Using Mathematical Modeling to Improve the Emergency Department Nurse-Scheduling Process

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CE Earn Up to 7.5 Hours. See page 474.

Contribution to Emergency Nursing Practice

- The purpose of this practice improvement project was to improve the ED nurse self-scheduling process.
- The primary outcomes of this practice improvement project were improved nurse-staffing levels, decreased time to reconcile the monthly nurse schedule, and the potential to increase nurse satisfaction.
- A key implication for emergency nursing practice based on this project is that the self-scheduling process can use mathematical modeling to create a daily schedule that meets required nurse-staffing levels and takes nurse preferences into account.

Abstract

Introduction: Nurse scheduling within an emergency department can be a very time-consuming process as nursing leadership works to reach sufficient nurse-staffing levels across every day of the schedule while also working to satisfy nurse preferences.

Methods: A mathematical model is formulated to determine nursing shifts to minimize the number of shifts across a day while accounting for staffing level requirements, nurse preferences, and meal breaks.

Results: A daily schedule based on nursing shifts was created and used within the self-scheduling process. Implementing the schedule improved nurse-staffing levels while decreasing the time necessary to reconcile the monthly schedule, resulting in the potential to increase nurse satisfaction.

Discussion: The emergency department can use mathematical modeling to improve the nurse-scheduling process.

Key words: Emergency department nurse scheduling; Nurse self-scheduling; Mathematical modeling

In emergency departments, nurses are a vital resource in treating patients; therefore, it is important that nurses are scheduled in a manner that provides a sufficient number of nurses during critical times of the day. The emergency department is uniquely different from other areas of the hospital in that the number of patients visiting emergency departments varies every day and across the day. There is no limit on the number of patients that can visit emergency departments, and each patient requires a different level of care. This creates complications for nurse scheduling, particularly as nurses typically work 8- or 12-hour shifts, and the number of nurses needed at each time of day may not easily align with the necessary set of 8- and 12-hour shifts.

In this article, we examine the scheduling process that was used at our partner hospital, UPMC's Children's Hospital of Pittsburgh (CHP), to improve nurse scheduling in an effort to improve service in the emergency department. Based on the scheduling problems in the current process, we determined a set of daily shifts that can be used to create a standard daily schedule. We formulated a mathematical model that minimized the number of shifts required to

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TABLE 1
Literature review summary

Operations research literature		Nursing literature	
Topic	**Papers**	**Topic**	**Papers**
Daily nurse scheduling	2, 3	Staffing levels	10, 11
Nurse staffing levels	4, 5, 6, 7	Self-scheduling	12, 13, 14, 15
Monthly schedule	8, 9		

reach the target nurse-staffing level at each hour. Two key aspects captured by our model include the consideration of the length of nursing shifts and meal coverage. Our results demonstrate the benefits CHP has experienced with the implementation of the new scheduling process.

Literature Review

Nurse scheduling is a widely studied topic in the operations research and nursing literature, particularly in the inpatient unit setting. These studies adjust nursing schedules to increase staff participation and include preferences as a motivator to boost morale and reduce nurse call-offs. Despite the work done in the academic setting, it is rarely applied in practice, with only 30% of systems discussed in research articles actually implemented.[1] Table 1 summarizes the different topics and fields studied in ED nursing literature.

In the operations research field, most of the nurse-staffing literature comprises a number of different optimization strategies to solve the nurse-staffing problem. Simulation was used to compare different nursing schedules and analyze which was best for patient care.[2] Goal programming was used to consider multiple goals—including a nurse-to-physician ratio—to determine the weekly 8-hour shifts while accounting for over- and understaffing.[3] In addition, multiple papers have tackled the problem by determining staffing levels and then the aligning shift schedules.[4-7] In addition to shift schedules, mathematical models were used to create monthly schedules that take into account both ED staffing requirements, legal regulations, and nurse preferences to improve nurse satisfaction while significantly decreasing the amount of time required to compile a monthly schedule.[8,9]

