Proceedings of Science and Mathematics
Faculty of Science, Universiti Teknologi Malaysia

Vol. 18, 2023, page 165 – 173

Nurse Scheduling in Hospital Emergency Department using Goal Programming

Tengku Nurfakhira Tengku Farid, Hang See Pheng*
Department of Mathematical Sciences, Faculty of Science, Universiti Teknologi Malaysia
*Corresponding author: sphang@utm.my

Abstract
The emergency department (ED) is a crucial and often overcrowded department in hospitals, playing a vital role in healthcare. Day by day, the emergency department are getting busier. Unreasonable staffing of nurses in the ED can be stressful for the staff as it gave them a work chore more than 12 hours a day. This can give a bad environment to the healthcare staff and the patients in the emergency department. Therefore, in this study present a goal programming technique to develop a model for nurse scheduling. The model includes different purposes as its goal to achieve them. Some hard constraints and soft constraint take into account on achieving the allocation of nurse through goal programming. This model has been solved by using Microsoft Excel Solver and also Python in allocating the nurses into their respective shift daily and weekly.

Keywords: Goal Programming; Nurse Scheduling; Hard Constraints; Soft Constraints

1. Introduction

The hospital is one of the most significant areas of healthcare, and the emergency department (ED) is one of the most critical and busy hospital departments (Hosseini-Shokouh et al., 2022). Day by day, the emergency department is getting busier. Many non-emergency patients present to EDs at times, owing to a shortage of primary healthcare services and a lack of understanding of the purpose of emergency services (Al Owad et al., 2018). On the other hand, these EDs are always under pressure related to financial limits and new government rules.

Every country's healthcare industry is extremely sensitive, and it plays a significant role in national politics. As the world's population grows, so does the demand for emergency treatment in practically every country (Derlet, 2002). Many non-emergency patients present to EDs at times, owing to a shortage of primary healthcare services and a lack of understanding of the purpose of emergency services. From this situation, The Bureau of Labor Statistics predicts a nursing shortage as the sector grows and nurses leave. Many remedies to the nurse crisis have been proposed, including boosting staffing by accounting for patient workload rather than overall volume (Svirsko et al., 2019). They also discovered that overstaffing can be caused by the 8- and 12-hour shifts that nurses choose to work, or by 4-hour gaps that are difficult to fill. As a result, any divergence from the expected healthcare service may place additional strain on healthcare staff. According to the World Health Organization (2014), there is a worldwide shortfall of 7.2 million health care professionals. This shortage is expected to grow to 12.9 million by 2035 (World Health Organization, 2014), and it is especially severe in the nursing profession, which is the largest group of health care professionals in hospitals, accounting for one-third of the Canadian health-care workforce; approximately six out of ten Canadian nurses work in hospitals (Canadian Federation of Nurses Unions, 2013). Furthermore, according to the World Development Indicators, Malaysia's nurse increase from year of 2010 until 2017, where it has 3200 nurses to 4200 nurses in 7 years. Unfortunately, in the year 2019, the number of nurses decrease about 18.18% (3500 nurses).

This nurse scheduling problem can be solved by many mathematical methods such as genetic algorithm (Leksakul & Phetsawat, 2014), mixed integer linear programming (Bixby, 2012), multi-commodity-network flow model (El Adoly et al., 2018), tabu search (Noman et al., 2021), heuristic algorithm (Constantino et al.,2014) and also constraints programming (Alade & Amusat, 2019). However, for this particular study of nurse scheduling problem, the method that will be applied is goal programming that extension from the Multi-Objective Decision Making (MODM) method. This MODM method is also known as Multi-Criteria Decision Making (MCDM), and used to solve the decision-making problem until now. MCDM is a strategy for selecting the best option based on numerous criteria for a specified purpose. To assess the priority value of the alternatives, the approach offers impartiality and analyses the alternatives relative to one another. In the Operational Research (OR) field, MCDM is one of the most important subfields to be grown rapidly. MCDM is regarded as a complicated decision-making method that takes into account in both quantitative and qualitative aspects. Choosing the best likely possibilities has been recommended using a number of MCDM strategies and approach in recent years. The method is developed as an aspect of operations research, which is focused with creating computational and mathematical tools to enable the judgmental assessment of performance criteria by decision-makers. The existence of uncertain goals (i.e., the decision goal is unidentified) and imprecise goals (i.e., the target value of a goal, or "goal target," is imprecise) is frequent in the practice of multi-objective decision-making (MODM). The MODM employs a number of mathematical models in which the course of action is not predetermined but rather is a collection of objective functions that must be optimized. The many types of multi-attribute decision-making processes include:

