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ORIGINAL ARTICLE

A new formulation and solution for the nurse scheduling problem: A case study in Egypt

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Abstract Nurse Scheduling Problem (NSP) is the assignment of a number of nurses to a number of shifts in order to satisfy hospital's demand. The objectives of NSP are the minimization of the overall hospital cost, and the maximization of nurses' preferences while taking into consideration the governmental rules and hospital standards. In this article, a proposed mathematical model for the NSP is presented, which is based on the idea of multi-commodity network flow model. The proposed model was verified using hypothetical instances as well as benchmark instances, then, it is applied to a real case study in an Egyptian hospital. The results demonstrate the advantage of using the proposed model in generating schedule required to solve the problem. Furthermore, it proves the superiority of the obtained schedule to those generated manually by the supervisor head nurse as it improves the level of nurses' satisfaction by creating fair schedule system take care about nurses' preferences as well as decreases the overall overtime cost by 36%.

1. Introduction

The ability to have an excellent staff on duty at the right time is an important factor for organizations to satisfy their customers' requirements. So that, staff scheduling problem is of importance for many organizations in industry as well as in services. Generally, scheduling problems have received attention over the past years as they based on the small-action-big-effect concept that maximizes the profitability of different organizations through exploitation of workers and equipment in the best possible way. In the last twenty years, more than 300 articles discussed various problems related to the scheduling problem [1].

Nurses' main responsibility is to take care of the patient in order to improve patient satisfaction. However, nurses nowadays spend a lot of time in recording health care related documents through electronic medical records to improve care coordination. As a result, in USA, more than 50% of full-time nurses work an average of seven hours of overtime each week. This situation may solve the NSP in hospitals in short term, but it has a lot of consequences in the long term for example, the nurses who work 40 h in a week or 12 h in a shift are more likely to have job dissatisfaction. This in return negatively affects the hospital profitability [2].

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Egypt is facing the shortage number in nurses compared to the number of patients. According to undersecretary of the faculty of Nursing in Cairo University, nowadays one nurse services 20 patients although in nursing standers one nurse services 8–10 patients.

Nurse Scheduling Problem (NSP) aims to assign a number of nurses to a number of shifts in order to satisfy hospital's demand. During latest 50 years, NSP became important problem in field of operation research and artificial intelligence. The automatic generation of high quality schedules can lead to improvements in: hospital resource efficiency, staff and patient safety, staff and patient satisfaction, and administrative workload.

The main target of NSP is to assign an optimum number of different skilled nurses for each shift, while minimizing the hospital's cost, and maximizing the nurses' preferences [3]. There are several factors affecting the NSP: the governmental regulations, labor laws, hospital policy, and the status of nurses.

In NSP, there are three main terms:

- **Planning horizon:** Time span covered by a particular plan
- **Shift:** Each day is divided into time slots called shifts. The number of nurses required in each shift is pre-specified.
- **Off day:** A day when a nurse has no shifts to work.

The output of the NSP is as shown in Fig. 1. The planning horizon is K days, each day is divided into a number of shifts (e.g. morning, evening, and night), each shift has a pre-specified number of nurses should be satisfied while considering the maximum number of shifts that a nurse can work.

Due to governmental rules and hospital policy, a set of constraints must be satisfied as follows:

1. Each nurse can have at most two shifts a day.
2. Each nurse must have at least a pre-specified number of night shifts in the week.
3. Each nurse must have at least a pre-specified number of evening shifts in the week.
4. Each nurse should work between a minimum and a maximum number of shifts during the planning horizon.
5. If a nurse has a shift in a specific day, then, he/she should be off for next two consecutive shifts. However, if a nurse has two consecutive shifts in a specific day, he/she should be off for next three consecutive shifts.

The rest of the paper is organized as follows; review of recent literature is presented in the next section. In the third section, the proposed mathematical model is presented. Finally, the results of implementing the proposed model in a real case study are discussed.

2. Literature review

In addition, and in order to elaborate the progress in the NSP, the articles related to the problem were presented in their chronological appearance. At the end of the literature, we focused on our contribution which is based on proposing a new model that captures most of the aspects related to the NSP based on the idea of MCF.

2.1. Exact techniques

There are several articles which use exact methods to solve the NSP. Yilmaz et al. [4], developed a mathematical model that minimize nurses' total idle time during a week planning horizon. The model was verified using a numerical example and then LINGO8.0 software is used to ensure the global optimum solution.

Alkhabbaz et al. [5] studied a real case study in Kuwaiti health care units. They developed a mixed integer model that minimize outsourcing nurses, and considered nurses' preferences. EL-Rifai et al. [3], proposed a stochastic mixed integer programming model that used sample average approximation approach to create suitable shift schedule for the emergency department in the University Hospital Center of Lille France. Then, they evaluated the solutions using a discrete-event simulation model.

Legrain et al. [6] studied the scheduling process for two types of nursing teams, regular teams and float teams. Float teams are used to cover the shortages in the hospital. They proposed two different models that are flexible and easy enough to be implemented on spreadsheets. The first model that minimized the total cost, while maximizing the nurses' preferences. The second one was a local search-based model. They illustrated the advantages of their proposed models over commercial software packages by comparing the models results with optimization software.

Bateni et al. [7] proposed a mathematical model that maximized the nurses' preferences and minimized the total outsource nurses to cover the demands of each day. Their proposed model considered hospital's policies and governmental regulations.

Hamed Jafari et al. [8] developed a mathematical model that maximize nurses' preferences. An optimal solution was generated by their proposed model, and then they used simulated annealing approach to solve the problem in a reasonable time. The experiments showed that the computation time of the mathematical model was 6128.70 s, and the computation time of the simulated annealing approach was 502.48 s.

Liang et al. [9] developed two multi-objective optimization models, the first one was functional care delivery model, and the other one was primary care delivery model. Those models aimed to minimize the total patient waiting time and find optimal appointment times to minimize the total nurse overtime. They applied the models in one of largest oncology clinics. The results showed that the proposed models were flexible, competitive and capable of reaching an optimal solution.

Zakria et al. [10] proposed stochastic optimization model and sample average approximation method to obtain an optimal case-mix plan for a surgery department with considering nurses capacity constraints. Their model was solved under three capacity constraints: nurses, beds, and operating room time.

Ohki et al. [11] proposed an effective mutation operator that guarantee the consistency of the nurse scheduling generation. They used a new penalty function which evaluates the difference between the original schedule and the optimum schedule. Edmund et al. [12] proposed a multi-objective model that use integer programming and variable neighborhood search heuristic. Their model has two steps. In the first step,

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