THE IMPLEMENTATION OF NURSE SCHEDULING
USING MATHEMATICAL PROGRAMMING

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SECTION 1. INTRODUCTION

Anyone who has ever been associated with hospital management is aware of the problems surrounding scheduling days on and days off for nurses. On one hand, there must be enough nurses on duty in the appropriate nursing classes to meet the demands for their services on each shift of each day of each week. On the other hand, the schedules which the nurses finally receive must satisfy their preferences for rotation patterns, weekends off, long working stretches, etc.

In this paper, a Nurse Scheduling System (NSS) is described which is in operation at a number of hospitals in the United States and Canada. The system deals with hospital and nursing requirements for nurse schedules in a manner which trades off the seemingly conflicting desires of administrator and nurse and, in so doing, arrives at configurations of nurse schedules which are enthusiastically received by both hospital administrators and the individual nurses.

Section 3 is devoted to the process of implementation. Mention is made of the data requirements and various problems encountered. This section highlights what is perhaps the NSS' strongest point - its ability to be implemented at various sites with diverse characteristics. Section 4 contains results for six months for the Rush-Presbyterian-St. Luke Medical Center. The NSS was compared to the prior scheduling system and was found to be superior in virtually all categories. In Section 5 the scheduling rationale behind the nurse scheduling model is presented. The three primary modules, which sequentially address the scheduling problem, and the solution algorithm are discussed.

SECTION 2. REVIEW OF THE LITERATURE

A number of mathematical programming applications to nurse staffing have appeared in the literature beginning with Wolfe and Young [14, 15] who constructed mathematical models which minimized the cost of assigning nurses of various classes to do various tasks. Liebman [4, 5] also proceeded from a task orientation by assigning nursing tasks in a manner which maximized the effectiveness of nurses performing tasks on various patients. Warner and Prawda [11, 12] sought to minimize a "shortage cost" of nursing care services for a period of three to four days subject to total personnel capacity, integral assignment and other relevant constraints. Abernathy, Baloff, Hershey and Wandel [1, 2] considered three different decision levels impinging on the nurse staffing problem, and formulated an interactive model where the outputs of one level (e.g. staffing policies) are the inputs of another.

Much of the work relating to nurse scheduling has concerned cyclical scheduling (see Morrish and O'Conner [8], Price [9], Howell [3], and Maier-Rothe and Wolfe [6]), where each nurse works a cycle of n weeks, where n is the length of the scheduling period. Cyclical schedules are easily generated but are characterized by excessive rigidity vis-a-vis variations in the supply of and demand for nursing services. Two noncyclical scheduling papers of note have been by Rothstein [10] and Warner [13]. Rothstein's application was to hospital housekeeping operations. He sought to maximize the number of day off pairs (e.g. Monday-Tuesday) subject to constraints re-

quiring two days off each week and integral assignments. Warner presented a two phase algorithm to solve the nurse scheduling problem. Phase I is involved with finding a solution to various staffing constraints while Phase II seeks to improve the Phase I solution by maximizing individual preferences and a function of the surplus variables from the constraint set.

SECTION 3. THE IMPLEMENTATION PROCESS

At this point the hospital's top administrators have decided to install the computerized Nurse Scheduling System and now the implementation process begins. This process proceeds through a series of steps over several months. The initial step is to meet with the Director of Nursing to explain the system, gather data on hospital scheduling policies such as the number of weekends off-on, maximum and minimum stretches, beginning day and length of pay periods, schedule horizon (usually four or six weeks), rotation, use of part-time and/or float personnel, etc.

Next there is a group meeting with the head nurses to explain the operations of the system, what it can and cannot do for them, the types of reports and schedules they will receive, the time savings to them, the problems which it eliminates for them, and the need for timely data on special requests. Emphasis is placed on the importance of cooperation on both sides and that the computerized schedules do not take away any of the authority of the head nurse in approving special requests or changing the schedules to meet unanticipated needs. The computerized Nurse Scheduling System is a tool which removes some onerous tasks so that they may have more time for more important tasks related to health care delivery.

