering the possibility for nurses to work overtime, in [10], the author proposed a scheduling method that will help medical facilities in dealing with the nurse scheduling problem by balancing the workload of each worker, so that the shifts' constraints and wards' constraints are satisfied. The focus in this paper is on the non-cyclical scheduling, which can be more suited when dealing with emergency scenarios where schedules might change very fast. In [14], the authors' study yield to an optimal solution that considerably improved the company's management of its human resources during emergency situations such as epidemic crises, at the lowest possible costs. A study with similar objectives is given in [9]. A summary of the latest studies that deal with various scheduling problems in the healthcare systems is given in [2].

The problem of allocation of medical personnel, especially the so called Nurses Scheduling Problem (NSP), has been investigated long before the COVID-19 outbreak. Literature on NSP is quite extensive. For comprehensive reviews on the literature on this subject prior to 2004 that provide in-depth studies on the NSP, we refer to [4] and [5]. Methods that have been used for NSP include various types of mathematical programming, constraint programming, hybrid methods, simulation, etc. In [12], the author describes a nurse scheduling system and states that the scheduling decision is a large multiple-choice programming problem. In [13], the authors reduced the complexity of constraints satisfaction problem (referred therein as constraint programming), through the merger of some of the constraints and the elimination of the interchangeable values, and in this way managed to reduce their domains. In order to maximize the fairness of the staff working schedule, along with the minimization of the number of nurses who handle the hospital needs at Coimbatore City Hospital, considering the number of nurses needed during equally distributed time periods covering 24 hours and eight consecutive working hours per shift, the Linear Programming (LP) model is used in [6] to solve the scheduling problem, thus demonstrating how a very simple LP method can be used to schedule nurses. In [7] a similar approach was used to solve the NSP when considering the number of nurses needed each day during a week. Another noteworthy study on NSP is the one made in [3] for a hospital in Egypt. Since the country had a problem of nurse deficiency, they adopt a nurse scheduling model by considering the government regulations and the demand for the hospital's services. The proposed solution was proven as a fair schedule system.

The scheduling of the available personal in order to minimize the number of personal, with or without additional minimization of the cost (or some other constraints upon the resources), is a problem in many other industries or companies that provide services. Perhaps the most illustrative examples are those concerning the scheduling of the drivers in the transportation companies. In many of the cases, the mathematical models can be simplified so that the functions used in the model are linear and a satisfactory solution to the problem is obtained via the LP method. An example for this is given in [8], were the authors used the Integer Programming (IP), a special case of LP method, and obtained a new optimal solution regarding the drivers' schedule and shifts that produced some amount of cost saving: the number of drivers was minimized and the cost that should be paid to the reserved drivers was reduced.

2. Methodology

The problem with the scheduling of medical staff, hotel staff, employees in kindergartens, nursing staff, etc., will always be present. It will appear whenever the company faces some crises or any situation which mandates major reorganization of the employees. In the healthcare systems around the world, the problem of scheduling medical personnel became especially popular with the emergence of the last global pandemic. For the purposes of this paper, an insight was made into the work diaries of the medical staff in a local hospital in North Macedonia in order to determine the time periods (covering 24 hours) when the average number of the nurse needed significantly variated between two consecutive time periods. Then, an analysis was made of the current legislation regarding the organization and duration of the shifts of already employed nurses. The coefficients for determining the payment points for day and night work have also been analyzed. Finally, based on the Linear Programming methods, a model was created for the number of shifts that would cover 24 working hours, with a minimum number of temporarily hired nurses per shift.

3. Problem Description

During the last pandemic, most hospitals had to make major changes in terms of reallocating of their medical staff and appropriate adjustments of their shifts. This led to a shortage of medical staff in hospital wards outside of the Covid-centers or modular hospitals. The most evident was the lack of nurses. Based on the data obtained from one of the local hospitals in North Macedonia, for the days during the pick weeks of COVID-19 pandemic we've determined the daily time periods (with equal duration), where the average number of additional nurses needed significantly changed between two consecutive time periods. The results are given in Table 1.