1) Weighting methods (linear additive model, AHP and the multi-attribute utility theory)
2) Multiple objective programming (multi-objective linear programming)
3) Outranking approaches (ELECTRE, PROMETHEE)

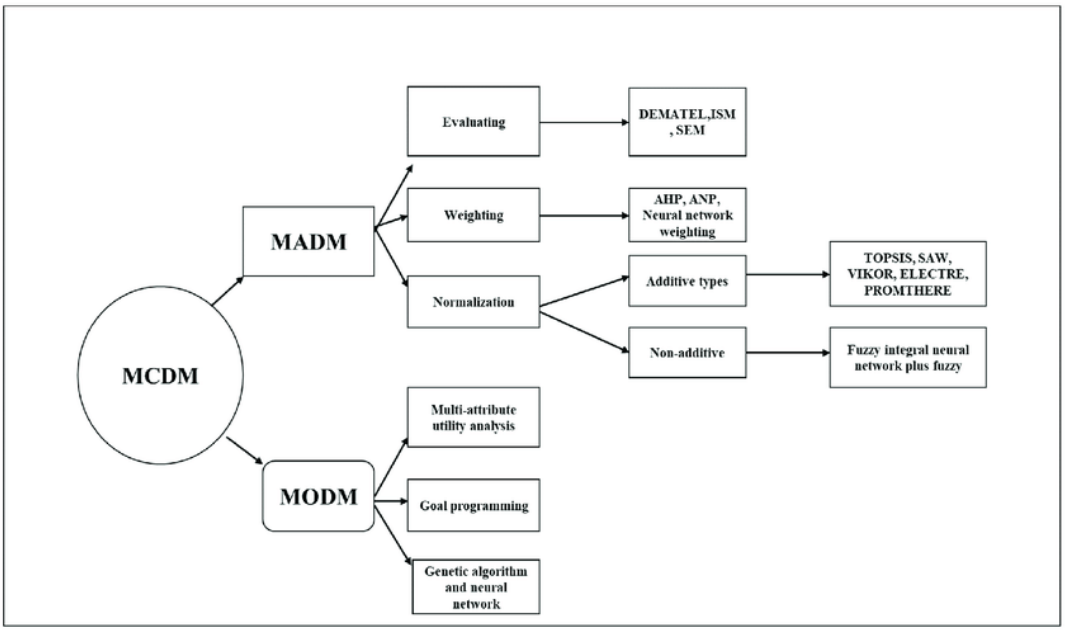

Figure 1 MCDM classification split between MADM and MODM (Mugiyo et al., 2021)

Table 1: Summary of the studies on nurse scheduling

Author	Year	Research methodology
Hosseini-Shokouh et al.	2022	Discrete Event Simulation (DES) Artificial Neutral Network (ANN) algorithm
Ahsan et al.	2019	Agent-based modelling and simulation (ABMS) Mathematical modelling computed tomography Queuing Model
El Rifai et al.	2014	Stochastic mixed-integer programming model
Amaral & Costa	2014	PROMETHEE II

2. Problem statement

The unreasonable staffing of nurses in the emergency department can be stressful for the staffs as it gave them a big work chore for more than 12 hours a day. This scenario gives a bad environment to the healthcare staff and the patients in the emergency department. This is due to the number of nurses that are assigned in their respective shift hours is not that helpful for giving the best working time in the emergency department. Nursing staff overwork and understaffing have a negative impact on not only the service quality of healthcare operations, but also on patient-nurse interaction (Bridges et al., 2019) and patient safety (Liu et al., 2012) and (Baker et al., 2019).