Following the group meeting, individual meetings are scheduled with each head nurse. The purposes of the individual meetings are to answer any system questions but more importantly to gather data needed by the NSS. This data consists of such items as who are the charge nurses, what groups and subgroups must be scheduled together, minimum and desired group and subgroup staffing levels, what specific scheduling problems are on the unit such as parallel people, part-time restrictions, rotation restrictions, fixed patterns, team vs. primary care groups, etc. Another important purpose of this meeting is to explain the limitations of the scheduler. For example, any group on a unit may specify which two days, Friday-Saturday or Saturday-Sunday, constitute a weekend; however, all of the nurses in that group must use the same definition for their weekend.

The next step is an orientation meeting with groups of nurses on the units. The main purpose here is to remove the fear of impersonalization by the computer and emphasize that the head nurse still controls the schedules and that the computer gives them fairer and more individualized schedules that meet their particular requests and preferences.

After the general orientation meetings each individual is interviewed (with more time devoted to nurses' aides, orderlies, and medical technicians) to obtain rankings of her (or his) preferences for weekends, stretches, split days off, etc. and to explain to her the interactions of such preferences on her schedules. They are also informed that all schedule changes or requests must be approved by the head nurse just as in the past.

Following each of the interviews, data are prepared and stored in the Master File of the NSS. After all of the above data have been stored, trial schedules are

run to adjust the various hospital and individual parameters. These trial schedules are reviewed by the respective head nurses to catch any items missed in prior interviews.

The Nurse Scheduling System now is in operating condition and periodic schedules are produced. Even in this production phase, however, the schedules are reviewed every time and adjustments are made for new hires, terminations, changes in workload requirements and/or nurse preferences, etc. On a continuing basis it usually requires the full-time work of one trained high school graduate, who works well with people and enjoys the challenge of producing the best schedule for each head nurse, to operate the NSS for a 40 unit hospital with 900 full and part-time nursing personnel. If the hospital is one-half this size, then only one-half the work is needed since the effort in running and maintaining the NSS is essentially linear with respect to the number of units and people being scheduled.

The savings in head nurse time alone has been pointed out in other studies but at a minimum it is one day per month per head nurse and usually two to four days per month. Of course, head nurse time is not the only advantage of the Nurse Scheduler. Other advantages are: fairer schedules which meet nurse preferences, more even staffing of units and a flexibility which allows the nursing administration to examine the effects of changes in policies prior to the implementation of such changes.

SECTION 4.   COMPARATIVE STATISTICS FOR NSS AT THE
RUSH-PRESBYTERIAN-ST. LUKE MEDICAL CENTER (RPSL)

RPSL is a 40 unit, 800 bed hospital with approximately 900 full and part-time nursing personnel. The hospital had collected historical data regarding nurse schedule preferences and minimum and desired staffing levels. This data was used in the application of the NSS. Because the NSS schedules and the hospital schedules were generated from the same base data, it was possible to compare the algorithm schedules and the hospital schedules.

NSS GENERATED SCHEDULES

Figure 1 presents some schedules generated by an early version of the NSS for four weeks of the six month trial period: October 22 to November 18. Note that on fourteen of the twenty-eight days the actual staffing levels were identical with the desired staffing levels. The unit is understaffed by one nurse on two days and overstaffed by one nurse on twelve days.

Table 1 presents data relating to what percent of the schedules in $\mathscr{A}_i$ have employee dissatisfaction costs greater than or equal to that of the chosen schedule.

Note that in all cases except one, the nurses were given a schedule better than 90% or more of those in the feasible pattern set. Moreover, we see that in most instances the number of schedules in the set of feasible patterns, i.e. $|\mathscr{A}_i|$, was well over 100 so there were many schedules to choose from.

