A Flexible Nurse Scheduling Support System

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ABSTRACT

Scheduling nursing personnel in hospitals is very complex because of the variety of conflicting interests and objectives. Also, demand varies 24-hour a day 7-day a week, is skill specific and hard to forecast. In the face of this complexity, the present nurse scheduling models have met with little success. In this paper, we propose a more flexible decision support system that will satisfy the interests of both hospitals and nurses through alternative models that attempt to accommodate flexible work patterns as it integrates time of the day (TOD) and day of the week (DOW) scheduling problems.

KEY WORDS: Decision support systems (DSS), flexible scheduling, goal programming.

1. INTRODUCTION

The scheduling of nursing services in urban hospitals is relatively complex. There are different levels of skill in the nursing pool. The work preferences differ considerably between individuals. Demand for nursing services can vary widely and is often skill specific and hard to forecast. The demand for nursing services covers 7 days a week and 24 hours a day while nurses with families would prefer the traditional 8 to 5 weekday patterns. In the face of this complexity, nurse scheduling models have met with little success. In this paper, we propose a more flexible decision support system that considers many more of the problems and complexities and allows for the searching of alternative solution spaces.

The proposed system includes a component that allows for the specification of a wide variety of schedule preferences. Another component uses linear goal programming to generate alternative base schedules. The base cases can then be modified via a solution modifier component. The generated schedules can be evaluated relatively to a variety of objectives. Finally the schedules can be assigned to individuals according to their preferences.

2. NURSE SCHEDULING ENVIRONMENT

Nursing talent exists at a variety of levels. Some individuals are trained to handle special needs such as intensive care and rehabilitation therapy. Depending on their training, individuals can function as registered nurses (RNs), licensed practical nurses (LPNs) or aides (AIDs). The labor pool typically consists of people who are assigned to specific units, those in a hospital pool and temporaries available through agencies.

In addition, the problem is complicated by the diversity of working preferences. At present, nursing skills are in short supply and retaining qualified people is important. Job satisfaction, turnover and absenteeism have all been related to personnel scheduling flexibility. Some individuals might prefer longer but fewer days while others might prefer shorter days but don't mind 6-day weeks. Some nurses would choose part time work if available. Some people, irrespective of shift, would like to start earlier while others would opt for a later start time. No fixed personnel scheduling policy can satisfy all interests and flexible alternatives are needed to increase satisfaction and retention.

Nonetheless, flexibility cannot compromise the demand for nursing services. Patient census is hard to forecast but can be somewhat controlled via elective admission policies. Short term adjustments are necessary but should be held to a minimum. The demand for care varies more on the day shift than on afternoon and midnight shifts. Weekend needs are frequently 20 to 30 percent lower than the average weekday demand. Addressing these variations in requirements with the traditional three fixed 8-hour shifts and 5-day work week results in significant imbalance between nursing supply and nursing demand which in turn, is a significant cause of job dissatisfaction.

In the past few years, nursing administrators have been exploring non-traditional scheduling patterns, to find new approaches to the challenge of adequate coverage. It is expected that flexible patterns allowing some degree of personal choice will improve job satisfaction and have a positive effect on staff retention and recruitment [9].

Reports in the literature of scheduling efforts that produce shortened work weeks have been generally positive. The most popular of these is the 10-hour day, 4-day work week (known as the 4/40 work week). For the U.S. hospitals in particular, 4/40 work week accounts for 83% of the alternative scheduling practices. The 12-hour day, combined with either the 4-day week or the 7-day on, 7-day off pattern, accounts for another 11%, and the combination of the 8-hour, 10-hour and 12-hour shifts accounts for the remainder of the programs [14,p.463].

One major disadvantage of these various alternative flexible scheduling patterns was the increased complexity of management control. As long as a nursing shortage exists, nursing administrators must either accept the added complexity of work schedules or find themselves paying more for nursing and accepting reduced quality of nursing care.