At the same time, the rigorous working circumstances have a severe impact on nurses' health, including exhaustion, obesity, sleep disorders, and a variety of chronic illnesses (Uekata et al., 2019). Furthermore, if an organization does not have the right skills of roasted in that particular area, it can lead to staff dissatisfaction, absenteeism, losing productivity of the staff and low staff morale. Therefore, this study aspires to propose a better quality of allocation of nurse by using Goal Programming mathematical methods.

3. Goal Programming

Goal programming is extended by linear programming. Although linear programming is employed frequently in decision-making processes, it has a key restriction which confines the users of the approach to restricting their issues to a single objective function. Goal programming (GP) was created to deal with situations that have multiple objective decision-making problem. This approach, if utilized correctly, has the potential to be exceptional in strategic planning, demonstrates how an incorrectly structured goal programming approach produces misleading results (Ahmed, 1996). Orumie and Ebong (2014) stated that goal programming is one of the earliest multi-criteria decision-making strategies, employed in the optimization of several objective goals by limiting the deviation from the intended goal for each of the objectives. Goal programming seeks to minimize the accomplishment of each real goal level.

The main idea behind goal programming is to combine numerous objectives into a single goal. The resultant model produces a satisfying answer; however, it might not be the best one given all the competing goals of the issue. In other words, GP does not produce the best answer to the problem, it merely produces an effective and satisfying result. Goal programming seeks to achieve a suitable level of the numerous objectives under consideration because it is unusual to constantly meet every goal. Goal normalization is used to minimize any potential bias that may result from applying the solution to multiple measurement units (Orumie & Ebong, 2014).

The decision makers can use GP to develop realistic solution based on ideal scheduling qualities with goal values. The problem is solved by reducing the undesirable deviation from the goal values. At this point, the priority level of the goals can be set depending on management interests. A study discusses about replacing the manual- made schedule with a computerized one to optimized fair weekly schedule that satisfying the stated hospital's policies and outpatient nurses' preferences (Wang et al., 2014).

The goal programming provides more satisfactory treatment where in many cases, problems can still be solved using standard linear programming algorithm. Two sorts of variables are employed in the formulation of goal programming model to accommodate mathematical programming with multiple objectives. There are two types of variables: choice variables and deviational variables. As far as the constraints, two types of constraints can be identified.

1. Hard (rigid) constraints, the same as in regular linear programming model. These constraints cannot be violated.
2. Soft constraints (goal constraints, representing the present desired level of achievement for each objective). These goal constraints allow for underachievement and over achievement of goals.

The goal programming formulation is followed by these step as it should be part for any goal programming strategy:

Step 1: Define the decision variables ($\boldsymbol{d_1^+, d_2^+, d_3^+, x_1, x_2}$)
Step 2: State the constraint s
Step 3: Determine the relative weights if needed
Step 4: Determine the pre-emptive priorities if needed
Step 5: State the objective function
Step 6: State the non-negativity of given requirement

3.1 Problem description

Nurse schedule is needed in every hospital emergency department. This study is developing a weekly schedule plan for 15 nurses that working in the green zone emergency department. The main assumption of this study is that the nurses scheduling starts from Monday to Sunday in a week. The business day started for morning shift from 8 a.m. until 4 p.m., followed by evening shift from 4 p.m. until 12 a.m. and night shift from 12 a.m. until 8 a.m. of next day. The schedule period of 7 days. The following regulations are enforced to create a model of this plan and considered hard and soft constraints in the model:

1. The first set of the hard constraints ensure that the amount of manpower for every shift is predicted. Since the number of nurses number necessities is different for different days, the model helps the user to consider shifts in different days.
2. The second set of the hard constraints are every nurse must work only one shift in one day throughout the schedule.
3. The last hard constraints are to ensure all nurse work according to the number of required shifts per schedule.
4. The first set of the soft constraints are to consider that working in morning shift followed by an evening or night shift is avoided.
5. The second set of the soft constraints are to consider that working in an evening shift followed by a night or morning shift is avoided.
6. The first set of the soft constraints are to consider that working in a night shift followed by a morning or an evening shift is avoided.
7. The fourth set is to ensure each nurse has at least one day off per schedule.