The nursing literature presents successful scheduling processes that have been implemented in emergency departments. A common theme within the nursing literature is the idea of self-scheduling, in which nurses select their work schedule by signing up for specific shifts available throughout the day. A study exploring work-life balance for shift workers showed improved work-life balance when self-scheduling was an option for workers.[10] The Bureau of Labor Statistics expects a nursing shortage as growth in the sector increases and nurses decrease. Many solutions to the nursing shortage have been discussed, including improving staffing by accounting for the patient workload instead of staffing based on overall volume.[11] This is difficult, as emergency departments across the United States vary in size and staffing profiles, which affects how they employ nurse scheduling within their units. A benefit reiterated in every scenario is that nurses learn to work together to schedule as a group. However, in multiple hospitals, they found that overstaffing can result from the 8- and 12-hour shifts nurses decide to work, or sometimes there can be 4-hour holes that are difficult to fill.[12] Another method used a patient-to-nurse ratio to have scheduling patterns reflect the expected patient census pattern.[13] In line with self-scheduling, "shared scheduling" requires all the nurses in the emergency department to work together to complete the schedule. They found that nurses preferred the flexibility and control over the schedule, which led to improved morale and less staff turnover.[14] The idea of self-scheduling was also employed at Novant Health, where they used Microsoft Excel (Microsoft Corporation, Redmond, WA) to help guide the idea of self-scheduling by coding the schedule into Excel and having staff sign up in the Excel model based on commonly filled 8- and 12-hour shifts.[15]

Most of the previous mathematical models have determined specific shifts by considering over- and understaffing or have created monthly schedules with nurse preferences. In the nurse-staffing literature, most of the systems use self-scheduling methods, which allow nurses to sign up for any shift while the department attempts to schedule enough nurses to meet the staffing levels set by nursing management. In this paper, we use operations research to develop a method for self-scheduling, which has reduced the total time necessary to reconcile the final monthly schedule while ensuring that the emergency department has adequate staffing at all times.

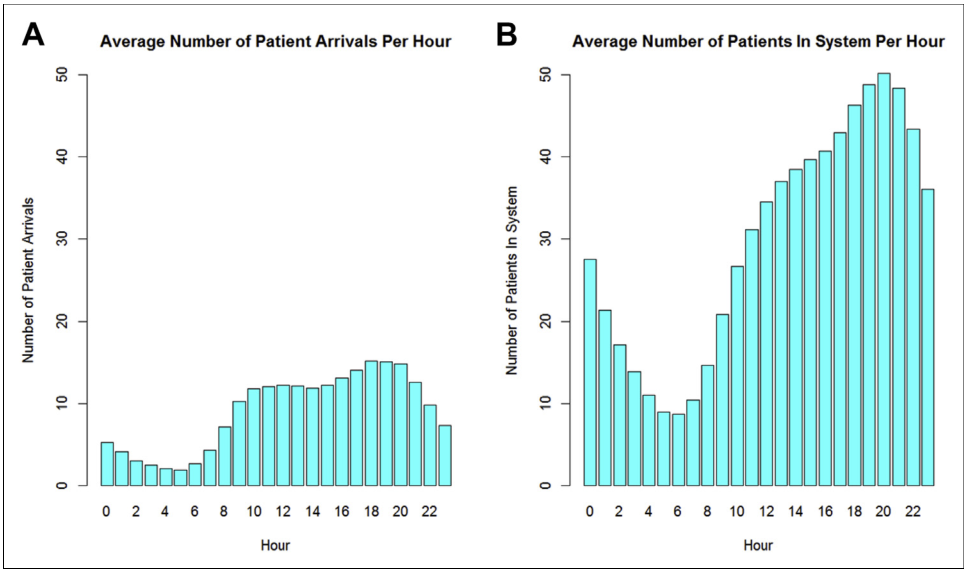

FIGURE 1
Average emergency department (A) patient arrivals and (B) number of patients by hour.

Background

CHP is a Magnet-recognized tertiary-care facility with a level-1 trauma program and has made the list of US News and World Report Honor Roll of America's Best Children's Hospitals. The emergency department treats approximately 80,000 patients annually. The average patient arrivals and average number of patients at each hour of the day are given in Figure 1A and B, respectively.

