Planning and Modeling Nurse Timetabling at an Intensive Care Unit in a Tunisian University Hospital

Zeineb Fourati · Badreddine Jerbi · Hichem Kammoun

Abstract Timetabling is to allocate resources to objects in a time interval in order to best meet a set of objectives such as improved quality of service and improved working conditions. In hospitals, a number made up of nurses and doctors should be attributed to personal shifts so as to obey certain hospital management rules. So it often requires periodic and strategic development of personal work schedule. The reasons for this development are multiple, they range from reduced productivity costs to the improvement of quality of service to customers, through the assurance of a good quality of life for employees. In this paper we treat the nurse rostering problem, in order to help the supervisor of the hospitals intensive care unit of Habib Bourguiba Hospital to plan the schedule of nursing work. We formulated this problem as a Weighted Goal Programming and we chose as a programming tool a combination of AMPL language with the CPLEX solver. Our contribution in this research, is to apply the method of Weighted Goal Programming on a real hospital cases taking into account the competence of nurses in the planning horizon. Intensive Care Unit has a limited number of nurses who handle the dialysis machine, for this we have divided all the nurses in two cathegories (competent nursing handling the dialysis machine and other less competent who have more than two years experience but do not handle the dialysis machine). During each day and each shift, the ICU must have at least one qualified nurse.

Keywords Nurse timetabling · Intensive Care Unit · Goal Programming

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1 Introduction

Nurses timetabling consists in designing periodic (daily, weekly, or monthly) schedules for nursing staff. A feasible schedule satisfies a set of constraints that reflect the local regulations, human resources policies, nurses preferences, and any context specific requirement [12]. The nurses timetabling problem is a decision problem. Generally, it is transformed into an optimization problem whose objective function assesses the quality or attractiveness of the Timetable [12]. The Nurse Scheduling Problem is particularly challenging because health care institutions work permanently and face fluctuating service demand on different days and shifts. Moreover it is particularly important to evenly balance the workload among nurses and to satisfy their preferences. The extent to which the schedule satisfies the nurses has an impact upon the working environment. A high quality schedule can lead to a more contented and thus more effective workforce [13]. A critical measure for the quality of a nurse schedule is the perceived fairness or balance for nurses [13]. The number of nurses scheduled per shift varies among hospitals and depends on a number of factors, usually including annual budgets and estimated patient volume and/or acuity [7]. The specific labor laws of each country, the different circumstances defining the resources and demand of each hospital, the scarcity/availability of nurses, and the nurses credentials make nurses timetabling context dependent [13] [10]. This paper discusses the timetabling problem for the case of the nurses at the University Hospital Habib Bourguiba in ICU which has several problems:

- Organizational Problems: nurses work according to rigid, unsatisfactory and not rigorous schedules, that contradict with their rights weekly rest. This problem is mainly due to the frequent and unplanned absenteeism.
- Information system problems: at the ICU there is a lack of communication between nurses, this problem is a major obstacle and a source of failure related to incomplete and inaccurate reversals instructions.
- Psychological problems: the rigidity of the schedule resulting in mental and physical fatigue for nurses.
- Planning problems: are due to the lack of computerized timetabling.

In this paper we use an effective multi objective method, the Weighted Goal Programming to assign nurses to different shifts, taking into account the competence of nurses and nurses preferences. The manager complained about the unexpected and frequent absenteeism of nurses, this problem requires him to change the schedule already prepared which usually takes too much time. For this reason we have chosen to use the acyclic schedule where a new schedule is generated for each planning horizon. This type of schedule requires considerable time, but it has the advantage of being relatively flexible against a variation of the load and allows easier integration of individual preferences [14]. The use of acyclic schedule will enable us to increase the level of flexibility, satisfy the desires of nurses of our case study Habib Bourguiba hospital ICU and deal with the unexpected absenteeism.