Notations

The following notations are used to specify the model:
n: refer to the number of scheduling days (*n*=7)
m: number of nurses available for the unit (*m*=15)
i: is the index of nurses (*i*=1…., m)
j: is the index of days (*j*=1…., n)
A_i = nurse requirements for morning shift for a day *j*
B_i = nurse requirement for evening shift for a day *j*
C_i= nurse requirement for night shift for a day *j*

Decision variable

There are other symbols that will be defined in the future. The decision variable will be introduce as following:

$$M_{j,i} = \begin{cases} 1 & \text{If the nurse } i \text{ is allocated to the morning shift in the day } j \\ 0 & \text{Otherwise} \end{cases} \quad (1)$$

$$E_{j,i} = \begin{cases} 1 & \text{If the nurse } i \text{ is allocated to the evening shift in the day } j \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

$$N_{j,i} = \begin{cases} 1 & \text{If the nurse } i \text{ is allocated to the night shift in the day } j \\ 0 & \text{Otherwise} \end{cases} \quad (3)$$

$$C_{j,i} = \begin{cases} 1 & \text{If the nurse } i \text{ is assigned day off in the day } j \\ 0 & \text{Otherwise} \end{cases} \quad (4)$$

Deviation variables

d_1^- = underachievement of a nurse allocated morning shift followed by an evening or night shift on the next day
d_1^+ = overachievement of a nurse allocated morning shift followed by an evening or night shift on the next day
d_2^- = underachievement of a nurse allocated an evening shift followed by a night or morning shift on the next day
d_2^+ = overachievement of a nurse allocated an evening shift followed by a night or morning shift on the next day
d_3^- = underachievement of a nurse allocated a night shift followed by a morning or evening shift on the next day
d_3^+ = overachievement of a nurse allocated a night shift followed by a morning or evening shift on the next day
d_4^- = underachievement of a nurse has at least one day off.
d_4^+ = overachievement of a nurse has at least one day off.

Modeling the constraints

Hard constraints:

Set 1: Minimum necessary nurses in every shift for morning, evening and night shifts must be satisfied.

$$\sum_{i=1}^{m} M_{j,i} \geq A_j , \quad j = 1,2,\ldots,n \quad (5)$$

$$\sum_{i=1}^{m} E_{j,i} \geq B_j , \quad j = 1,2,\ldots,n \quad (6)$$

$$\sum_{i=1}^{m} N_{j,i} \geq C_j\,, \quad j = 1,2,\ldots,n \tag{7}$$

Set 2: Each nurse works only one shift per day**:**

$$M_{ji} + E_{ji} + N_{ji} + Cji = 1, j = 1,2,\ldots,n \; and \; i = 1,2,\ldots,m \tag{8}$$

Set 3: Each nurse works according to the number of required shifts per schedule.

$$\sum_{j=1}^{n} M_{j,i} \geq 5\,, \quad i = 1,2,\ldots,m \tag{9}$$

$$\sum_{j=1}^{n} E_{j,i} \geq 5\,, \quad i = 1,2,\ldots,m \tag{10}$$

$$\sum_{j=1}^{n} N_{j,i} = 3\,, \quad i = 1,2,\ldots,m \tag{11}$$

Soft Constraints:

Set 1: Working in a morning shift followed by an evening or night shift on the next day is avoided:

$$M_{ji} + E_{j+1,i} + N_{j+1,i} \leq 1, j = 1,2,\ldots,n \; and \; i = 1,2,\ldots,m \tag{12}$$

$$M_{ji} + E_{j+1,i} + N_{j+1,i} + d_1^- - d_1^+ \leq 1, \quad j = 1,2,\ldots,n-1 \text{ and } i = 1,2,\ldots,m \tag{13}$$

Set 2: Working in an evening shift followed by a night or morning shift on the next day is avoided:

$$E_{ji} + M_{j+1,i} + N_{j+1,i} \leq 1, \quad j = 1,2,\ldots,n \; and \; i = 1,2,\ldots,m \tag{14}$$

$$E_{ji} + M_{j+1,i} + N_{j+1,i} + d_2^- - d_2^+ \leq 1, \quad j = 1,2,\ldots,n-1 \text{ and } i = 1,2,\ldots,m \tag{15}$$