The patient arrival pattern can be seen in Figure 1A. We see that there are very few patients arriving to the emergency department between the hours of 1 AM and 6 AM. However, the number of patient arrivals increases from 7AM until approximately 8 PM, with the highest number of patients arriving typically around 6 PM to 8 PM. In comparison, Figure 1B shows the number of patients in the system at every hour of the day. Although we see similar patterns between the two, the average number of patients in the system is much higher than the average number of patients arriving to the system. In particular, we see large increases in the number of patients in the system starting at 8 AM, and the number of patients continues to increase until approximately 9 PM, after which the number in the system begins to decrease.

Based on patient arrivals, volume, and the number of nursing hours available each week, the nursing leadership identified nurse-staffing targets for the number of nurses they would like in the emergency department at each hour of the day. The number of nurses was based on the sections of the emergency department that were open, the nurse-to-room ratio for each section, and the additional positions—such as rapid triage, full triage, and sedation—that were staffed at each time. The staffing targets, given in Table 2, were assigned in 4-hour increments beginning at 7 AM and increasing through the day. The maximum number of nurses staffing the emergency department occurs from 3 PM to 11 PM, when the maximum number of patients are in the system.

Although the administration was able to identify the ideal number of nurses that should be staffing the emergency department, there were no predetermined shifts within the daily staffing schedule. Instead, the process used a grid of 4-hour blocks, and nurses would self-select their shifts by signing up for 2 or 3 4-hour blocks to create an 8- or 12-hour shift. An example of the grid can be seen in Figure 2.

As shown in Figure 2, Nurse A signs up for a 12-hour shift from 7 AM to 7 PM. After the grid is completely filled, the 2 nurses that comprise the scheduling team meet to finalize the schedule. This can be a tedious process, as they may have to search through the schedule to determine if a nurse is working an 8- or 12-hour shift. For instance, the highlighted nurses in orange, red, and yellow are scattered throughout the sign-up sheet. In addition, in this schedule, there are 8 4-hour blocks, indicated with bold outlines, that no one has selected. If Nurse Y decides to work a 3-PM to 11-PM shift, we see that there is an isolated block, denoted in pink, at 11 AM. This 4-hour block is an undesirable shift,

TABLE 2

Nurse staffing targets by time of day

Time	11p – 3a	3a – 7a	7a – 11a	11a – 3p	3p – 7p	7p – 11p	11p – 12a
Nurse staffing target	15	8	8	15	19	19	15

so the scheduling group will either try to move Nurse Y's time to 11 AM to 11 PM, add another nurse from 11 AM to 11 PM, or leave the spot unstaffed. In the first scenario, if Nurse Y moves, they can make the remaining blocks into 1 12-hour block and 1 8-hour block and reach their ideal staffing. In the second scenario, the emergency department will be overstaffed from 3 PM to 3 AM. Although overstaffing is not a problem for the day it occurs, it could lead to understaffing on other days of the week. Finally, in the last scenario, the emergency department is understaffed from 11 AM to 3 PM, when we typically see a rapid increase in the number of patients arriving to the emergency department.

One way to prevent overstaffing and understaffing problems is to have a set of 8- and 12-hour shifts that allow the emergency department to meet their target nurse staffing, as demonstrated in Figure 3. Figure 3 organizes Figure 2 into a set of 8- and 12-hour shifts that gives us the correct number of nurses at every hour to meet our staffing targets. Ideally, the schedule in Figure 3 could be used each day, and nurses would sign up for 8- or 12-hour shifts. Use of a daily schedule, as in this example, would reduce the number of shifts that the scheduling team must adjust to get full coverage throughout the day and eliminate instances of overstaffing and understaffing that can occur as a result of using the 4-hour grid in Figure 2.