2 Overview of the Problem

From the systemic point of view, a hospital system is described as a socio-technical system whose main mission is to provide the best care to patients [4] it is a real production care system. Compared to the conventional production system, the health care system of production is distinguished by two fundamental aspects: the uncertainty and complexity of the care processes. For these reasons, many researchers have focused on hospital systems. Some of them worked on the surgeries scheduled on each workday in an operating room suite [9] to Maximize the efficiency and the use of nurses under uncertain surgery durations. [5] worked on the planning of operating theatres to reduce staff work period or improve the utilistion rate of the blocks. Other authors are interested in optimizing the scheduling of patients' Emergency Departments examinations [8]. In the literature several works focused on human resources, [11] propose a new methodology that incorporates the shift scheduling phase in the nurse staffing decision in order to determine an optimal nurse staffing and shift scheduling plan simultaneously. [1] use the Analytical Hierarchy Process and goal programming technique for modeling a schedule for nurses in an intensive care unit. The weights in the objective function of the goal programming model are obtained through The AHP method.

The performance and quality of any health care system depends on the quality and motivation of hospital actors such as medical and paramedical personnel [15] and Nurse dissatisfaction causes nurses frustration leading to either working under high stress, absenteeism and a high turnover rate [3]. Thus, the hospital shows an increasing need to provide assistance in planning tools, allocation and scheduling of its human resources. In our case, we are interested in the nurse scheduling problem in the ICU of the hospital Habib Bourguiba as it has several organizational problems.

Reanimation is defined as the care of patients with or at risk of acute organ failure involving life-threatening and requires both the use of specific techniques, expensive hardware and permanence 24/24h of medical and paramedical staff. The ICU by definition requires much attention and increased monitoring by nursing staff. The activity of an ICU is the problem of coordination of actors in critical situations or when a sudden influx of patients. This is an extremely dynamic environment, and adapting a tool for coordination needs to take into account strong constraints [6]. For modeling the nursing planning problem, we chose the techniques of Goal Programming developed by Charnes and Cooper to adapt mathematical programming to solve concrete problems. Indeed, operational researchers soon realized the weakness in using a single objective function. They were led in practice to break this economic function following several goals they posed as constraints by setting an aspiration levels. This method has the advantage of being very flexible; and it helps stimulate many variations in constraints and priority goals. It is an extension or a generalization of linear programming, which is to address problems with conflicting goals. The Goal Programming model is based on the definition of the levels of aspiration or goal (goals) for each target while trying to find the closest

solution to these goals. This model aims to minimize the sum of positive and negative deviations from the objectives and goals to be met in order to obtain a satisfactory solution and a good compromise. Goal Programming takes account simultaneously several objectives that may be in conflict, and the solution obtained by Goal Programming procedure represents the best compromise that can be made by the decision maker [2]. The Goal Programming has several variants, we will focus at the weighted Goal Programming wich requires no pre-emptive ordering of the objective functions. Instead, all the different deviations are placed in a single priority level objective with different weights to represent their importance. By minimizing excess and lack of nurses and giving a weight to each deviation, the WGP will allow us to approach the goal and satisfy the request of the number of nurses on duty.

3 Mathematical Formulation of the Problem

The nursing planning problem at the Habib Bourguiba hospital and specifically in the ICU is to assign a set of nurses to different shifts including rest, morning, afternoon, and night periods during a planning horizon through a full working week. The ICU has 42 nurses. They must be fairly distributed between shifts. Table 1 provides the starting times, end times and durations of the three shifts Morning, Afternoon and Night. The following tables 1 and 2 present the time interval of the shifts and their associated needs in number of nurses.

Table 1 Types and duration of ICU at shifts

	Time code	Start times	End times	Net length
Morning	1	07H : 00	13H : 30	6h
Afternoon	2	13H : 00	19H : 30	6h
Night	3	19H : 00	07H : 00	12h

Each type of shift has a daily requirement of nursing staff to cover the workload.

Table 2 Daily needs in nursing workforce for each shift

	From Monday to Saturday	Sunday
Morning	12	6
Afternoon	6	6
Night	6	6

From table 2 we see that in the morning the workload is much higher compared to other shifts which imply a need for higher nursing totalling 12 nurses, while on Sunday the ICU has a need for only 6 nurses during the hole day since it is a holiday. The nursing schedules are developed and reported for

a week and they vary from one week to another because they are acyclic. For the formulation of our problem we need:

Settings

- N: the set of all nurses in the ICU, N = 1, 2, 3...42.
- D: all days covering the planning horizon from monday to sunday, D = 1,2... 7.
- D0: all days covering the planning horizon from monday to saturday, D0 = 1,2... 6.
- S: time codes associated with each type of shift; S = 0, 1, 2, 3 which represent shifts rest, morning, afternoon and the night.
- SZ: time codes associated with shifts of the day and night; with SZ = 1, 2, 3 which represent the morning, afternoon and night shifts.
- SM: time codes associated with shifts of the day; with SM = 1, 2 which represent the morning and afternoon.
- T1: volunteer nurses who want to work only at night.
- T2: nurses who must work only in the day.
- T3: nurses who handle the dialysis machine.
- T4: the indifferent nurses who have no requirements and can work during any shift.

Decision variables

The decision variables are of binary types. They take the value 1 if the nurse is assigned to a type of shift S = 0, 1, 2, 3 and 0 otherwise.

$$x_{nds} = \begin{cases} 1 \text{ if the nurse n is assigned on the day d to the shift s} \\ 0 \text{ otherwise} \end{cases}$$

Deviation variables

- δ^{+}_{d3} : Positive deviations from nurses goal demand of the night shift from monday to saturday. For example from monday to saturday on the night there is a surplus of 4 nurses, that is to say that there are ten staff on duty instead of 6, or $\delta^{+}_{13} = \delta^{+}_{23} = \delta^{+}_{33} = \delta^{+}_{43} = \delta^{+}_{53} = \delta^{+}_{63} = 4$.
- δ^{-}_{d3}: Negative deviations from nurses goal demand of the night shift from monday to saturday.
- $\delta^{+}_{d2}, \delta^{-}_{d2}$: Positive and negative deviations from nurses goal demand of the afternoon shifts from monday to saturday.
- $\delta^{+}_{d1}, \delta^{-}_{d1}$: Positive and negative deviations from nurses goal demand of the morning shift at the hospital from monday to saturday.
- $\delta^{+}_{7s}, \delta^{-}_{7s}$: Positive and negative deviations from nurses goal demand throughout the sunday shifts.

To ensure the needs of the ICU in the required number of nurses we minimize the positive and negative deviations from the objectives obtained from the ICU staff.

Defining the objective of the problem

The goal in solving the problem is to generate a schedule for the ICU nurses that respects the regulations of working time and desires of staff while maximizing the equity of the distribution of workload allocation to the various shifts. To ensure the needs of the ICU in required number of nurses we have minimized the positive and negative deviations from the objectives obtained from ICU staff. After discussion with the ICU responsible, we decide to assign a weight of 0.75 for the positives deviations and 0.25 for the negatives deviations.

Our objective function can be formulated as follows:
Min $\sum_{d \in D} \sum_{s \in SZ} (0,75 * \delta^{+}_{ds}) + (0,25 * \delta^{-}_{ds})$

Identification of Constraints

To develop a schedule, certain rules must be respected. They come from regulations but also agreements between managers and nurses. The constraints that must be met in the timetable, in the case of ICU of Habib Bourguiba hospital are:

- Every nurse should be assigned to one and only one shift for each day of the planning horizon or is at rest (constraint 1).
- Nurses must work 36 hours per week whatever the type of shift (constraint 2).
- The nurse who works at night must necessarily have a day off tomorrow (constraint 3).
- Nurses who work the night on sunday must be at rest on monday (constraint 4).
- For sunday and for any type of shift, the ICU must have 6 nurses (constraint 5).
- From monday to saturday and during the morning, the ICU must have 12 nurses (constraint 6).
- From monday to saturday and during the afternoon, the ICU must have 6 nurses (constraint 7).
- From monday to saturday and during the night shift, the ICU must have 6 nurses (constraint 8).
- For each day of the week and for any type of shift, the surplus of nurses should be distributed almost equally (constraint 9).
- Each volunteer nurse should be assigned only to night shift (constraint 10).
- For each day of the week and for each shift, the ICU must have at least one competent nurse who can handle the dialysis machine (constraint 11).

– Nurses having an age greater than 50 years or pregnant women must necessarily be affected to the morning or afternoon shifts (constraint 12).