Set 3: Working in a night shift followed by a morning or evening shift on the next day is avoided:

$$N_{ji} + M_{j+1,i} + E_{j+1,i} \leq 1, \quad j = 1,2,\ldots,n \; and \; i = 1,2,\ldots,m \tag{16}$$

$$N_{ji} + M_{j+1,i} + E_{j+1,i} + d_3^- - d_3^+ \leq 1, \quad j = 1,2,\ldots,n-1 \text{ and } i = 1,2,\ldots,m \tag{17}$$

Set 4: Each nurse has at least one day off.

$$O_{i,j} + O_{i,(j+1)} \geq 1 \quad i = 1,2 \ldots m\,, j = 1,2 \ldots n-1 \tag{18}$$

$$O_{i,j} + O_{i,(j+1)} + d_4^- - d_4^+ \geq 1, \quad i = 1,2,\ldots,m \tag{19}$$

The objective function for the model is incorporated from the positive and negative deviations of the soft constraints. Each goal from the soft constraints will be minimized according to its rank of priority. The goal of this model is to minimize the goal 1 (from Set 1 in soft constraint), followed by goal 2 (from Set 2 in soft constraint), goal 3 (from Set 3 in soft constraint) and goal 4 (from Set 4 in soft constraint). Goal 1 aims to minimize the positive deviational variables in order to avoid a morning shift followed by evening or night shift. Goal 2 also aims to minimize positive deviational variables in order to avoid evening shift followed by morning or night shift. Goal 3 also aims to minimize positive deviational variables in order to avoid night shift followed by morning or evening shift. Furthermore, goal 4 aims to minimize the negative deviational variables in order to guarantee at least one day off for each nurse. Thus, the objective function for the model is according to below:

Goal Programming Model:

[Minimizing total deviation]

$$\sum_j \sum_i d_1^+ + \sum_j \sum_i d_2^+ + \sum_j \sum_i d_3^+ + \sum_i d_4^- \quad (20)$$

[Subject To]

Eq (5), Eq (6), Eq (7), Eq (8), Eq (9), Eq (10), Eq (11), Eq (13), Eq (15), Eq (17), Eq (19).

4. Results and discussion

The results of the application of goal programming method in this study of nurse scheduling problem is done by using python programming code for the weekly schedule plan in the hospital emergency department. The programming code had been solving to allocate the 15 nurses in their respective shifts (morning, evening and night) in a day for seven working days.

Shift 1, shift 2 and shift 3 indicates morning, evening and night shifts respectively. Day 0 until day 6 indicates Monday until Sunday. Table 2 shows the output that generate using Python code.

Table 2: The output from Python programming code

	Day 0	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**DAY 6**
Shift 1	Nurse 2, Nurse 4, Nurse 5, Nurse 6, Nurse 7	Nurse 2, Nurse 5, Nurse 7, Nurse 8, Nurse 11	Nurse 1, Nurse 2, Nurse 6, Nurse 13, Nurse 14	Nurse 5, Nurse 7, Nurse 8, Nurse 10, Nurse 14	Nurse 4, Nurse 5, Nurse 6, Nurse 8, Nurse 12	Nurse 3, Nurse 5, Nurse 6, Nurse 12, Nurse 13	Nurse 1, Nurse 2, Nurse 3, Nurse 11, Nurse 15
Shift 2	Nurse 1, Nurse 8, Nurse 9, Nurse 12, Nurse 13	Nurse 1, Nurse 6, Nurse 12, Nurse 14 Nurse 15	Nurse 3, Nurse 8, Nurse 10, Nurse 12, Nurse 15	Nurse 1, Nurse 2, Nurse 4, Nurse 9, Nurse 15	Nurse 3, Nurse 7, Nurse 11, Nurse 14, Nurse 15	Nurse 1, Nurse 4, Nurse 7, Nurse 14, Nurse 15	Nurse 4, Nurse 5, Nurse 6, Nurse 10, Nurse 13
Shift 3	Nurse 3, Nurse 10, Nurse 11	Nurse 3, Nurse 4, Nurse 13	Nurse 4, Nurse 9, Nurse 11	Nurse 3, Nurse 6, Nurse 12	Nurse 1, Nurse 10, Nurse 13	Nurse 2, Nurse 8, Nurse 9	Nurse 8, Nurse 9, Nurse 12