Table 1. Preliminary data

Average number of additional nurses needed per day for the critical days during the pandemic		
Time periods during 24 hours		Minimum number of nurses needed
T1:	7:00-10:00	48
T2:	10:00-13:00	21
T3:	13:00-16:00	45
T4:	16:00-19:00	15
T5:	19:00-22:00	30
T6:	22:00-1:00	13
T7:	1:00-4:00	15
T8:	4:00-7:00	10

The standard number of shifts for full time employed nurses in hospitals financed by the government in North Macedonia, are usually only two: the day shift, which starts at 7:00 and ends at 19:00, and the night shift, which starts at 19:00, and ends next morning at 7:00. In general, every nurse works two consecutive days (each day in a different shift) and then has two days off. Based on the current labor legislation in North Macedonia, as night work is considered the work done between 22:00 and 6:00 and the cost per hour during this period is 135% of the cost per hour for the work done during the hours between 6:00 and 22:00. Hence, the hospital's costs per additional nurse will be 100 NC per hour during the period from 6:00 to 22:00, and 135 NC per hour during the period from 22:00 to 6:00, where NC=N*MKD, for some N>0.

If the shifts for the additional nurses are the same as the shifts of the employed nurses, in order to meet the demands in Table 1, for the first shift we will simply take the maximum of the numbers in the right column corresponding to the first four daily periods in Table 1 (i.e., 48) and for the second shift we will take the maximum of the numbers in the right column corresponding to the last four daily periods (i.e., 30). Thus, we will obtain the following table for the hospital's daily costs.

Table 2. Hospital's daily costs before optimization

Hospital's costs for two shifts	Shift costs per nurse	Nurses per shift	Total daily costs per shift
Shift 1 (7:00-19:00)	1200 NC	48	57600 NC
Shift 2 (19:00-7:00)	1480 NC	30	44400 NC
Total		**78**	**102000 NC**
*NC=N*MKD*			

In this paper we will consider an alternative number of shifts, as well as the shifts' starts and duration, with the following objective: find the number of nurses per each shift so that the hospital's demands listed in Table 1 are satisfied and that the hospital's costs are as low as possible.

4. Four Shifts Model

In order to achieve the objective, instead of two shifts, we will consider four shifts such that:

- each shift covers nine consecutive hours and starts three hours before the previous shifts ends,
- the overlapping period of two consecutive shifts coincides with one of the time periods in Table 1.

Thus, we'll have one of the following two options.

Option 1: the overlapping periods of the shifts coincide with the time periods T1, T3, T5 and T7,

Option 2: the overlapping periods of the shifts coincide with the time periods T2, T4, T6 and T8.

For the first option, let Shift 1 denote the shift that starts at 7:00, and Shift 2, Shift 3 and Shift 4 denote the next shifts. Let $X1$, $X2$, $X3$ and $X4$ denote number of additional nurses in the corresponding shifts.

Based on Table 1 and the hospital's hourly costs per additional nurse during the period from 6:00 to 22:00, and from 22:00 to 6:00, for the shifts' coverage of the time periods in Table 1 and the daily costs per nurse in each shift, we obtain Table 3.

Table 3. Daily periods coverage and costs per nurse for Option 1

Time periods during 24 hours	Shift 1	Shift 2	Shift 3	Shift 4	Min. number of nurses needed
7:00-10:00	*X*1			*X*4	48
10:00-13:00	*X*1				21
13:00-16:00	*X*1	*X*2			45
16:00-19:00		*X*2			15
19:00-22:00		*X*2	*X*3		30
22:00-1:00			*X*3		13
1:00-4:00			*X*3	*X*4	15
4:00-7:00				*X*4	10
Daily costs per nurse in each shift	**900 NC**	**900 NC**	**1110 NC**	**1075 NC**	
*NC=N*MKD*					

Based on Table 3, the total daily hospital's costs will be:

$$Z = 900X1 + 900X2 + 1110X3 + 1075X4\,.$$

In order to find the number of additional nurses per each shift so that the minimum requirements listed in Table 1 are fully satisfied and that the daily costs of the hospital be as low as possible, based on Table 3 we have the following mathematical formulation of the problem in a form of a Linear Programming Problem (LPP), or more precisely, an Integer Programming Problem of minimization with *X*1, *X*2, *X*3 and *X*4 as decision variables:

Min $Z = 900X1 + 900X2 + 1110X3 + 1075X4$

s.t.

$$\begin{cases} X1 + X4 & \geq & 48 \\ X1 & \geq & 21 \\ X1 + X2 & \geq & 45 \\ X2 & \geq & 15 \\ X2 + X3 & \geq & 30 \\ X3 & \geq & 13 \\ X3 + X4 & \geq & 15 \\ X4 & \geq & 10 \end{cases} \quad (1)$$

For consider the second option, i.e., when the overlapping periods of the shifts coincide with the time periods T2, T4, T6, T8. Let Shift 1 denote the shift that starts at 10:00, and let Shift 2, Shift 3 and Shift 4 denote the next shifts. Once again, let *X*1, *X*2, *X*3 and *X*4 denote number of additional nurses in the corresponding shifts. Now, for the shifts' coverage of the time periods T1, T2, …, T8 and the daily costs per nurse in each shift, we obtain the following table.

Table 4. Daily periods coverage and costs per nurse for Option 2

Time periods during 24 hours	Shift 1	Shift 2	Shift 3	Shift 4	Min. number of nurses needed
7:00-10:00				*X*4	48
10:00-13:00	*X*1			*X*4	21
13:00-16:00	*X*1				45
16:00-19:00	*X*1	*X*2			15
19:00-22:00		*X*2			30
22:00-1:00		*X*2	*X*3		13
1:00-4:00			*X*3		15
4:00-7:00			*X*3	*X*4	10
Daily costs per nurse in each shift	**900 NC**	**1005 NC**	**1180 NC**	**970 NC**	
*NC=N*MKD*					

Based on Table 4, the total daily hospital's costs will be:

$$Z = 900X1 + 1005X2 + 1180X3 + 970X4,$$

and the corresponding mathematical formulation in a form of LPP is:

Min $Z = 900X1 + 1005X2 + 1180X3 + 970X4$

s.t.

$$\begin{cases} X4 & \geq & 48 \\ X1 + X4 & \geq & 21 \\ X1 & \geq & 45 \\ X1 + X2 & \geq & 15 \\ X2 & \geq & 30 \\ X2 + X3 & \geq & 13 \\ X3 & \geq & 15 \\ X3 + X4 & \geq & 10 \end{cases} \quad (2)$$

5. Results

Since the number of decision variables and the constrains is relatively small, in order to obtain the optimal solution of the above problems as fast as possible, we are going to use Classic LINDO (Linear Interactive and Discrete Optimizer) software which has a simple user interface and a quite simple input method. The input for the above problem is given in Figure 1.

```
Min 900X1+900X2+1110X3+1075X4
st
X1+X4>=48
X1>=21
X1+X2>=45
X2>=15
X2+X3>=30
X3>=13
X3+X4>=15
X4>=10
```

Figure 1. Classic LINDO input for LPP (1)

The output obtained by Classic LINDO is given in Figure 2.

```
LP OPTIMUM FOUND AT STEP      5

      OBJECTIVE FUNCTION VALUE

      1)      74680.00

 VARIABLE        VALUE          REDUCED COST
       X1        38.000000          0.000000
       X2        17.000000          0.000000
       X3        13.000000          0.000000
       X4        10.000000          0.000000

      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.000000       -900.000000
       3)        17.000000          0.000000
       4)        10.000000          0.000000
       5)         2.000000          0.000000
       6)         0.000000       -900.000000
       7)         0.000000       -210.000000
       8)         8.000000          0.000000
       9)         0.000000       -175.000000

NO. ITERATIONS=       5
```

Figure 2. Classic LINDO solution for LPP (1)

According to the results obtained by Classic LINDO, the minimal daily hospital's costs will be 74680 NC for $X1$=38, $X2$=17, $X3$=13, $X4$=10 (Table 5). In comparison with the costs listed in Table 2, this means that we have nearly 26.78% of costs reduction.