We also note how the NSS schedules equitably over time. In all cases except one a nurse received the lowest cost schedule pattern in the feasible set during

Group 1

RN's	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S
1A	V	V	R	1	1	1	1	R	M	1	1	1	0	0	0	1	M	1	1	1	1	0	M	1	1	1	0	0
1B	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	M	1	1	0	0	0
1C	1	1	1	1	0	0	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0
1D	1	0	0	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	0	1	1	1
1E	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	0	B	0	1	1	1	0	0	1	1
1F	1	1	1	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	0	1	1	1	1
1G	V	V	1	1	1	0	0	1	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	1

Group 2

LPN

RN's	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S
2A	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	R	R	R	1	1	1	R	1	1
2B	1	1	0	B	1	1	1	1	0	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	0	0	0
2C	1	1	1	C	0	0	0	1	1	0	C	1	1	1	1	1	0	C	1	1	1	1	0	1	C	1	0	0
2D	0	1	1	1	1	1	1	V	V	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1
2E	0	1	1	1	1	0	0	1	1	1	0	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	1

	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S
Total Desired	9	9	9	9	9	5	6	9	9	9	8	8	6	5	9	9	9	9	9	5	6	9	9	9	8	8	7	6
Total Actual	8	9	9	9	9	6	6	9	9	10	9	8	6	6	9	10	10	10	9	5	5	10	10	10	9	8	7	7

Legend:

1 = Day Scheduled On   R = Requested Day Off

0 = Day Scheduled Off   B = Birthday Off

M = Day On For Meeting   C = Day On For Class

V = Vacation Day off

FIGURE 1

A FOUR WEEK SET OF NURSE SCHEDULES GENERATED BY THE SOLUTION ALGORITHM

Nurse	$\|\mathscr{S}_i\|$	Pay Period 1 Percentile	$\|\mathscr{S}_i\|$	Pay Period 2 Percentile
1A	15	100	167	92
1B	331	100	233	93
1C	331	100	370	94
1D	302	99	128	99
1E	331	93	166	100
1F	390	94	331	100
1G	156	100	349	100
2A	235	80	1	100
2B	202	100	331	95
2C	163	100	182	92
2D	52	98	331	100
2E	390	100	390	100

Legend:

$\|\mathscr{S}_i\|$ = Number of Schedules in Feasible Schedule Set of Nurse i.

Percentile = Percent of Schedules in Feasible Schedule Set With Employee Dissatisfaction Cost Greater Than or Equal to Schedule Selected by the Solution Algorithm.

TABLE 1

RANKING OF SCHEDULES CHOSEN BY SOLUTION ALGORITHM AS JUDGED BY EMPLOYEE DISSATISFACTION COST CRITERIA

one of the two pay periods, and in that one instance the nurse received a schedule in the 99th percentile in each of the two periods. The effect of the aversion index is evident when we note the general pattern of nurses who receive their best schedules during the first two weeks receiving a slightly worse schedule in the second two weeks and vice versa.

More extensive results will now be given for the entire six month scheduling test. Figure 2 presents a histogram of deviations from desired staffing levels.

On 90% of the days the deviation from the desired staffing level was either 0 or ± 1. Moreover we do not include measures of under or overstaffing on the units in question. Hence if a unit was understaffed for a pay period we would expect a number of negative deviations. Similar results would hold for overstaffed units. In light of this we see how well the NSS works in meeting staffing criteria.

In Figure 3 a histogram presents data taken over the six months relating to what percentile of a nurse's feasible schedule pattern set the schedule pattern chosen fell in (where percentile is defined as in Table 1 and where $\mathscr{A}_i$ such that $|\mathscr{A}_i| \geqq 10$ were the only sets considered).

Note that the NSS chose the lowest cost schedule from a nurse's feasible schedule pattern set almost 44% of the time and the NSS chose a schedule that was in the 90th percentile or better of the feasible pattern set almost 88% of the time.

The CPU times for the solution algorithm range from about $2\frac{1}{2}$ seconds to 8 seconds (on a CDC 6400), depending on the number of nurses and the number of schedules in their feasibility sets. The average solution time was around 5 seconds. In most instances the groups consisted of from five to seven nurses with an average of about 200 schedules in their feasible schedule sets. The current NSS is coded for the IBM 360 and 370.