3. EXISTING SOLUTIONS TO THE PROBLEM

Much of the work relating to nurse scheduling has been concerned with cyclical scheduling, in which each nurse's work pattern is repeated in a cycle of n weeks. Cyclical schedules are easily generated but rigid in the face of variations in the demand. Howell [7] outlined the steps necessary to develop cyclical schedules and described procedures for their development. Maier-Rothe and Wolfe [8] presented a cyclic schedule that utilized favorable patterns regarding days off. Warner [18], Warner and Prawda [17], Miller et. al., [10] developed mathematical programming models of cyclic nurse scheduling. Warner's model minimized the negative feelings of the nurses toward their schedules [18]. Penalty costs for violating minimal RN, LPN, and total staffing levels were also included in the objective function. Warner and Prawda [17] developed a scheduling procedure where the objective was to minimize shortage cost of nursing personnel for only a 3-4 day scheduling horizon. The short scheduling horizon makes it difficult to include constraints on the individual nurses' preferences. Miller, et. al., [10] formulated the nurse scheduling problem that balances a trade-off between staffing coverage and individual schedule preferences. The problem was solved using the cyclic coordinate descent algorithm that seeks a near optimal solution.

Several researchers in the past decade have examined and developed computerized nurse scheduling systems. They are generally systems that select among the alternative cyclic patterns, or represent computerization of the traditional approach that satisfies only the nurses' preferences, or some inflexible models or heuristics which do not provide for user interaction.

Smith and Wiggins [15] developed an heuristic to generate monthly shift schedules. Their scheduling system covers several staff categories, considers individual preferences, and provides a convenient interface for the scheduling clerks who make final adjustments to the computer generated schedules. Although it produces suboptimal schedules substantial time reductions have been observed in scheduling with this computerized system. Finally, the model dictates that special requests must be satisfied before an attempt is made to meet the prescribed staffing requirements.

The nurse scheduling system described by Ahuja and Sheppard [1] combined the advantages of a cyclical approach with the speed and flexibility of a computer to aid the development of work schedules. The scheduling system consists of four basic components, which are: a work pattern selector, a schedule assembler, a schedule projector and a workload predictor.

The assignment of nurses to units is based on the predicted unit load index for each unit. The unit load index is calculated daily for each unit. Comparison of the staffing level available and the level required indicates whether an increase or decrease in staff must be made to meet the patient requirements.

Finlayson [6] described a computerized nursing management system developed by Medicus Corp. of Chicago for the Kingston General Hospital in Canada. One of its four major components is a nurse scheduling system.

The system generates cyclical schedules for different units and approximately forty hours of manual manipulation is required before the schedules are posted. Even though this system has proven to be manageable, the amount of manual manipulation is considered to be high.

Goal programming (GP) was first applied to nurse scheduling by Arthur [2,3]. He scheduled four RNs in one ward. The algorithm begins by assigning the weekend pattern for each nurse as dictated by the individual preference forms and the hospital policy on every other weekend off. Also, included at this time are mandatory constraints specifying that each nurse must work a total of five shifts per week. Then the algorithm begins to consider the goals according to their importance or priority. The constraints corresponding to each goal are generated and added to the problem, and the zero-one goal programming algorithm is used to solve the resulting problem. The algorithm initially determines the day on and off pattern for each nurse, then assigns the specific shifts for each day.

Recently, the zero-one GP heuristic procedure was used to schedule 11 nurses in one unit for the day shift by Musa and Saxena [11]. The schedule, for a two-week period was designed to satisfy the following goals set by the management:

1- All nursing staff members are scheduled for their contracted time.

2- A minimum number of nurses of each skill classification is needed.

3- A predetermined number of nurses is desired for patient care.

4- All full time nurses get at least one weekend off per cycle.

In the literature, the models presented for the nurse scheduling problem either ignore many constraints in the scheduling problem environment or use suboptimal heuristics. The mathematical models are too inflexible and user interaction is insufficient. Finally, there are no reported optimization models which integrate both the TOD and DOW problems and also accommodates flexible alternative shifts combination.

In spite of all the past efforts, 97% of hospitals in USA are still using traditional scheduling approach [14] which is done manually in a trial and error fashion. Such approaches are flexible but produces grossly suboptimal schedules.

