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A two-phase adaptive variable neighborhood approach for nurse rostering

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ABSTRACT

This contribution presents a two-phase variable neighborhood search algorithm for solving nurse rostering problems. In order to demonstrate the efficiency of the proposed algorithm, it is firstly applied to all nurse rostering problem instances as proposed in the First International Nurse Rostering Competition (*INRC-2010*). Computational results assessed on all three sets of sixty competition instances demonstrate that the proposed algorithm improves the best known results for two instances, inside the time limits of the competition, while achieving the best known bounds for forty eight other instances. The proposed algorithm was also applied to seven other nurse rostering instances reported in the respective literature and managed to achieve the best known result in six of them while improving the best known result in one instance. The proposed algorithm, as well as its differences from existing approaches are presented, described and discussed in detail.

1. Introduction

In this contribution, the problem of nurse rostering is faced. This problem represents a class of timetabling problems which refer to the schedule of the personnel's shift in a hospital. It consists in generating daily (or weekly) schedules for nurses by assigning a number of daily (or weekly) demanding shifts to nurses with different skills in order to satisfy certain predefined hard and soft constraints. Nurse rostering real world problems have to satisfy a large number of constraints and requirements and are affected by many parameters. As a result, they are complex and difficult to solve and comprise a great challenge not only for personnel managers in hospitals but also for researchers in universities. The entities involved in the construction of a feasible and effective roster are the nurses, the shifts and the time periods. More precisely, nurses have to make some specific shifts in specific time periods considering many different issues like workload of nurses, coverage demand, day-off/on requirements, weekend-related requirements, consecutive assignments of shifts, etc. [3].

In the last few decades, nurse rostering has been extensively studied and many different approaches have been applied in order to solve real world nurse rostering problems [4]. These approaches can be classified in two major categories: deterministic algorithms and heuristics. As stated above, the first category's main disadvantage lies in its high computational complexity which limits their application only to small size instances. Therefore, alternative optimization methods, namely heuristics and metaheuristics have been developed in order to find suboptimal solutions of good quality in a reasonable time.

Heuristics and metaheuristics comprise a major class of methods to solve the nurse rostering problem. They are applied to complex optimization problems in cases where other optimization methods have failed to be either effective or efficient. Heuristic and metaheuristic representative methods solving the nurse rostering problem include evolutionary algorithms [5,6], memetic algorithms [7], variable neighborhood search [8–11], scatter search [12,13], tabu search [14,15], iterated local search [16], simulated annealing [17], ant colony optimization [18], particle swarm optimization [19], etc.

The algorithm presented in this contribution comprises a heuristic method to solve the nurse rostering problem. More precisely, it is a two-phase stochastic variable neighborhood approach, which uses nine different swap mechanisms. Some of them are innovative while the rest ones are well known and established swap mechanisms which, in our case, are applied in a total different way compared to other variable neighbourhood approaches presented in the literature [8,11,20,30]. More details concerning the differences of the proposed approach with former variable neighbourhood approaches are presented in Section 3. The use of nine different swap operators enriches the search capability of the proposed algorithm since it enables it to search in nine different neighborhoods of the problem's search space. The way these nine swap operators are applied in order to solve the *INRC-2010* test instances, as well as seven other nurse rostering instances reported in the respective literature, is the main innovation of the proposed approach and are presented in detail in Section 3.

The *INRC-2010* competition aimed to further develop interest in nurse rostering by presenting more challenging problems with an increased number of real world constraints [3]. Next, we present a brief review of the methods proposed by the *INRC-2010* competition finalists as well as two other efficient methods applied to the *INRC-2010* test instances after the competition.

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Valouxis et al. [21] used a two-phase algorithm to produce feasible and high quality rosters. At the first phase, the work and rest days of all nurses for a specific planning period are defined. At the second phase nurses assigned to each day of the planning period are scheduled to certain shifts according to the shift type demand of each day. For each problem an integer programming problem is defined and solved. Moreover, three additional local search processes are employed in the first phase to enhance its performance.

Burke and Curtois [22] proposed two different algorithms to solve the *INRC-2010* test instances. The first algorithm is an ejection chain method and it was applied to the *sprint* instances. The second algorithm is a branch and price method and it was applied to the *medium* and *long* instances. The second algorithm was in general able to solve many of the competition instances to proven optimality within the competition time limit.

Nonobe [23] formulated the nurse rostering problem as a constraint optimization problem (COP) and then used a general-purpose COP solver to achieve feasible and high quality rosters. The solver adopts tabu search for the modification of the current solution and employs mechanisms to control dynamically the constraints weights used for solutions' evaluation and the tabu tenure.

