Can optimization methods reduce expenditures in nurse rostering?

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Nurse rostering is the task of generating work schedules for nurses. When generating a schedule, one needs to balance three aspects: The nurses' working hours and conditions, sufficient staffing levels to ensure patient safety, and lastly budgetary restrictions.

As the Danish population is gradually aging, pressure on hospital budgets is growing. Thus, it is vital that hospitals ensure high-quality treatments, while keeping the length-of-stay of patients as low as possible. Achieving this is costly, and therefore an efficient resource utilization is of the utmost importance in hospitals today. With cost-efficient planning, the hospitals are given the choice to either: Do the same with less, or do more with the same. In this article, we investigate the potential of employing mixed integer programming to create cost-efficient rosters under Danish legislation. Thus, we have assessed the potential for Danish hospitals to do the same, but with lower expenses for their personnel resources. Manually generating rosters results in a poor utilization of the resources, as criticized by The National Audit Office of Denmark [4]. They concluded that the work schedules were not cost-effective, and emphasized that most of the investigated wards did not assign all of the working hours corresponding to a fixed monthly salary.

In 2013, the expenditures related to human resources in Danish hospitals amounted to 45 billion DKK, or a total of 60% of the hospital expenditure [4]. In 2017, the hospitals in Denmark had over 35 thousand full-time equivalent nurses, or close to half of the full-time equivalent health care personnel in the hospitals [5]. Therefore, the expenditures related to nurses in Danish hospitals are substantial.

The salary expenditures for nurses can generally be divided into several categories as seen on Figure 1. The spendings within some of these categories depend on the allocation of the resources, for example the cost of substitute staff or time-related supplements (for working evenings, nights and weekends).

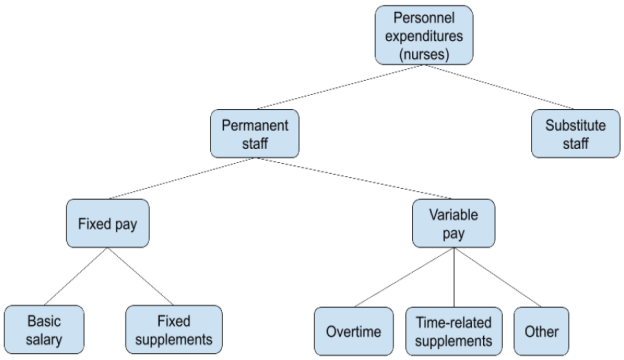

Figure 1: A hierarchical categorisation of salary expenditures

Figure 2 shows an example of a one-week work schedule for nine nurses. The nurses have been assigned to shifts to satisfy a pre-defined staffing requirement for day, evening and night shifts. All nurses get two consecutive days off, and work between three to five shifts each. Although creating a small schedule like this one is not the most challenging task, managers will quickly loose oversight when creating longer schedules for 50-100 nurses. Nurse rostering is a complex combinatorial problem, but it is solved manually in most hospitals in Denmark.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
n1		D	D	D	D		
n2		E	E	E	E		
n3	N	N	N	N			
n4	D	D			N	N	N
n5	E		D			D	D
n6	E	E			E	E	E
n7	D			D	D	D	D
n8	D	D	E	E			
n9			D	D	D		

Figure 2: An example of a roster with nine nurses working 3-5 shifts a week to meet a predetermined staffing requirement

Problem description

We analyzed the potential for reducing time-related supplements (cf. Figure 1), by a better allocation of the personnel. Table 1 shows the rate for different times. All these supplements are paid by the hour and calculated for every 30 minutes begun. Furthermore, the supplements are additive, e.g., during Saturday evening the nurses obtain the combined supplement for evening and weekends, corresponding to 69% of the nurse's hourly rate.

As the supplements are calculated based on the salary of individual nurses, the allocation of nurses to shifts can have a huge impact on the spendings. For example, assigning a senior nurse with many years of experience to a night shifts is substantially more costly than assigning the same shift to a newly educated nurse.