4. PROPOSED SOLUTION TO THE PROBLEM

In the complicated problem of nurse scheduling where there are conflicting objectives between nurses and hospital, no single model will always be applicable. The detail of model's objective function and constraints can change dynamically even within the same unit. The solution space, therefore, should consist of various models with changeable coefficients each serving a different need. The choice of the right model and correct coefficients could be properly driven by an expert system front end. The needed expertize is that of an OR analyst selecting and parameterizing the proper model. Whenever the whole system is implemented this expert like capability would be at the user interface querying the user needs and driving the proper model combination in the nurse scheduling model complex.

Underlying the approach being developed here is an application of a GP version of the traditional "set covering" model. The flexibility of GP allows for a richer resolution to "what if" questions coupled to optimal solution seeking algorithms. An expert like capability is proposed to formulate linear or GP constraints with proper objective or achievement functions based on changing assumptions about the demand profile, hospital management's objectives and work preferences of the nurses. Finally, in a decision support system context, the system would be capable of changing assumptions, running alternative base case solutions, manually altering solutions and evaluating alternatives relative to conflicting objectives.

Thus, the application scenario would be as suggested in Figure 1 [13]. The nurse scheduler would establish a unit by unit demand profile forecast for a coming one or two week period. These forecasts would be aggregated into hospital wide demands for each of the several nursing categories (e.g., pediatric nurses, special care nurses, hospital pool nurses). These forecasts would be used to schedule nurses in each unit. Based on each unit's need, pool nurses would be assigned shifts using the extension of the Assignment Model developed in [13]. The work preferences of the nursing staff would be polled to incorporate any changes that may have occurred. Work preferences would be stated as a set of acceptable shifts and/or work patterns with desirability indices.

The demand profile and work preferences data would be fed into a computerized expert like system designed to for-

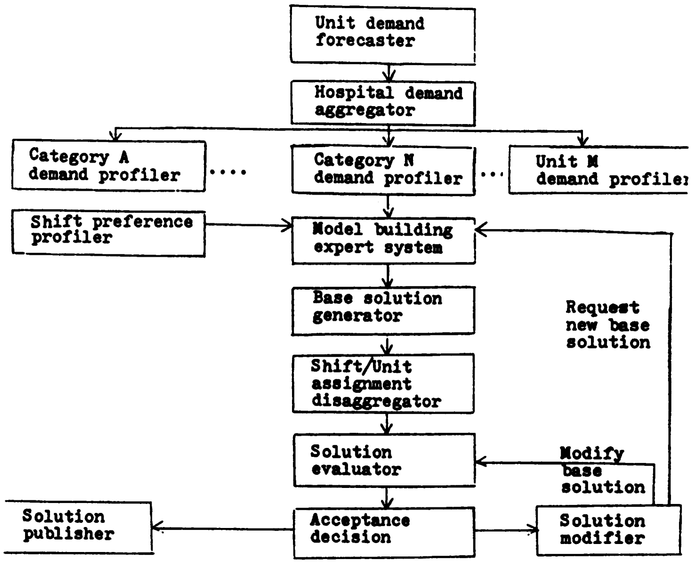

Figure 1. Nurse scheduling solution scenario

mulate alternative models. The solutions to the linear and/or the goal programmed models with various goal priority options form the base case schedules from which the nurse scheduler would work. Each solution would be disaggregated into specific schedules (or assignments) for specific units and nurses. The utility of these solutions would be viewed from the perspective of coverage, shift desirability and cost. Unacceptable coverage conditions and assignments would be located and changes made to reduce these problems.

The impact of these changes would be evaluated, in terms of coverage, shift desirability, and cost. Satisfactory solutions would then be automatically published. An expert like capability can also be used to evaluate the base case solutions so that unacceptable schedules can be identified.

4.1. Architecture of the Nurse Scheduling Decision Support System

The architecture of the DSS for nurse scheduling support system is shown in Figure 2 [13]. Following the bridge architecture suggested by Sprague and Carlson [16], the system consists of nine subsystems connecting a database with seven user interfaces. In reality, the five components at the bottom of Figure 2 are used by the nurse scheduler to set up the model and iteratively examine and modify the solution.

The patient admission interface would be another, hopefully existing, automated system. The remote nursing station interface would function through the existing unit data entry terminals. This system has not been developed in detail. The emphasis of the reported study is on the development of the models of the nurse scheduling model base complex and the aggregation/disaggregation subsystem.

