A two-stage heuristic approach for nurse scheduling problem: A case study in an emergency department

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ABSTRACT

Nurse scheduling is a critical issue in the management of emergency department. Under the intense work environment, it is imperative to make quality nurse schedules in a most cost and time effective way. To this end, a spreadsheet-based two-stage heuristic approach is proposed for the nurse scheduling problem (NSP) in a local emergency department. First, an initial schedule satisfying all hard constraints is generated by the simple shift assignment heuristic. Second, the sequential local search algorithm is employed to improve the initial schedules by taking soft constraints (nurse preferences) into account. The proposed approach is benchmarked with the existing approach and 0–1 programming. The contribution of this paper is twofold. First, it is one of a few studies in nurse scheduling literature using heuristic approach to generate nurse schedules based on Excel spreadsheet. Therefore, users with little knowledge on linear programming and computer sciences can operate and change the scheduling algorithms easily. Second, while most studies on nurse scheduling are situated in hospitals, this paper attempts to bridge the research gap by investigating the NSP in the emergency department where the scheduling rules are much more restrictive due to the intense and dynamic work environment. Overall, our approach generates satisfactory schedules with higher level of user-friendliness, efficiency, and flexibility of rescheduling as compared to both the existing approach and 0–1 programming.

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1. Introduction

The healthcare expenditure in Hong Kong has reached HK$84.4 billion in 2009, about 5.1% of the Hong Kong GDP and a projected increase to 9.2% by 2033. However, Hong Kong's total healthcare expenditure as a share of GDP is still far behind the world leading economics such as United Kingdom (9.8%), Australia (8.7%), Canada (11.4%), and United States (17.6%) in year-on-year comparison [1]. Due to the economic recession, an increasing number of experienced nurses have flowed to private healthcare institutes for higher salaries and lighter workload. This trend has led to a nurse shortage, especially the senior nurses in public hospitals. Emergency Department (ED) is the frontline of providing emergency care in a hospital, unfortunately it also suffers from the nurse shortage problem and has been under the criticism of declined service quality. At the meantime, there are more non-urgent patients seeking for ED services these years for the better facility and lower cost as compared to private clinics, and this further increases the workload of nurses. The problem mentioned can be boiled down to the mismatch between the increasing demands and the shrinking nursing manpower in the public healthcare institutes.

Nurse Scheduling Problem (NSP) is a critical part of ED resources management. A good schedule can contribute to improving nurse well-being and workload distribution, and hence enhance the work efficiency and patient experience. More importantly, it allows ED decision makers to better manage the scarce ED resources. Therefore, a good schedule can benefit both sides of patients and nurses. To a larger extent, NSP belongs to a broad topic of staff scheduling. This topic has been extensively studied by operational researchers and computer scientists for many years. According to Ernst et al. [2], staff scheduling can be defined as "the process of constructing work timetables for its staff so that an organization can satisfy the demand for its goods and services". A good schedule should maximize the satisfaction of well-defined constraints such as government regulations, working practices, and personnel preferences, etc. A significant number of scheduling problems have been studied over the past few years in other commercial sectors, such as manufacturing [3–6], sales [7], airline crew [8–13], bus driver [14–16], and call center [17,18]. Unlike many commercial organizations, EDs provide

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around-the-clock services and the scheduling rules are very restrictive due to frequent manpower turnovers and unpredictable changes of shifts. Therefore, it may be difficult to apply the similar scheduling techniques that have been successfully used in other industries to solve the NSP in ED. Even the NSP in ED can be formulated in mathematical expressions without much difficulty, it is still very challenging to generate quality schedules using low-end computer tools that nurses can operate without extra knowledge.

In this study, we attempt to propose a heuristic approach to solve NSP in a local ED. Fig. 1 illustrates an overview of the NSP which involves several phases from macro-level planning to task rosters for each 8-h shift and three shifts a day. In the planning phase, the nurse staffing level of three shifts is estimated based on daily patient visits and upper limit of waiting times [19]. Other information such as the qualification/seniority of nurses, legal regulations, and nurse preferences on shifts have also been collected. In the scheduling phase, a two-stage heuristic approach combining simple shift assignment heuristic and sequential local search (SLS) is proposed, and it is benchmarked with 0–1 programming. Real-time rescheduling is very useful in ED environment where there are frequent changes of shifts/day-offs. Shift task rostering assigns primary ED duties such as triage, resuscitation, minor patient handling, etc. This paper focuses on the scheduling part.