7 am	11 am	3 pm	7 pm	11 pm	3 am
Nurse A	Nurse A	Nurse A	Nurse G	Nurse L	Nurse L
Nurse B	Nurse B	Nurse B	Nurse H	Nurse M	Nurse M
Nurse C	Nurse C	Nurse C	Nurse I	Nurse N	Nurse N
Nurse D	Nurse D	Nurse D	Nurse K	Nurse O	Nurse O
Nurse E	Nurse E	Nurse E	Nurse L	Nurse P	Nurse P
Nurse F	Nurse F	Nurse F	Nurse M	Nurse Q	Nurse X
Nurse J	Nurse G	Nurse G	Nurse N	Nurse R	
	Nurse H	Nurse H	Nurse O	Nurse S	
	Nurse I	Nurse I	Nurse P	Nurse T	
	Nurse J	Nurse K	Nurse Q	Nurse U	
	Nurse K	Nurse Q	Nurse R	Nurse V	
	Nurse W	Nurse R	Nurse S	Nurse X	
		Nurse S	Nurse T	Nurse Y	
		Nurse T	Nurse U		
		Nurse U	Nurse V		
		Nurse V	Nurse Y		
		Nurse W			
		Nurse Y			

FIGURE 2

Example of former scheduling process.

Some key features regarding the current process include the following:

- Every nurse signs up for his or her own shifts, so they set their schedule.
- Every nurse works a combination of 8- and 12-hour shifts a week based on his or her contract.
- The day begins and ends at 7 AM, so no shift spans 7 AM.

We preserved these features when we created the daily schedule.

Methods

Using mathematical modeling, we solved the problems that resulted from scheduling with the 4-hour grid by creating a schedule, which can be used every day, consisting of 8- and 12-hour blocks. Within this model, we considered meal breaks as well as the types of nursing shifts available and nurse preferences. We defined the following variables:

- x_j: The number of 12-hour shifts beginning at block j
- y_j: The number of 8-hour shifts beginning at block j

We assumed that all nurses working 12-hour shifts take their half-hour meal breaks during the middle 4-hour block of their shifts and that all nurses working 8-hour shifts take their meal breaks during the second block of their shifts, except any 8-hour nurses who work at 11 PM, who take their meals during the first block of their shifts.

7 am	11 am	3 pm	7 pm	11 pm	3 am
Nurse A	Nurse A	Nurse A			
Nurse B	Nurse B	Nurse B			
Nurse C	Nurse C	Nurse C			
Nurse D	Nurse D	Nurse D			
Nurse E	Nurse E	Nurse E			
Nurse F	Nurse F	Nurse F			
Nurse J	Nurse J				
	Nurse G	Nurse G	Nurse G		
	Nurse H	Nurse H	Nurse H		
	Nurse I	Nurse I	Nurse I		
	Nurse K	Nurse K	Nurse K		
	Nurse W	Nurse W			
		Nurse Q	Nurse Q	Nurse Q	
		Nurse R	Nurse R	Nurse R	
		Nurse S	Nurse S	Nurse S	
		Nurse T	Nurse T	Nurse T	
		Nurse U	Nurse U	Nurse U	
		Nurse V	Nurse V	Nurse V	
			Nurse L	Nurse L	Nurse L
			Nurse M	Nurse M	Nurse M
			Nurse N	Nurse N	Nurse N
			Nurse O	Nurse O	Nurse O
			Nurse P	Nurse P	Nurse P
				Nurse X	Nurse X

FIGURE 3
Schedule in Figure 2 with a set of 8- and 12-hour shifts.

Using these variables, we created the following linear program:

$$Minimize \sum_{j=1}^{4} x_j + \sum_{j=1}^{5} y_j \qquad (1)$$

$$Subject\ To\ x_1 + y_1 \geq 8 \qquad (2)$$

$$\frac{7}{8}x_1 + \frac{7}{8}y_1 + x_2 + y_2 \geq 15 \qquad (3)$$

$$x_1 + \frac{7}{8}x_2 + \frac{7}{8}y_2 + x_3 + y_3 \geq 19 \qquad (4)$$

$$x_2 + \frac{7}{8}x_3 + \frac{7}{8}y_3 + x_4 + y_4 \geq 19 \qquad (5)$$

$$x_3 + \frac{7}{8}x_4 + \frac{7}{8}y_4 + \frac{7}{8}y_5 \geq 15 \qquad (6)$$

$$x_4 + y_5 \geq 8 \qquad (7)$$

$$\sum_{j=1}^{4} x_j \geq 0.80 \left(\sum_{j=1}^{4} x_j + \sum_{j=1}^{5} y_j \right) \qquad (8)$$