Our nursing planning problem in the ICU is formulated as a standard Weighted Goal Programming model with the following goals:

$$\min \sum_{d\in D}\sum_{s\in SZ}(0,75 * \delta^{+}_{ds}) + (0,25 * \delta^{-}_{ds}) \quad \forall n \in N$$

Subject to

$$\sum_{s\in S} x_{nds} = 1 \quad \forall n \in N \wedge \forall d \in D \tag{1}$$

$$\sum_{d\in D}\sum_{s\in SM} 6 * x_{nds} + \sum_{d\in D} 12 * x_{nd3} = 36 \quad \forall n \in N \tag{2}$$

$$x_{nd3} + x_{nd+1s} \leq 1 \quad \forall n \in N \wedge \forall d \in D0 \wedge \forall s \in SZ \tag{3}$$

$$x_{n73} + \sum_{s\in SZ} x_{n1s} \leq 1 \quad \forall n \in N \tag{4}$$

$$\sum_{n\in N} x_{n7s} + (\delta^{-}_{7s}) - (\delta^{+}_{ds}) = 6 \quad \forall s \in SZ \tag{5}$$

$$\sum_{n\in N} x_{nd1} + (\delta^{-}_{d1}) - (\delta^{+}_{d1}) = 12 \quad \forall d \in D0 \tag{6}$$

$$\sum_{n\in N} x_{nd2} + (\delta^{-}_{d2}) - (\delta^{+}_{d2}) = 6 \quad \forall d \in D0 \tag{7}$$

$$\sum_{n\in N} x_{nd3} + (\delta^{-}_{d3}) - (\delta^{+}_{d3}) = 6 \quad \forall d \in D0 \tag{8}$$

$$(\delta^{+}_{ds}) - \sum_{k\in D}(\delta^{+}_{ks}/7 + 1) <= 0 \quad \forall d \in D \wedge \forall s \in SZ \tag{9}$$

$$\sum_{d\in D0} x_{nd3} \geq 3 \quad \forall n \in T1 \tag{10}$$

$$\sum_{n\in T3} x_{nds} \geq 1 \quad \forall d \in D \wedge \forall s \in SZ \tag{11}$$

$$\sum_{d\in D}\sum_{s\in SM} x_{nds} \geq 6 \quad \forall n \in T2 \tag{12}$$

$$x_{nds} \in [0,1] \quad \forall n \in N \wedge \forall d \in D \wedge \forall s \in S \tag{13}$$

$$\delta^{+}_{7s}, \delta^{-}_{7s} \geq 0 \quad \forall s \in SZ \tag{14}$$

$$\delta^{+}_{d1}, \delta^{-}_{d1} \geq 0 \quad \forall d \in D0 \tag{15}$$

$$\delta^{+}_{d2}, \delta^{-}_{d2} \geq 0 \quad \forall d \in D0 \tag{16}$$

$$\delta^{+}_{d3}, \delta^{-}_{d3} \geq 0 \quad \forall d \in D0 \tag{17}$$

To program this optimization problem, we used the AMPL language, which is a modeling language which can help us to formulate optimization problems by using sets, sums... It is a very powerful language for modeling linear problems, nonlinear and integer problems. It has several advantages, it can communicate with a large variety of solvers, ensure better flexibility and speed, enables a very concise and readable definition of problems in the field of optimization ...

To specify the classes of mathematical programming models, AMPL should be incorporated into a system that manages the data, the models and the solutions. Thus they should contact a solver. To solve our nursing schedule planning problem of the ICU we chose the CPLEX solver which is used for linear programming, integer and networks and can work with large number of constraints especially when the variables are real.

4 Results and Discussion

After 373 iterations of the simplex algorithm, the program has generated an objective function which is equal to 18, and the time (in seconds) to obtain the results is distributed as follows:

- Input = 0.006
- Solve = 0.087
- Output = 0.003

All results generated by the CPLEX solver for all shifts are illustrated in table 3 in appendix, which shows the weekly timetable of nursing at the ICU.

We observe that nurses are divided into 4 groups:

- Volunteer nurses who want to work only at night.
- Day nurses who want to work only on the morning or afternoon shift.
- Competent nurses who manipulates the dialysis machine. During the week and for each shift we must have at least one competent nurse.
- Indifferent nurses are those who do not have requirements and can work any shift.