The organization of this paper is as follows: Section 2 provides an extensive literature of NSP studies in the last decade. Section 3 describes the nursing resources and existing scheduling approaches of the target ED. Section 4 presents the details of the proposed approach. Section 5 describes the formulation of 0–1 programming model. Section 6 reports the comparison between different approaches in terms of several measures. Section 7 gives concluding remarks and future work.

2. Literature review

In general, there are four scheduling methods which have been widely used. They are cyclical scheduling, mathematical programming, heuristic scheduling, and artificial intelligence (AI). In cyclical scheduling, the shift and vacation assignment are fixed and repeated over certain time period. Hence, cyclical scheduling can minimize the shift uncertainty and allow nurses to be well-prepared for their assigned duties over a certain time period [20]. Marchionno [21] identified seven steps to help schedule the nurses in three-shift rotation. However, this approach is not

suitable to the target ED in which the shifts/day-offs are often changed to accommodate unexpected urgent issues of nurses.

Mathematical programming approach is a traditional technique which has been widely applied to NSPs. This approach aims to search over a large solution space in order to locate the best solution such that the objective function can be optimized. Some previous studies have dedicated to mathematical programming approach, including integer programming [22–28], multi-objective goal programming [29–32], multicommodity flow [33]. Unlike other three approaches, mathematical programming approach guarantees optimal solutions. However, when the number of variables and constraints become large, the searching of optimal solutions would become very time-consuming. Therefore, in many recent studies, mathematical programming is integrated with other approaches such as GA [34] and local search approaches [32,35]. In this hybrid approach, the mathematical programming searches for the preliminary solutions satisfying all hard constraints, and then GA and local search approaches refine the solutions by maximizing the fulfilment of soft constraints. Such approach is able to find near-optimal solutions but consume much less computational time.

In heuristic scheduling, a set of scheduling rules are collected for constructing a decision-making tree which guides the generation of a feasible schedule under a variety of scenarios. These rules are formulated based on ED policies and regulations, service pledges, nurse preferences, etc. Some major heuristic techniques include knowledge-based techniques [36], adaptive heuristic [37], combinations of heuristic approaches [35,38], tabu and other local search [23,24,28,39–47], mix of tabu search and integer programming [23,32,35,48–50]. A typical example of local search technique is variable neighbourhood search (VNS) which is based on the idea of systematic change of neighbourhood area to identify better local optima [51]. It has been applied to a wide range of decision and optimization problems [32,35]. A comprehensive summary of VNS can be found in [52]. The motivation of developing heuristic approaches is to overcome the challenge of long computation time required by traditional mathematical programming approach, but the optimality of solutions cannot be guaranteed.

Many AI techniques have been applied to solve NSP, such as simulated annealing [31,53], ant colony optimization [54], and genetic algorithm (GA). Among them, GA is the most popular one. Cheang et al. [55] and Burke et al. [56] conducted extensive literature review on the application of GA since it was first introduced to NSP by Colorni et al. [57]. Unlike the local search techniques such as tabu search, GA can search the global near-optimal solutions in multiple points
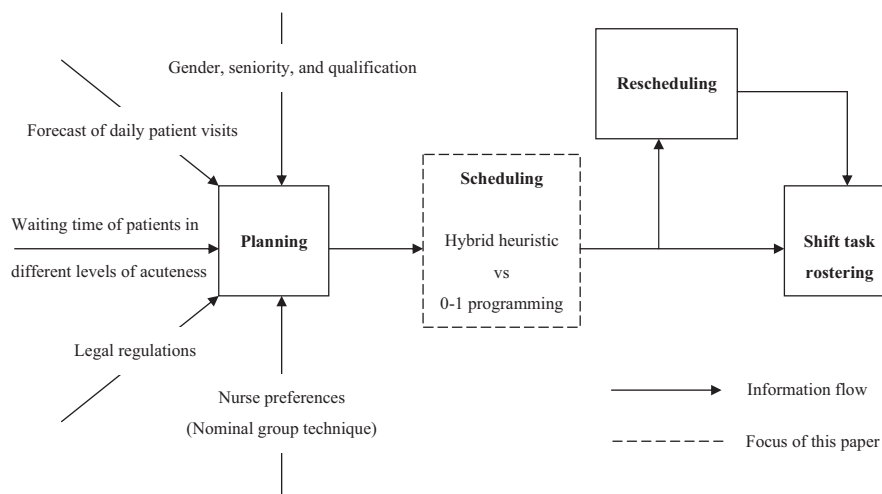

Fig. 1. Nurse scheduling procedures for the target ED.