In this linear program the objective function (1) minimized the total number of shifts needed to reach the target nurse staffing levels. Equations (2-7) ensured that the number of nurses available at each block is at least the target nurse staffing levels. As the nurse meal break is one-half hour of a 4-hour block, we assumed that a nurse works $\frac{7}{8}$ of the block that included their meal break. We ensured that we had the appropriate balance of 8- and 12-hour shifts in equation (8). Note that the target value for this balance is determined by the nursing contracts, which state how many 8- and 12-hour shifts a nurse is expected to work each week.

In addition to these constraints, we included constraints to accommodate nursing preferences for the 8-hour shifts. For instance, if a nurse works 5 8-hour shifts each week and prefers working from 11 PM to 7 AM, we accommodated this nurse by requiring at least 1 8-hour shift at night. Based on our work force, we needed 2 8-hour shifts from 7 AM to 3 PM and 1 from 11 AM to 7 PM, 7 PM to 3 AM, and 11 PM to 7 AM. So the model had the following constraints:

$$y_1 \geq 2 \qquad (9)$$

$$y_2 \geq 1 \qquad (10)$$

$$y_4 \geq 1 \qquad (11)$$

$$y_5 \geq 1 \qquad (12)$$

Results

When we solved the linear program given in equations (1) to (12), we generated multiple solutions. The one that aligned best with the nurses for CHP is listed in Table 3.

This solution required 28 additional nursing hours compared with the current schedule to cover meal breaks and meet the nurse-staffing targets. This breaks down to 16 hours to cover meal breaks and an additional 12 hours, which supplements the staffing requirements. Table 4 compares the number of hours between the nurse-staffing targets set by management and the nurse-staffing levels throughout the day resulting from the optimal solution. Note that we have modeled the problem to account for meal breaks, so the nurse-staffing levels are adjusted so that nurses who are taking a meal break account for $\frac{7}{8}$ nurses during the meal-break period. The majority of additional nursing resources are allotted during 3 PM and 11 PM, when we have the highest number of patients in the emergency department. In addition to adding nursing coverage, these nurses help increase the throughput of patients in the emergency department when they are not required to cover meal breaks.

From the optimal solution, we generated the daily schedule depicted in Figure 4. Note that there are 6 blocks from 7 AM to 7 PM, which corresponds to 6 12-hour shifts beginning at block 1 (7 AM) and 2 blocks from 7 AM to 3 PM, which correspond to 2 8-hour shifts. In each shift, there is one block, which is highlighted in orange, indicating when the nurse should take his or her meal break to have full coverage.

TABLE 3
Optimal solution to the linear program

Optimal Solution	
$x_1=6$	$y_1=2$
$x_2=7$	$y_2=1$
$x_3=7$	$y_3=0$
$x_4=7$	$y_4=1$
	$y_5=1$

TABLE 4
Comparison of nurse staffing targets and staffing levels from the optimal solution

Time	7a – 11a	11a – 3p	3p – 7p	7p – 11p	11p – 3a	3a – 7a
Nurse staffing target	8	15	19	19	15	8
Nurse staffing levels	8	15	20.125	21	15	8

In comparison to the original sign-up method, the daily schedule improves the scheduling process. First, nurses have fewer options to consider when they are signing up for shifts. When there are empty shifts, nurses can sign up for overtime and work a full 8- or 12-hour shift compared with the original schedule, in which they needed nurses to work overtime for only 4 hours. Because there are no 4-hour blocks, the scheduling team does not need to change the shifts nurses originally signed up for to ensure coverage. In addition, because there are no 4-hour blocks, understaffing cannot occur at only 1 time slot unless an entire shift is not covered. Because the shift is either an 8- or 12-hour shift, it is more desirable as an overtime shift.