COMPARISON BETWEEN SCHEDULES GENERATED BY THE NSS AND THOSE USED BY THE HOSPITAL

As was mentioned, the actual schedules used by the hospital in which the test was made were on record. Table 2 presents data relating to various schedule characteristics.

Weekends of four or more days off were nearly the same in both cases. This is not surprising since most of these were due to special requests by the individual nurses. The NSS, however, generated 13 more three and two day weekends than the hospital did. This is a favorable feature since most nurses desire as many weekends off as possible. Moreover the NSS generated far fewer split weekends. Again this is favorable since the hospital often does not desire to have such patterns. Both the NSS and the hospital performed equally well in generating stretches under the individual nurse's minima but the hospital generated far more stretches over the nurse's maxima. In considering consecutive split days, the NSS generated more in all instances although the only significant difference occurred in the generation of two consecutive split days.

We now define X_k as the number of personnel in a group scheduled for day k, d_k as the desired number of personnel needed on day k, and $D = |X_k - d_k|$ as the absolute deviation of actual from desired. This gives us some measure of the deviation of the actual staffing levels from the desired staffing levels. Table 3 gives more data relating to these deviations over the schedule periods in question.
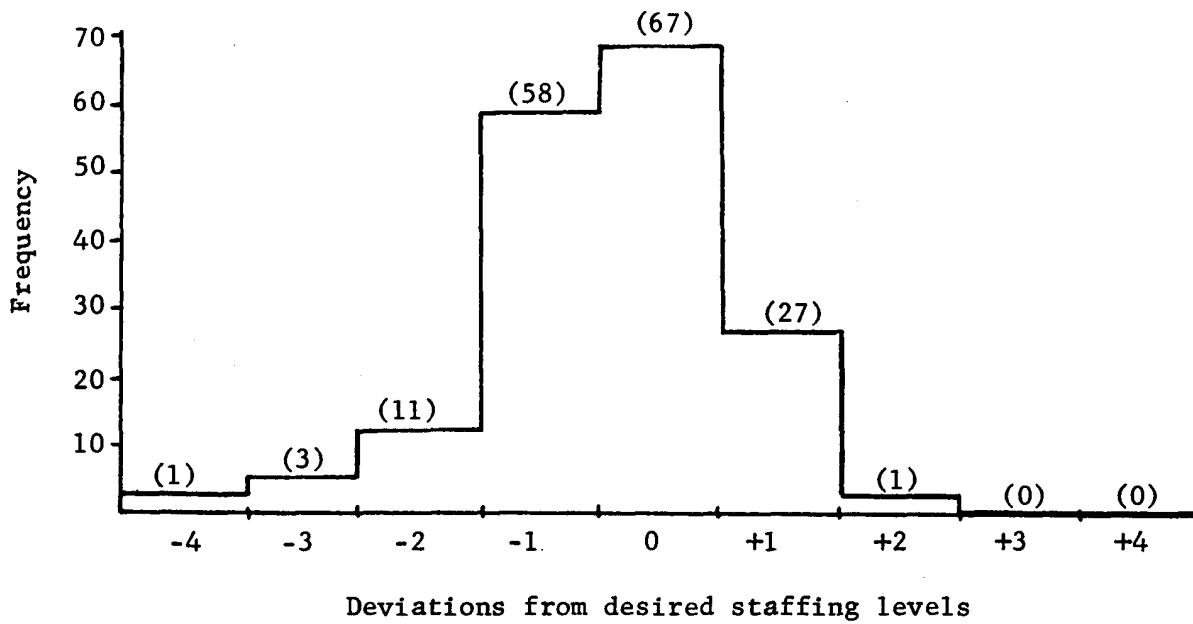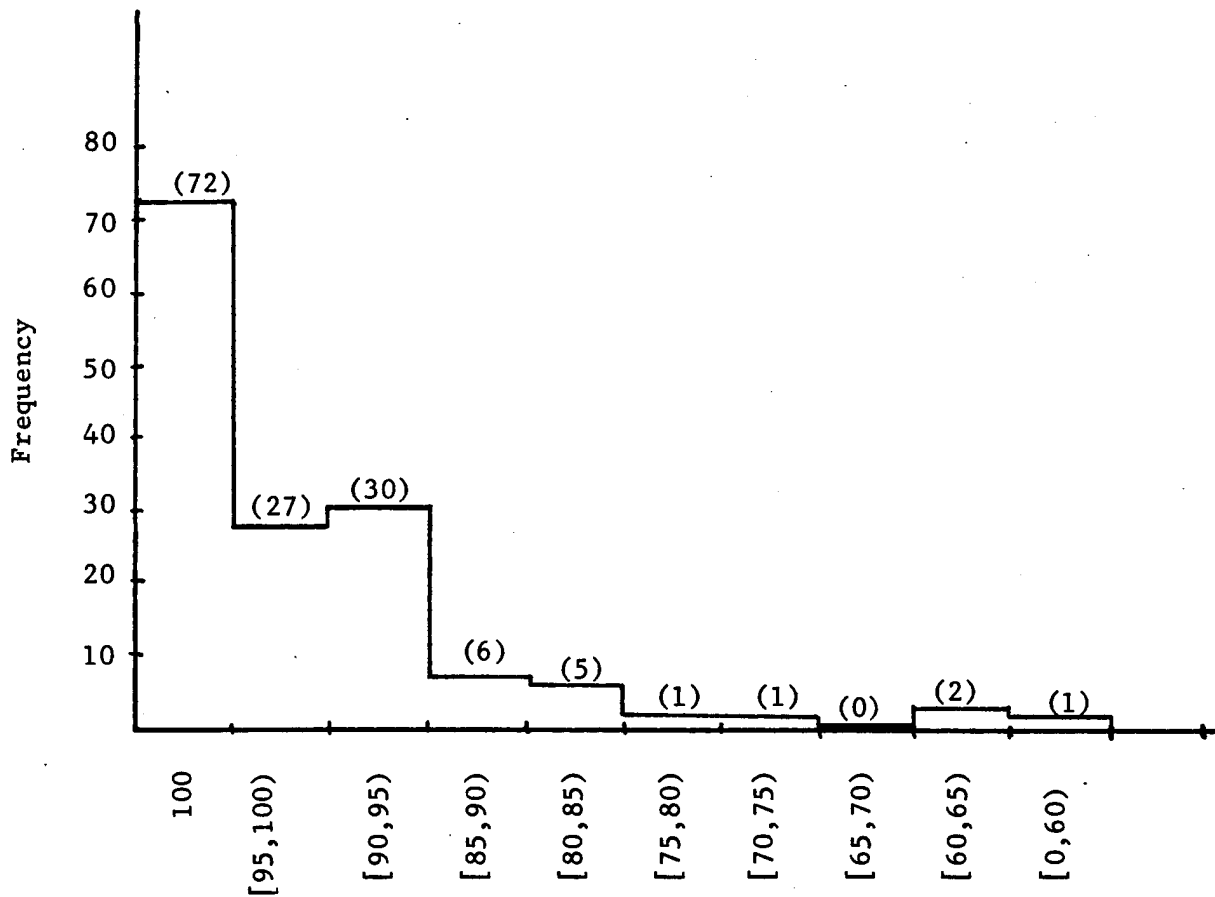
FIGURE 2

DISTRIBUTION OF DEVIATIONS FROM DESIRED STAFFING LEVELS BY SCHEDULES
CHOSEN BY SOLUTION ALGORITHM DURING THE SIX MONTH TEST PERIOD

Percent of Schedules with Greater Dissatisfaction Costs than that of the Schedule Chosen.