	Time	% of hourly rate
Evenings	From 18:00 to 23:00	27%
Nights	From 23:00 to 06:00	32.5%
Weekends	From 06:00(Sat) to 24:00(Sun)	42%

Table 1: Time-related supplements

We obtained real data for two wards in a Danish hospital, Ward A and Ward B. Ward A has 70 nurses and schedules 231 nurse-to-shift assignments each week, while Ward B has 64 nurses and a total of 205 assignments each week. Furthermore, Ward A has a great variability in the tasks that they perform, resulting in different competences required for different shifts.

These wards create the schedules manually, and the cost of time-related supplements is substantial in both wards. In Ward A, the supplements amount to 15% of the total salary costs for nurses or 8% of the total salary costs for all employees in the entire ward. In Ward B, they amount to 9% of the total salary cost for nurses or 3.5% of the entire salary cost for the ward.

To comprehend the immense extent of these supplements we compare them to the average fixed pay for a full- time nurse. **In Ward A, the time-related supplements correspond to a fixed annual pay for more than 18 full-time nurses, while in Ward B it corresponds to more than 11 full-time nurses.** In other words, each ward can hire one additional nurse for a mere 5-9% reduction of their time-related supplements.

Minimizing time-related supplements

We formulated a mixed integer programming model with the objective of minimizing time-related supplements to analyze the room for reductions. The model includes several constraints to ensure that lowering the cost does not negatively impact the patients or nurses.

min time-related supplements
s.t. pre-defined staffing requirements available personnel
legislation for nurses' working time
healthy and fair work schedules for each nurse

We assume a generalized planning horizon that omits various exceptions that occur from schedule to schedule and could bias the optimization. These exceptions include sick-leave, vacation and public holidays. As the generalized horizon is uniform, we can generate cyclic schedules, i.e., schedules that we can use repeatedly. We generate the schedules for a four-week horizon, as is current practice.

We consider several constraints that are needed in practice. The first constraint is to meet the current staffing requirements, thus obtaining the lowest expenditure for time-related supplements without reducing the service level offered to patients.

The second constraint relates to how we utilize the available personnel, as we do not want to lower the time-related supplements at the expense of overtime. We consider two scenarios for the availability. In the first scenario we assume all nurses are fully available during the rostering horizon (i.e., no sick-leave or vacation). In the second scenario we consider the average absentees of a nurse on an annual basis.

In general, employees in the public sector are entitled to six weeks of vacation every year. Additionally, nurses take 13 sick days on average during a calendar year [2]. In total, this corresponds to 15.07% absentee days during a year for an average nurse, where 11.51% correspond to vacation and 3.56% correspond to sick-leave. Thus, the second scenario sets the upper bound for each nurse as 85% of the contractual hours, instead of fully utilizing them.

Less than 25% of absentees are due to sick-leave, which we cannot plan. The remainder is vacation days, which the planners have some flexibility in assigning to the nurses. Moreover, having fewer resources available than required should not affect the time-related supplements, but rather spendings on float nurses or overtime.

The legislation imposes two types of constraints, which we will describe in their strictest form [1, 6]. First, each nurse should get at least 11 consecutive hours off for resting within every 24 hours. Second, they should get protected days off, which should on average be two days off for every workweek. The law states that these days should be distributed in an equal manner, with at least two protected days off within every eight days. For a protected day off we require a certain number of hours off between the adjacent work shifts. This number is 35 hours for a single protected day off, 55 hours for two consecutive days and 79 hours for three consecutive days.

Even though the legislation allows room for relaxing these requirements, for example by reducing the number of hours off or increasing the number of days between protected days off, we exclude all relaxation. The main reason is that all individual nurses need to accept any relaxation for their schedule, and

including them when estimating the possible savings paints an incorrect picture as the nurses should not be pressured into any relaxations.

At last we analyze the cost of including additional constraints for the nurses' working time. The constraints we consider are common, both in practice and in nurse rostering research. These constraints are not legally binding, but should ensure that the nurses get healthy schedules. The constraints that we analyze are:

1. Forbidding certain shift successions.
2. Restricting weekend work.
3. Restricting night work.

For forbidden shift successions, we defined a new constraint stating that when we assign a nurse to a night shift we cannot assign her to a day shift until two days have passed. This constraint should ensure that although the nurses need to alter their sleeping patterns they should still get sufficient sleep between shifts.