5. UNDERLYING MATHEMATICAL MODELS

There exists three major models and their extensions all of which satisfy both hospitals', nurses' objectives and eliminate factors that nurses' dislike in scheduling that were identified at several hospitals in Phoenix, Arizona [13]. These models were programmed and their validity was tested by use of the manual scheduling data of the St. Luke's Medical Center in Phoenix, Arizona. There also exists an assignment model that can be used optionally after two of the models for assigning shifts to the individual nurses. In this paper, we will focus on only one of the various alternative optimization models of the nurse scheduling support system [13]. The complete formulation and testing this model is presented in [12,13].

Traditionally, the personnel scheduling research has either examined the TOD or DOW scheduling problems without considering their interactions.

For the more realistic limited staff size, the DOW/TOD problem integration was performed by Bailey [5]. Bailey's integration formulation is the following:

$$\textit{Minimize } Z = \sum_{j=1}^{J} C_j X_j + \sum_{i=1}^{7} \sum_{l=1}^{L_i} \alpha_{il} U_i$$

subject to

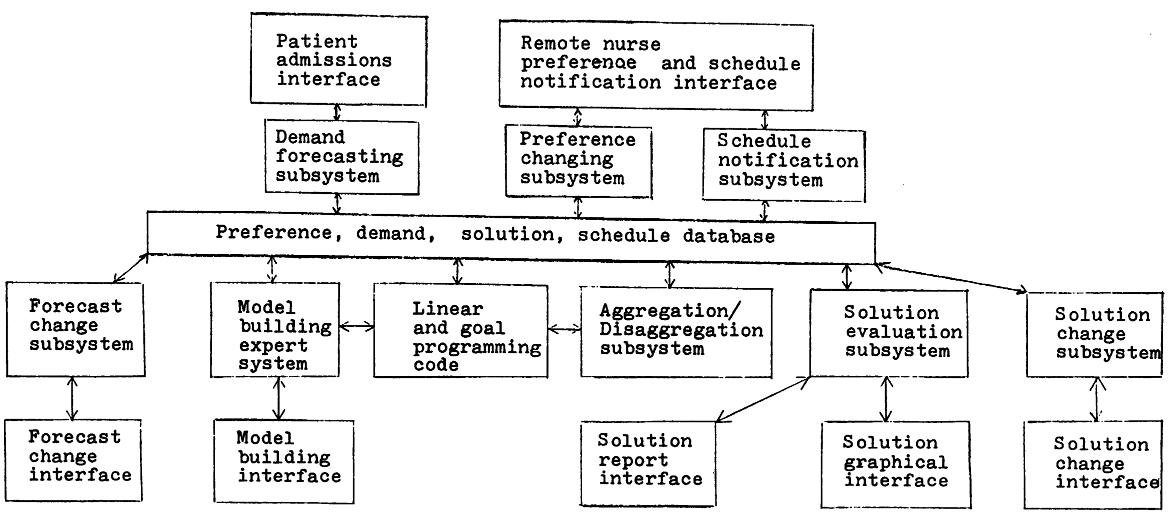

Figure 2. Architecture for nurse scheduling decision support system

$$\sum_{j=1}^{J} A_{ij} X_j - \sum_{k=1}^{K} X_{ik} = 0; \text{ for } i = 1,\ldots,7.$$

$$\sum_{k=1}^{K} A_{lk} X_{ik} - O_{il} + U_{il} = D_{il} \text{ for } l = 1,\ldots,L_i \text{ and } i = 1,\ldots,7.$$

$$\sum_{j=1}^{J} X_j = W_{total}$$

$X_{ik}, X_j \geq 0$ and integer

where

- A_{lk} = an $L_i \times K_i$ matrix where $a_{lk} = 1$ if pattern k is working during period l and $a_{lk} = 0$ otherwise
- D_{il} = demand for workers during period l on day i
- K_i = number of feasible patterns on day i
- L_i = number of periods to be scheduled on day i
- X_{ik} = number of workers scheduled to work shift pattern k on day i
- O_{il} = overstaffing surplus during period l of day i
- U_{il} = understaffing slack
- α_{il} = customer inconvenience cost per worker due to understaffing
- X_j = the number of workers working days off pattern j
- C_j = cost of one worker on pattern j
- A_{ij} = a $7 \times J$ matrix where $a_{ij} = 1$ if pattern j calls for working on day i and $a_{ij} = 0$ otherwise
- W_{total} = total size of the work force