FIGURE 3

DISTRIBUTION OF THE NUMBER OF SCHEDULES IN THE FEASIBILITY SETS WITH
EMPLOYEE DISSATISFACTION COSTS GREATER THAN THAT OF THE SCHEDULES
CHOSEN BY THE ALGORITHM (OVER A SIX MONTH PERIOD)

	Weekend Days Off				Working Stretches		Consecutive Split Days Off (101 pattern)		
	≧ 4 Day	3 Day	2 Day	Split	Under min	Over Desired	1	2	3
Hospital Schedules	11	17	43	25	19	57	26	13	5
Algorithm Schedules	9	21	52	10	21	44	27	21	6

TABLE 2

COMPARISON OF SCHEDULE PATTERN CHARACTERISTICS BETWEEN HOSPITAL
AND THE NSS GENERATED SCHEDULES

Schedule Period	Pay Period	Average D		Variance of D		$\sum_{k=1}^{14} (X_k - d_k)^2$	
		ALG	HOS	ALG	HOS	ALG	HOS
9/24	1	.786	.929	.169	.352	11	17
	2	1.071	1.071	.209	.495	19	23
10/22	1	.357	.786	.229	.454	5	15
	2	.643	.786	.230	.454	9	15
11/19	1	.357	.786	.229	.312	5	13
	2	.429	.571	.245	.387	6	10
12/17	1	1.000	1.286	.714	1.061	24	38
	2	1.143	1.429	1.694	1.673	42	52
1/14	1	.214	.786	.168	.454	3	15
	2	1.000	1.143	.429	.551	20	26
2/11	1	1.071	1.214	.495	.455	23	27
	2	.643	.786	.230	.454	9	15

Legend:

$$D = |X_k - d_k|$$

HOS = Hospital Generated Schedule

ALG = Algorithm Generated Schedule by NSS

TABLE 3

COMPARISON OF SOME STAFFING LEVEL STATISTICS FROM HOSPITAL
AND THE NSS GENERATED SCHEDULES

In every pay period of every schedule period the average deviation D of the actual staffing level from the desired staffing level was as small as or smaller for the schedules generated by the algorithm than those generated for the hospital. Moreover in all cases but two, the variance of D was smaller for the algorithm generated schedules. One of these two occasions occurred in the pay period containing New Year's Day and in the second occasion, the variances differed by only .04.

Another measure of the variability of the actual vs. desired staffing levels is given in the last two columns of Table 3. This is the sum of the squares of the deviations. In all cases the sum of the squared deviations arising from the algorithm generated schedules is less than those from the hospital generated schedules.

SECTION 5. THE NURSE SCHEDULING SYSTEM

In any comprehensive, effective, equitable scheduling system there are many factors that must be handled. Some of these factors are:

- Shift rotation from day to evening and night shifts.
- Acceptable rotation patterns.
- Equitable assignments regarding who shall rotate.
- Differing pay periods and starting dates.
- Acceptable number of weekends off in a scheduling period.
- Differing definitions of weekends.
- No unduly long or short working stretches.
- Equitable weekday and weekend patterns, over time.
- The presence of various nursing classes (RN, LPN, Aide) and the existence of various subgroups within those classes.
- The existence of special requests by the nurses.
- New hires, terminations and part-time and float nurses.
- The necessity to meet staffing requirements which change from day to day and/or week to week.
- The ability to generate schedules relatively fast and without using too much computer storage.
- The ability to implement the model at a number of hospitals with different operating policies.

This list is only a partial enumeration of the many factors that must be considered. The list does, however, highlight certain aspects:

1. The model must be comprehensive enough to take into account all the detail present in real world settings.

2. The data requirements must not be so great to render the model unimplementable. The input and output requirements must be simple enough to facilitate application of the model.

3. The model must be based on some logical foundation so that the schedule configurations generated are of low cost to hospital administrators and nurses.

4. Nurse scheduling is a large problem with only approximations of many parameter values; hence optimal solutions have little meaning and may be expensive to obtain. Rather, good solutions, acceptable to all parties involved based upon multidimensional qualitative and quantitative criteria, are what is needed.

To meet these criteria and handle the many factors, an NSS with three modules was developed: a Rotation Module, a Weekend Module and a Weekday Module. The modules are applied sequentially; the final product is a complete set of nurse schedules ready for posting on each unit. Each module employs a variant of the same mathematical programming solution algorithm. Figure 4 gives an overview of NSS and how the modules interact.