Table 5. Results after optimization for Option 1

Hospital's costs for Option 1	Shift costs per nurse	Nurses per shift	Total daily costs per shift
Shift 1 (7:00-16:00)	900 NC	38	34200 NC
Shift 2 (13:00-22:00)	900 NC	17	15300 NC
Shift 3 (19:00-4:00)	1110 NC	13	14040 NC
Shift 4 (1:00-10:00)	1075 NC	10	10750 NC
Total		**78**	**74680 NC**
*NC=N*MKD*			

Using the Classic LINDO again, for Option 2 we obtain that the daily hospital's costs will be 134910 NC and will be obtained if $X1$=45, $X2$=30, $X3$=15, $X4$=48 (Table 6).

Table 6. Results after optimization for Option 2

Hospital's costs for Option 2	Shift costs per nurse	Nurses per shift	Total daily costs per shift
Shift 1 (7:00-16:00)	900 NC	45	43200 NC
Shift 2 (13:00-22:00)	1005 NC	30	30150 NC
Shift 3 (19:00-4:00)	1180 NC	15	17700 NC
Shift 4 (1:00-10:00)	970 NC	48	43650 NC
Total		**138**	**134910 NC**
*NC=N*MKD*			

Clearly, for Option 2 we did not obtain the reduction of the cost. Instead, we've obtained an increase of nearly 32.26%. Hence, we need to reject this option.

6. Discussion

As Table 5 shows, the total number of additional nurses is still 78. This may not always be the case. To illustrate this, first note that the data in Table 2 will remain the same whenever we interchange any two values in the right column of Table 1 that correspond to the time periods T1, T2, T3 and T4, or any two values that correspond to the time periods T5, T6, T7 and T8. But this will not be the case with Table 5. For example, if we interchange the demands for the time periods T2 and T3, then the total daily hospital's costs will drop from 102000 NC to 80980 NC, while the total number of nurses will increase to 85 (in this case the optimal solution is obtained for $X1$=45, $X2$=17, $X3$=13 and $X4$=10). On the other hand, if we interchange the demands for the time periods T1 and T3, then the total daily hospital's costs will drop from 102000 NC to 71980 NC, and the total number of nurses will drop from 78 to 75 (in this case the optimal solution is obtained for $X1$=35, $X2$=17, $X3$=13 and $X4$=10).

The same optimal solution, as well as the same total daily costs, will be obtained with the MS Excel's Solver and the Solver in OpenOffice Calc (or LibreOffice Calc). We must point out that, sometimes, depending on the given LP problem, the solution obtained OpenOffice Calc (or LibreOffice Calc) may be different form the one obtained with MS Excel. For the users unfamiliar with the usage of the MS Excel's Solver or the Solver in OpenOffice (LibreOffice) Calc, we recommend using Classic LINDO, or some other application for solving LP problems.

Depending on the values in the right column of Table 1, Option 2 may yield to a better optimization. For example, if we interchange the values for the time periods T1 and T2, and for the time periods T3 and T4 as well, then the optimal solution for Option 1 will be X1=48, X2=45, X3=13, X4=10 and the total hospital's costs will be 108880 NC. Clearly this option does not provide reduction of the costs. On the other hand, for Option 2, the optimal solution will be X1=27, X2=30, X3=15, X4=21 and the total hospital's costs will be 92520 NC, which yields to the reduction of the daily hospital's costs.

7. Conclusion

The four shifts model will enable the hospital's management to determent the number of additional nurses so that certain minimal demands are meet at the lowest possible costs, and to create an appropriate schedule of the shifts. Due to relatively small number of constrains (only eight) and decision variables (only four), both LPP (1) and LPP (2) can be easily solved with Classic LINDO, MS Excel (or OpenOffice Calc, LibreOffice Calc), or some similar application.

The four shifts model can be successfully used in similar situations in other organizations or companies that employ a fixed number of workers and that, during long enough periods, need to employ additional number of workers so that the demands for company's services are successfully meet and, at the same time, to minimize the company's total costs for the payment of the additional workers.

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