The objective of the integrated problem is to minimize the weekly labor cost of the total workers plus the nurse frustration cost due to understaffing. The first constraint of the above formulation requires that the number of shifts X_j supplied by the days off (DOW) problem is equal to the number of shifts X_{ik} used in each of the shift scheduling (TOD) problems. The second constraint requires that the personnel needed during each period of each day is equal to the demand when over and understaffing are accounted for. The third constraint limits the shifts to the total available workers. For the 12-hour day, considering only 8-hour shift, the size of the A matrix is (92×210). This model can be extended to include the 24-hour day and alternative 4, 6, 8, 10 and 12-hour work days. However, the size of the matrix can be substantially reduced by breaking the day into two independent or three overlapping 12-hour periods. In the complex nurse scheduling environment, a goal programming (GP) version of this model can be applied to consider both overstaffing and understaffing. Because of the flexibility provided by GP, priorities of the goals can be changed depending on the scheduler's desire.

6. FORMULATION OF GOALS

As we shall see later, when the staff size is abundant, the GP approach allows us to relax the staff size constraint by assigning the lowest priority to the deviations from the limited staff size. The staff size is generally limited, therefore, let us first consider the integrated personnel scheduling model formulation given earlier. The following goal constraints can be written from this model.

Goal 1: Minimize deviations between the number of nurses scheduled during each period of a day and the demand. For a fixed staff size, this goal seeks schedules which maximizes coverage on an hour by hour basis. This reduces the understaffing and the cost of pool nurse or frustration due to over worked nurses.

$$\sum_{k=1}^{K_i} A_{lk} X_{ik} + d_{il}^- - d_{il}^+ = D_{il} \quad l = 1,\ldots,L_i$$

where

- i = Monday, Tuesday,...,Sunday
- d_{il}^- = amount of negative deviation from the goal for day i and period l
- d_{il}^+ = amount of positive deviation from the goal for day i and period l

If priority 1 (P_1) is assigned to Goal 1, then the objective function for this goal can be written as:

$$Minimize\ Z = P_1 \sum_{i=1}^{7} \sum_{l=1}^{L_i} (\alpha_l d_{il}^- + \beta_l d_{il}^+)$$

where

- α_l = cost per unit of negative deviation (understaffing)
- β_l = cost per unit of positive deviation (overstaffing)

And α_l and β_l can be estimated through sensitivity analysis as described by Baker [4]. Note also that α_l and β_l may not be included in the objective function. That is, if these unit costs are not included in the model, then the positive and negative deviations in staff size are minimized.

There are other ways of formulating this goal's objective function since there may be a period that the scheduler would like to minimize understaffing or overstaffing or both before the other periods (e.g., such as peak hours).

Goal 2: Minimize deviations between the sum of days on work patterns and the size of the work force. This goal insures that all staff are scheduled and allows for staff size sensitivity studies.

$$\sum_{j=1}^{J} X_j + d^- - d^+ = W_{total}$$

where d^- and d^+ are the negative and positive deviations from Goal 2 respectively. If the second priority (P_2) is given to Goal 2, then the objective function of this goal can be written as:

$$Minimize\ Z = P_2(d^- + d^+)$$

If the staff size is unlimited, then the lowest priority should be given to this goal. It may be desirable to break the total number of workers into part time and full time workers. If that is the case, the Goal 2 constraint takes the following form:

$$\sum_{j \in F} X_j + d_F^- - d_F^+ = W_F$$

$$\sum_{j \in P} X_j + d_P^- - d_P^+ = W_P$$

where

- d_F^- = negative deviation from the goal in the goal equation F
- d_F^+ = positive deviation from the goal in the goal equation F
- d_P^- = negative deviation from the goal in the goal equation P
- d_P^+ = positive deviation from the goal in the goal equation P

During vacation periods, it may be desirable to specify a smaller number of full time nurses as the essential work force while assigning as few part time nurses as possible to meet the demand. Depending on the hospital's need, it is possible to modify this goal's objective function.