ROTATION

The rotation module determines:

1. the rotation needs on the various shifts, based on staffing requirements and staffing assignments, taking into account days off and special requests,

2. the number of nurses who shall rotate and the aggregate number of days each shall rotate (these values are determined by comparing rotation availability and rotation needs, and then making appropriate selections),

3. the identities of the rotating nurses, on the basis of a long run index regarding rotation equity and specifies to which shift they rotate,

4. the set of feasible rotation patterns for the rotating nurses taking into account special requests and previous schedules. These patterns specify which days a nurse will be assigned to her rotated-to shift and which days on the day shift, and

5. the selection of one rotation pattern from each feasibility set via the solution algorithm given later.

WEEKEND

The weekend module determines:

1. the feasible weekend set for each nurse. When only weekends off or on are considered, there are 2^6 = 64 possible weekend patterns in a six week scheduling period, and 2^4 = 16 possible patterns in a four week scheduling period. In the absence of any special requests, these would constitute the set of feasible weekend patterns for each nurse. The presence of special requests reduces the set of feasible weekend patterns accordingly. For example, a request for the first weekend on would mean all weekend patterns would be of the form:

        11 xx xx xx xx xx

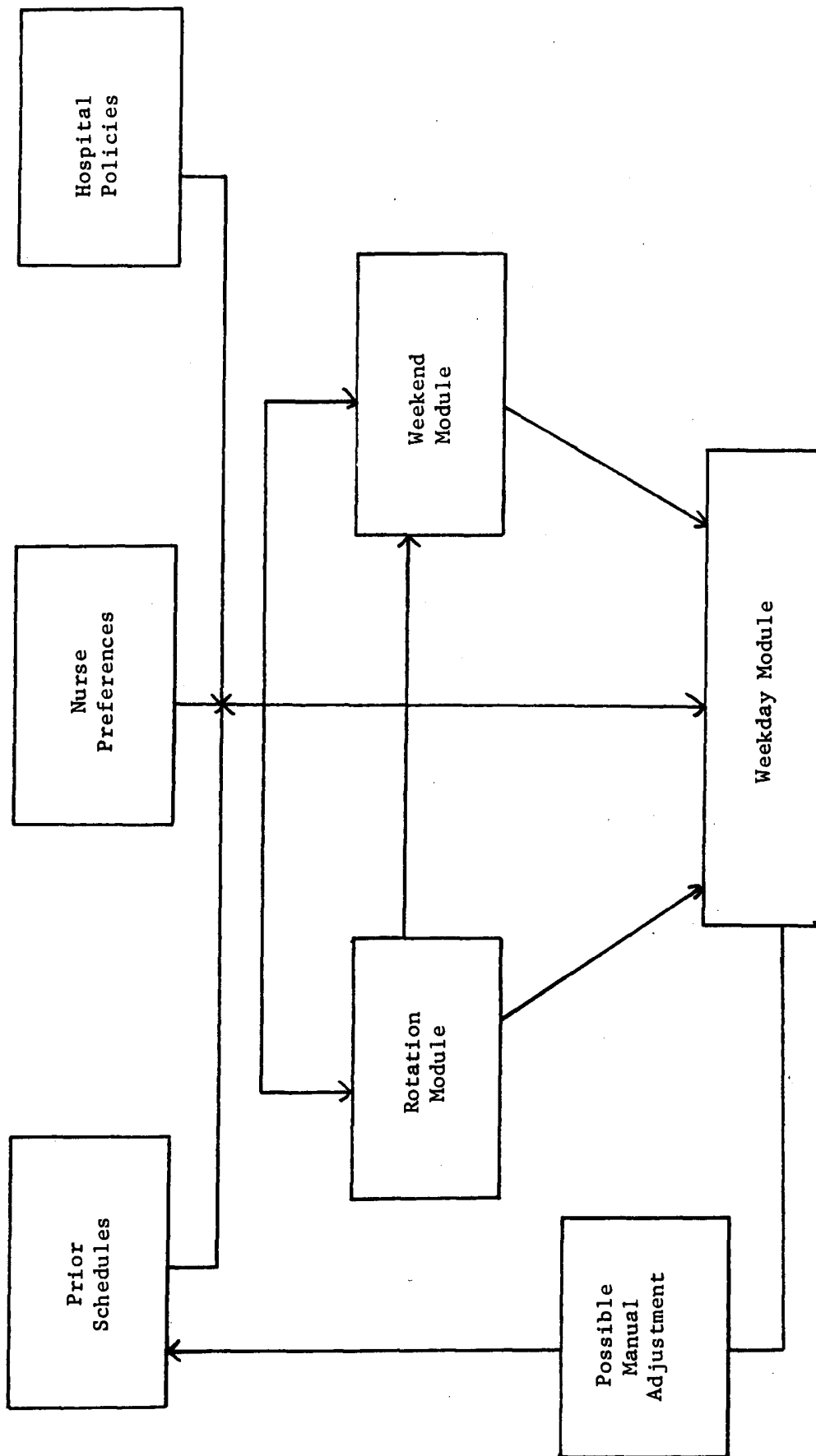where the x's indicate 0's or 1's. This would mean there would now be only 2^5 = 32 possible patterns.

