Simultaneous Optimization of Two-Shift and Three-Shift Nurse Rosters with Infection-Risk-Based Transition

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Abstract. Nurse shortages become particularly severe during infectious disease outbreaks, and some hospitals operating under a three-shift system are forced to make a transition to a two-shift system in emergency situations. Focusing on such situations, we propose a scheduling method that enables smooth transitions between three-shift and two-shift duty rosters based on infection risk estimates derived from simulations based on the susceptible–exposed–infectious–recovered (SEIR) model. The proposed method suppresses undesirable shift sequences and simultaneously generates both three-shift and two-shift duty rosters. This reduces handover-related infection risk while preserving roster stability. Compared with a conventional re-optimization approach, the proposed method improves the stability of duty rosters.

Keywords: Nurse rostering · Shift transition · Infection modeling

1 Introduction

Nurse shortages in Japanese healthcare settings became particularly severe during the COVID-19 pandemic. Frequent staff absences resulted in repeated revisions of duty rosters, increasing both operational and psychological burdens on nurses and schedulers.

In studies related to COVID-19, resource allocation and workforce deployment approaches based on epidemiological models such as susceptible–exposed–infectious–recovered (SEIR) model have been proposed [1]. Furthermore, in practice, work systems have been modified in response to the infection situation [2].

In Japan, many hospitals operate either a three-shift system or a two-shift system. During the COVID-19 pandemic, some hospitals changed their work systems from a three-shift system to a two-shift system in response to staff shortages. However, if such changes are not properly designed, they may lead to excessive consecutive working days and undesirable shift patterns.

In this study, we propose a unified framework that integrates infection risk prediction with mathematical optimization to simultaneously generate both three-shift and two-shift duty rosters. Transitioning to a two-shift system helps mitigate staff shortages during infectious disease outbreaks. Preparing both rosters in advance enables smooth transitions and reduces infection risk by limiting shift-change contacts. It also reduces the burden of sudden schedule changes. Furthermore, the rosters generated by the proposed framework are robust even when the transition timing is uncertain due to upcoming infection conditions. For brevity, this paper focuses on transitions from a three-shift system to a two-shift system.

2 Method

In this study, we construct an infection process model based on a stochastic SEIR framework that considers healthcare workers, patients, and community exposure, and we predict infection dynamics using Monte Carlo simulation. In particular, we evaluate the probability that the infection rate among nurses first reaches a hospital-defined critical threshold (i.e., first-passage probability). We define a daily risk weight w_t for each day t based on the predicted probability, which is used to penalize undesirable shift patterns and excessive consecutive working days near likely transition periods.

Let N denote the set of nurses and T the set of days. The three-shift system consists of day, evening, and night shifts, whereas the two-shift system consists of day and night shifts (including a post-night rest period). Both systems also include shift candidates called special duties and days off. A special duty represents non-regular daytime assignments, such as staff training or temporary support in other hospital departments. Let $S^{(3)}$ and $S^{(2)}$ denote the sets of shift candidates for the three-shift and two-shift systems, respectively.

Binary variables x_{its} and y_{its} indicate whether nurse i is assigned to shift s on day t in the three-shift and two-shift systems, respectively. In each system, each nurse is assigned to exactly one shift per day:

$$\sum_{s \in S^{(3)}} x_{its} = 1, \qquad \sum_{s \in S^{(2)}} y_{its} = 1 \qquad \forall i \in N,\ t \in T.$$

To suppress undesirable shift sequences across different systems near transition boundaries, we introduce a slack variable $\alpha_{itss'}$ and impose the following constraint:

$$x_{i,t-1,s} + y_{i,t,s'} \leq 1 + \alpha_{itss'}, \qquad \forall i \in N,\ t \in T,\ (s, s') \in Q,$$

where Q is the set of forbidden shift pairs. The slack variable $\alpha_{itss'}$ is penalized in the objective function, with weights w_t derived from the first-passage probability.

Additional constraints include staffing requirements, adjusted according to estimated infection-related absences, nurse preferences, workload limits, and off-duty consistency. Staffing requirements and consecutive-work limits are defined separately for the three-shift and two-shift systems based on Japanese hospital staffing practice. Soft constraints include transition-related forbidden patterns, excessive consecutive work near transition periods, and selected staffing requirements.