Goal 3: Number of days on patterns X_j supplied by the DOW problem should be equal to the number of shifts X_{ik} used in each of the TOD problems. This goal seeks in the limited staff size situation to strike a set of work day patterns which minimizes the payroll costs of premium time.

$$\sum_{j=1}^{J} A_{ij} X_j - \sum_{k=1}^{K_i} X_{ik} + d_i^- - d_i^+ = 0; \quad i = 1,\dots,7$$

Note that this constraint ties the DOW and TOD problems together. If the third priority (P_3) is given to Goal 3, the objective function of this goal can be written as:

$$\textit{Minimize}\ Z = P_3 \sum_{i=1}^{7} (d_i^- + d_i^+)$$

Whether Goal 3 is attainable or not within the limits of the available resources, the optimization of the stated objective function will give the results which comes as close as possible to the indicated goal.

The flexibility of the GP allows us to accommodate variety of circumstances by minimizing the appropriate deviational variables and by changing the order of the priorities. This flexibility frees our models from the disadvantages of the previous nurse scheduling models. Also this flexibility is essential if the models are going to be applied in different hospitals. The achievement function can take many forms. Depending on the scheduler's desire and the system's requirements. Let us give some examples:

Alternative achievement functions can be written as:

$$\textit{Minimize}\ Z = P_1 \sum_{i=1}^{7} \sum_{l=1}^{L_i} (\alpha_l d_{il}^- + \beta_l d_{il}^+) + P_2(d^- + d^+) + P_3 \sum_{i=1}^{7} (d_i^- + d_i^+)$$

$$\textit{Minimize}\ Z = P_1(d_F^- + d_F^+) + P_2 \sum_{i=1}^{7} \sum_{l=1}^{L_i} (\alpha_l d_{il}^- + \beta_l d_{il}^+) + P_3 \sum_{i=1}^{7} (d_i^- + d_i^+) + P_4(d_P^- + d_P^+)$$

with respect to the goal constraints listed above.

The priorities of the goals with the first achievement function given above are the following. Note that this function would act to optimize its first priority goal then, without sacrificing that goal optimize the second priority goal, finally optimize the third priority goal. That is:

Priority 1: First minimize understaffing and overstaffing costs for all periods of each day of a week.

Priority 2: Then minimize deviations from the limited staff size.

Priority 3: Finally minimize payroll costs due to desire to reduce overstaffing and understaffing by selecting more costly work day patterns.

The priorities of the goals with the second achievement function are the following:

Priority 1: Maximize the utilization of the full time staff.

Priority 2: Then minimize understaffing and overstaffing costs for all periods of each day of a week.

Priority 3: Third minimize payroll costs.

Priority 4: Finally minimize the part time staff costs.

As pointed out earlier should the size of the integrated model makes the solution computationally difficult and impractical, a two-phase optimization can be used to decompose this large model. For scheduling nurses, the 24-hour day and a combination of variety of flexible shift lengths can be included in the model. Therefore, for scheduling nurses, the GP version of the integrated personnel scheduling model would likely be decomposed into the two-phase model and extended to accommodate the 24-hour day and a combination of various flexible shift lengths. In order to accomplish this, the following procedures are needed:

- formulate goal programming version of the DOW and TOD scheduling problems
- perform integration of the goal programming version of the DOW and TOD scheduling problems
- develop an heuristic to assign start times to the days of the optimum work patterns

These procedures were developed in [12,13] which also includes the formulation and testing this model.

7. CONCLUSION TO DATE

The nurse scheduling problem is too complex for the straight forward application of traditional operations research models. What is needed is a decision support system that manages the complex environment and allows for the efficient combination of model based and heuristic modified solutions. At the heart of one such model is a GP version of the set covering problem. Connected to this model is an expert system designed to reduce the large solution space by formulating constraints that reflect the dynamics of the environment. The developments of the other components of the nurse scheduling support system given in Figures 1 and 2 are the goals of the ongoing research.

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