FIGURE 4

OVERVIEW OF NURSE SCHEDULING SYSTEM

2. the nurse dissatisfaction costs associated with each weekend pattern. These costs are a cost reflecting how the weekend pattern meets the particular nurse's desires for weekends off, and a cost reflecting how the weekend pattern meets a nurse's desires for consecutive weekends on.

3. the weekends off for each nurse and the shift on which she has the weekend off. A weekend assigned off indicates the nurse will definitely receive that weekend off. A weekend assigned on is tentative; i.e., the nurse may still have the whole or part of the weekend assigned off during the weekday module.

WEEKDAY

The weekday module is similar in logic to the weekend module except: (a) The feasible set contains schedules represented by a vector of 14 0's or 1's, one component for each day of the pay period, where a 0 indicates a day off and a 1 a day on. In addition, cases of days on or off are represented by M - Meeting, C - Class, R - Requested Day Off, V - Vacation Day Off, B - Birthday Off, and (b) The patterns generated are the final patterns; i.e., if a day is indicated as being off, that day will be off. This is in contrast to the possibility of a "1" in a weekend pattern being changed to a "0" in the weekday pattern.

The weekday module determines:

1. a set of feasible schedule patterns. For full-time nurses who work 10 days out of every 14, this initially means a total of 1001 schedules. However, this set is reduced due to (a) various restrictions stemming from hospital policies; for example, maximum working stretches of seven days and minimum working stretches of two days, and (b) special requests that must be satisfied.

2. the nurse dissatisfaction costs associated with each weekday pattern. Some of these costs are:

   A cost associated with the total number of split days off (a 101 pattern) in a pay period.

   A cost associated with the consecutive number of split days off in the schedule period to date.

   A cost exceeding the maximum stretch.

   A cost exceeding the desired stretch.

   A cost for being below the minimum stretch.

   A cost for more than two or three consecutive days off (not including vacation days).

   A cost for "nasty patterns" (i.e., five or more days on followed by a day off, then six or more days on and vice versa).

THE SOLUTION ALGORITHM

All modules mentioned above use the same solution algorithm, which is a cyclic coordinate descent method or in simpler terms, a one-at-a-time method. Given an initial configuration of patterns in a feasibility set, the algorithm starts with a selected nurse (Nurse 1), varying her patterns while holding the patterns of all

the other nurses constant. When it finds a better pattern it updates the lowest cost to date and the pattern configuration generating that cost, and then goes to the next nurse (Nurse 2). If Nurse 1 does not have a pattern which generates a lower cost, the algorithm proceeds directly to Nurse 2 without updating the best pattern configuration. The algorithm continues in this fashion until the patterns of all the nurses are cycled through without finding an improvement.

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