The generated timetable is flexible, it took consideration of nursing requirements which leads to employee satisfaction, which is a significant element impacting the quality of patient care. Timetabling generated by the CPLEX solver, have shown that the number of nurses in the ICU is more than enough to cover the horizon of work. With 42 nurses we have an excess of staff during night shifts for monday to saturday equally distributed.

5 Conclusions

This work focuses on the study of a specific link to an entire hospital system that represents all nurses in the ICU. Our ultimate objective in this work was to solve the timetabling problems encountered in the ICU. We highlighted

the need to address organizational problems, which can be solved through the use of a powerful computer tool favouring the automated construction of nursing staff schedules. The benefits of this research work can be assessed and improved as follows:

1. Our exact method is considered effective because it solves problems with large scale combinatorial variables.
2. The flexibility of our model has enabled us to integrate the preferences of the decision maker (general supervisor of the ICU) also other decision makers (nurses, patients, etc).

The major perspectives of this work are:

1. Establish schedules over a longer horizon (1 month for example).
2. Modelling the imprecision of some aspiration levels through integration of fuzzy parameters in the model.

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Appendix 1: weekly timetable of nursing ICU

Table 3 weekly timetable of nursing ICU

Name	Type	Mon	Tue	Wed	Thu	Fri	Sat	Sun	TH
Kammoun	NV	N	R	N	R	N	R	R	36
Krichen	NV	N	R	N	R	N	R	R	36
Jerbi	NV	N	R	N	R	N	R	R	36
Masmoudi	NV	N	R	N	R	N	R	R	36
Ben himden	NV	R	N	R	N	R	N	R	36
Jawa	NV	R	N	R	N	R	N	R	36
Yengui	NV	R	N	R	N	R	N	R	36
Abdelkafi	NV	N	R	R	N	R	N	R	36
Fourati	ND	M	AM	R	M	AM	M	M	36
Beji	ND	M	R	AM	M	M	M	M	36
Issaoui	ND	M	R	AM	M	M	M	M	36
Njeh	ND	M	AM	M	AM	R	M	AM	36
Trabelsi	ND	AM	M	M	M	M	M	R	36
Zahaf	ND	AM	M	M	R	M	AM	AM	36
Ghamgui	ND	AM	M	AM	M	M	M	R	36
Fakhfekh	ND	R	AM	AM	AM	AM	AM	AM	36
Maalej	ND	AM	M	M	R	M	M	AM	36
Nebli	ND	M	M	R	AM	AM	AM	M	36
Aloulou	NEC	N	R	AM	R	AM	N	R	36
Sellami	NEC	AM	N	R	AM	M	M	R	36
Mkawar	NEC	R	R	N	R	N	R	N	36
Fendri	NEC	M	AM	M	M	R	AM	M	36
Louati	NEC	M	M	M	N	R	R	AM	36
Mezghani	Ind	AM	N	R	AM	M	AM	R	36
Chabchoub	Ind	N	R	N	R	R	N	R	36
Charfi	Ind	M	M	N	R	N	R	R	36
Wali	Ind	M	AM	AM	M	M	M	R	36
Msaed	Ind	N	R	M	M	N	R	R	36
Tmimi	Ind	R	M	M	N	R	M	M	36
Bouzid	Ind	R	R	M	N	R	M	N	36
Hammemi	Ind	M	N	R	M	N	R	R	36
Khachlouf	Ind	N	R	N	R	M	M	R	36
Minywi	Ind	N	R	N	R	N	R	R	36
Chakchouk	Ind	R	AM	N	R	AM	R	N	36
Bradii	Ind	M	N	R	N	R	R	AM	36
Mnajja	Ind	R	N	R	M	AM	N	R	36
Amara	Ind	M	M	M	M	R	N	R	36
Memmi	Ind	R	M	R	M	N	R	N	36
Ben mrad	Ind	R	M	M	N	R	N	R	36
Away	Ind	R	M	M	N	R	R	N	36
Ben massoud	Ind	R	N	R	AM	M	N	R	36
Zribi	Ind	R	N	R	R	M	AM	N	36
Total nurses M		12	12	12	12	12	12	6	
Total nurses AM		6	6	6	6	6	6	6	
Total nurses N		10	10	10	10	10	10	6	