Bilgin et al. [24] used a hybrid algorithm which employs two different heuristic processes in order to solve the *INRC-2010* test instances. This hybrid algorithm applies a hyper-heuristic followed by a greedy shuffle heuristic approach. Moreover, they reported computational results of solving the nurse rostering problem as an integer linear programming using IBM CPLEX.

Santos et al. [25] proposed an Integer Programming technique to tackle the test instances of the *INRC-2010*. Starting from a compact and monolithic formulation of the problem, they applied improved cut generation strategies and primal heuristics. Combining an aggressive clique separation process with a Mixed Integer Programming heuristic managed to improve the till then best known solutions up to 15%.

Lü and Hao [10] presented an adaptive variable neighborhood search method which uses jointly two distinct neighborhood moves and adaptively switches among three intensification and diversification strategies based on search history. It succeeded in improving the till then best known results for 12 instances while matching the till then best bounds for 39 other instances.

This paper is organized as follows. Section 2 defines the nurse rostering problem and the constraints used, as defined in *INRC-2010*. Section 3 describes the proposed two-phase variable neighborhood algorithm. Section 4 assesses and compares the performance of the proposed algorithm to that of existing approaches, while Section 5 presents the discussion. Finally, Section 6 provides summary and future extensions.

2. Problem definition

Nurse rostering problems have been proved to be NP-hard in their general form, as far as their computational complexity is concerned [1,2,31,32,33]. The nurse rostering problem considered in this contribution is the one introduced by *INRC-2010* and consists of assigning shifts to nurses in accordance with a given set of constraints [3]. Two types of constraints are defined, namely, hard and soft constraints. Hard constraints are the ones that have to be strictly satisfied under any circumstances, while soft constraints are the ones which are not necessarily satisfied but whose violations should be desirably minimized. A roster satisfying all hard constraints is called a *feasible* roster. A single violation of a hard constraint renders the solution infeasible. The aim of an effective nurse rostering solver is to create feasible rosters satisfying as many soft constraints as possible. The number of soft constraints satisfied by a feasible roster characterizes the *quality* of a roster. The test instances used in order to check the performance of the proposed two-phase adaptive variable neighborhood approach are the ones used in *INRC-2010* and are grouped in three tracks, namely, *sprint*, *medium* and *long*. The interested reader can find a detailed description of the competition problem instances in [3]. A brief description of all hard and soft constraints used as well as a mathematical formulation of the nurse rostering problem introduced by *INRC-2010* is presented in the following subsections.

2.1. Constraints

As stated above, in this work, we considered the following hard and soft constraints, as defined in the *INRC-2010*:

- Hard constraints
  - *H1: Coverage requirement* – all shift type demands during the planning period must be met.
  - *H2: Single shift per day* – a nurse cannot work more than one shift per day.
- Soft constraints
  - *S1: Maximum assignment* – the maximum number of shifts assigned to a nurse.
  - *S2: Minimum assignment* – the minimum number of shifts assigned to a nurse.
  - *S3: Maximum consecutive working days* – the maximum number of consecutive days on which a nurse has a shift.
  - *S4: Minimum consecutive working days* – the minimum number of consecutive days on which a nurse has a shift.
  - *S5: Maximum consecutive free days* – the maximum number of consecutive days on which a nurse has no shift.
  - *S6: Minimum consecutive free days* – the minimum number of consecutive days on which a nurse has no shift.
  - *S7: Maximum consecutive working weekends* – the maximum number of consecutive weekends on which a nurse has at least one shift.
  - *S8: Maximum number of working weekends* – the maximum number of weekends in four weeks in which a nurse has at least one shift.
  - *S9: Two free days after a night shift* **–** after a night shift during the following two days, a nurse should not be assigned any shift.
  - *S10: Complete weekends* **–** if a nurse works on at least one day of the weekend, then she should work on all days of the weekend.
  - *S11: Identical shift types during the weekend* **–** a nurse should work the same shift types during all days of a working weekend.
  - *S12: Unwanted patterns* – a nurse should not work a specific unwanted pattern in a row (An unwanted pattern is a sequence of assignments that is not in the preferences of a nurse according to her contract. There are unwanted patterns involving specific shift types and unwanted patterns not involving specific shift types).
  - *S13: Requested day on* – Requests by nurses to work on specific days of the week should be respected, otherwise a penalty occurs.
  - *S14: Requested day off* – Requests by nurses not to work on specific days of the week should be respected, otherwise the solution is penalized accordingly.
  - *S15: Requested shift on* – Requests by nurses to work specific shifts on certain days of the week should be respected, otherwise a penalty occurs.
  - *S16: Requested shift off* – Requests by nurses not to work specific shifts on certain days of the week should be respected, otherwise the solution is penalized accordingly.