Discussion

The increased nurse coverage resulting from the new schedule has the potential to increase nurse satisfaction. Under the new schedule, nurses are guaranteed to work the shift that they signed up for on the original schedule. Furthermore, understaffing happens less frequently, so the number of nurses in the emergency department is more reliable. With the new schedule, there are enough nurses in the emergency department so that each nurse can have a fully covered meal break without increasing his or her patient load to cover fellow nurses during their meal breaks.

The new schedule is also beneficial to the scheduling team, as the scheduling team found a significant decrease in the total time to reconcile the schedule. Under the original process, reconciling the schedule occurred over a 2-week period and required 40 hours total, or 20 hours per nurse. When the new daily scheduling method was implemented, the nurses were able to reconcile the schedule during a single week, requiring approximately 18 hours, total.

Despite the advantages, there are disadvantages and limitations of the model. In this instance, the model determined a schedule that aligned with the staffing at CHP but required 12 additional nursing hours each day. Although we demonstrated that these 12 additional hours occur during the busiest time of day—improving the staffing levels—the additional annual cost is significant. In addition, the model requires the user to input previously determined staffing levels. Although the model can determine the best schedule for a given user's input, if the staffing levels are not appropriate (for example, far too low for the demand), the model is limited in its capability to improve nurse staffing. Finally, the model requires nurses to be able to make changes to the model and solve it whenever they adjust staffing requirements.

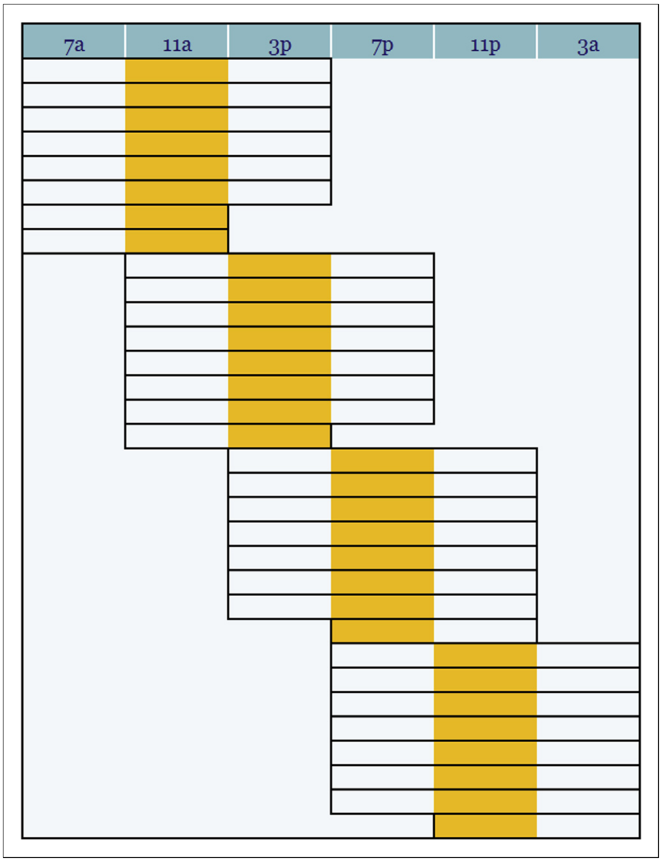

FIGURE 4
Schedule grid that results from solving the linear program.

Conclusion

In this paper, we demonstrated how mathematical modeling can be combined with self-scheduling to result in an implementable schedule within an emergency department. A unique aspect of our model is that our staffing results in each nurse having time for a fully covered meal break while the department will still maintain its target staffing levels. Through using this staffing approach, the emergency department we worked with improved its nurse staffing, increased staff morale, and reduced the total time necessary to complete the monthly schedule. Although the model has limitations, it is applicable to a wide variety of hospitals and shift work settings that use self-scheduling to complete schedules.

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