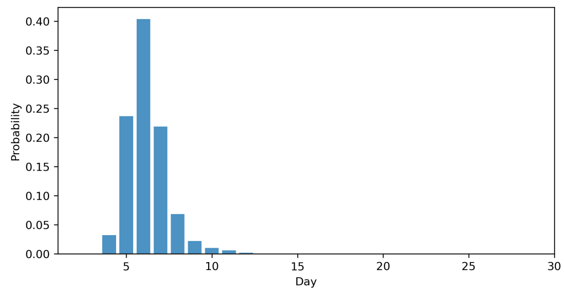

Fig. 1. Probability distribution of the first threshold-exceeding day.

Nurse	Type	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
Nurse 1	3-shift	O	O	D	S	E	N	O
Nurse 1	2-shift	P	O	D	D	O	N	P
Nurse 2	3-shift	O	D	D	D	N	O	O
Nurse 2	2-shift	O	O	D	D	N	P	O

D : Day E : Evening N : Night P : Post-night O : Off S : Special duty

Fig. 2. Duty roster generated by the proposed method around the transition period.

3 Numerical Experiments

The infection prediction model was calibrated using daily COVID-19 data in Japan. We considered a ward with 25 nurses and generated both three-shift and two-shift duty rosters over a one-month scheduling horizon. The critical threshold for the infection probability was set to 5%.

To evaluate the performance of the proposed method, we compared it with a conventional method under the same set of constraints. In the conventional method, a three-shift roster is first generated, and then re-optimization is performed to make a transition to a two-shift roster, where the transition day is selected from the days with high first-passage probabilities. All models were solved using Gurobi 11.0.3 with a 3600-second time limit on a computer with an Intel Core i5-11320H processor (3.20 GHz).

Fig. 1 shows the first-passage probability of each day, that is, the probability distribution of the day on which the infection probability first exceeds the threshold. The probability is highest around days 5 to 7, indicating that the likelihood of requiring a shift system transition is greatest during this period.

Fig. 2 shows the duty roster generated by the proposed method around the transition period. This figure illustrates that days off in the three-shift schedule correspond to either days off or post-night shifts in the two-shift schedule throughout the scheduling period. Furthermore, during the transition from the three-shift schedule to the two-shift schedule around the candidate transition days (5–7), no forbidden shift patterns or excessive consecutive work are observed, indicating that feasible and consistent shift sequences are maintained.

Table 1. Detailed comparison of the proposed and conventional methods.

Metric	Proposed	Conventional		
		Day 5	Day 6	Day 7
Forbidden pattern violations	0	0	0	0
Consecutive work violations	0	2	2	2
Holiday mismatch	1	0	0	0
Preference violations	0	0	0	0
Night shift lower bound violations	0	11	12	0
Day shift lower bound violations	1	1	1	1
Optimality gap (%)	0	0	0	0
Computation time (seconds)	2100	14	18	20

Table 1 summarizes the quantitative comparison between the proposed and conventional methods. For the conventional method, re-optimization was performed with the transition day set to days 5, 6, and 7, on which the first-passage probabilities are high. Although the proposed method requires longer computation time than the conventional method, it produces more stable schedules with fewer constraint violations, including no consecutive work violations and significantly fewer night-shift lower-bound violations.

4 Conclusion

We proposed a nurse rostering method that incorporates infection-risk-based transitions from a three-shift system to a two-shift system. In conventional approaches, rescheduling after determining the transition timing may make it difficult to maintain consistency between the pre- and post-transition rosters and to eliminate constraint violations. As a result, operational confusion may arise among staff. In contrast, by distributing both the two-shift and three-shift rosters to nurses in advance, the transition can be executed more smoothly, which is expected to mitigate such confusion in practice. Numerical experiments demonstrated that the proposed method improves roster stability around potential transition periods by reducing undesirable shift patterns and consecutive work violations.

Future work includes real-world validation, absence modeling, and better alignment between the two rosters.

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