The Python program generates the nurse scheduling for the emergency department, and the obtained results are then summarized and presented in an Excel format. This allows for a clearer understanding and visual representation of the nurse schedule. Table 3 showcases a patterned schedule for the nurses over a span of seven working days, providing a structured framework for their shifts.

Table 3: The schedule pattern for nurses in seven working days

Schedule's Pattern															
Number of nurses in emergency department															
Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	E	M	N	M	M	M	M	E	E	N	N	E	E		
2	E	M	N	N	M	E	M	M			M	E	N	E	E
3	M	M	E	N		M		E	N	E	N	E	M	M	E
4	E	E	N	E	M	N	M	M	E	M		N		M	E

5	N		E	M	M	M	E	M		N	E	M	N	E	E
6	E	N	M	E	M	M	E	N	N			M	M	E	E
7	M	M	M	E	E	E		N	N	E	M	N	E		M

Note: (M) Morning shift, (E) Evening shift, (N) Night shift, empty box for day off

Meanwhile, for Table 4 shows a summary for the number of nurses, number of working days, day off and also the total working hours for the schedule pattern.

Table 4: Summary of the nurse working days and off days

Number of staff	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Working Days	7	6	7	7	6	7	5	7	5	5	5	7	6	5	6
Off Days	0	1	0	0	1	0	2	0	2	2	2	0	1	2	1
Total Working Hours	56	48	56	56	48	56	40	56	40	40	40	56	48	40	48

The scheduling model has met conditions of the hard constraints of allocating a complete set of nurses for each required shift with five nurses assigned to both the morning and evening shifts and three nurses assigned to the night shift. Additionally, the model has achieved the objective of ensuring that each nurse works only one shift per day over the schedule of seven working days that satisfied set 2 in hard constraints. Regarding the soft constraints, which involve avoiding morning shift followed by evening and night shifts, consecutive evening shifts followed by night and morning shifts or consecutive the night shift followed by morning and evening shift on the next day, the model has partially succeeded. Specifically, three out of the 15 nurses have been scheduled to work the morning shift continuously for at least two consecutive days, four out of 15 nurses have been assigned to the evening shift continuously for at least two consecutive days while one out of 15 nurses have been assigned to the night shift continuously for at least two consecutive days in a schedule. For set 1,2,3 in the soft constraints, eight nurses in total who achieve the goals indirectly have minimize the total deviation $d_{1,}^{+}, d_2^{+}\ and\ d_3^{+}$. Finally, for the last set of soft constraints where each nurse has at least one day off is applicable for 9 out of 15 nurses (Nurse 2, Nurse 5, Nurse 7, Nurse 9, Nurse 10, Nurse 11, Nurse 13, Nurse 14 and Nurse 15) have achieve this set where they have 1 or 2 days off in a schedule. The other nurse had not achieved this set. As the soft constraints are not the main objective, it can be violated without exceptions. Overall, the model has performed well in meeting the hard constraints and has made some progress in addressing the soft constraints, although further improvements may be needed to fully satisfy other requirements.

Conclusion

This study is conducted with the objective of allocating the nurse in the emergency department to their respective shifts in a week by using Python. The goal programming method is effective in solving the problem by considering multiple objectives and providing a comprehensive solution that balances the needs of the nurses. The results of the goal programming are demonstrated the allocation of nurses to their respective shift. Python is a versatile programming language that has a wide range of libraries and framework that is designed for optimization and scheduling problems. The library that was uses in this study provide a powerful tool for modeling and solving the scheduling problems efficiently. This study can be improvised by considering other constraint to achieve a better scheduling plan for nurses in the emergency department.

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