For restrictions related to weekend work, we define two new constraints. The former constraint ensures that the nurses have compact work weekends, i.e., either a nurse works on both Saturday and Sunday, or she works neither day. The latter constraint ensures that all nurses work a maximum of two weekends during the four-week horizon. We note that we can expect these constraints to affect our objective, as the supplements related to weekend work are rather high.

For restrictions on night shifts, we define a single constraint that should ensure a fair distribution of night shifts between the nurses. We round up the average number of night shifts per nurse needed to cover the staffing requirements and ensure that no nurse exceeds that number of night assignments during the four-week horizon. In both wards, this maximum becomes three night shifts per nurse. As the nurses obtain supplements for night work, we can expect this constraint to affect our objective.

Results

Table 2 shows the different scenarios we analyzed along with the corresponding reduction in time-related supplements. All scenarios include constraints for the pre-defined staffing requirements along with legislative constraints, while we alter the availability for personnel along with the additional constraints for healthy work schedules.

Scenario	Availability	Additional constraints	Reduction Ward A	Reduction Ward B
1	Full	None	34.92%	22.72%
2	85%	None	34.23%	22.17%
3	Full	Forbidding certain shift successions	34.92%	22.72%
4	Full	Restricting weekend work	33.01%	20.69%
5	Full	Restricting night work	34.16%	21.60%
6	Full	All three constraints for healthy schedules	32.37%	19.82%
7	85%	All three constraints for healthy schedules	32.20%	19.50%

Table 2: Results

By comparing the first two scenarios we see that the results are not sensitive when reducing the availability. Even though the availability percentage for each nurses differ between rostering horizons throughout the year, the average is 85%, making scenario 2 representative for the overall room for reduction when only considering legally binding constraints on working time. The savings in Ward A correspond to 6.3 years' salary for a full-time nurse, while in Ward B they correspond to 2.5 years.

By looking at the remaining scenarios we can see that adding more constraints for healthy schedules results in a slight decrease in the savings. Nonetheless, the savings when including all three constraints and assuming 85% availability (scenario 7) still correspond to 5.9 years' salary for a full-time nurse in Ward A, and 2.2 years in Ward B.

Discussion

As additional constraints for the nurses' working time are important in practice, we find it intriguing to see how little extra costs are incurred. Nurses are an immensely valuable resource, and having satisfied nurses and maintaining qualified resources significantly outweighs this small increase in supplements.

We acknowledge that the results slightly overestimate the possible savings, as we do not take the supplements related to public holidays into account. However, including public holidays in the analysis would not paint the correct picture, as the planners often lower the staffing requirements on such days. When assuming no reduction in the requirements, the added cost of public holidays corresponds to only 2-4% of the annual supplement spending in the two wards. Therefore, we can conclude that the potential for expenditure reduction is substantial even when accounting for public holidays.

In practice, the nurses can choose either to get the supplements paid out or to get time off as compensation. If some nurses rather choose time off than paid supplements, the expenditures in this category would be reduced even further. This assumption creates a bias in our comparison to current expenditures, as they include the choices of each individual nurse at each point in time. Nonetheless, the assumption is necessary to conduct a macro analysis, and the bias does not lessen our results, but on the contrary, strengthen them.

Another category for variable cost is related to substitute staff. Nonetheless, the allocation of float nurses is often not planned along with the original schedule, but added to it later on due to various disruptions, e.g., sick-leave. Additionally, the planners may react differently when absentees occur with the permanent staff. In some cases, they would call in float nurses, but in other cases, they would ask the permanent staff to work additional shifts, either as over-time or without exceeding their contractual hours. Moreover, an absentee nurse is not always substituted in the plan and the wards sometimes operate below the staffing requirements [3]. In all scenarios, we manage to create schedules using only the

permanent staff, i.e., without any cost for substitute staff.

Concluding remarks

We conclude that there is substantial room for reducing the expenditures and producing cost-effective schedules that simultaneously are satisfactory for the nurses. Moreover, we have shown that the additional constraints to ensure healthier schedules only have a minor effect on potential expenditure reductions. We hope that the results we have obtained become a motivation for the Danish health care sector to increase their use of optimization methods in personnel scheduling.

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