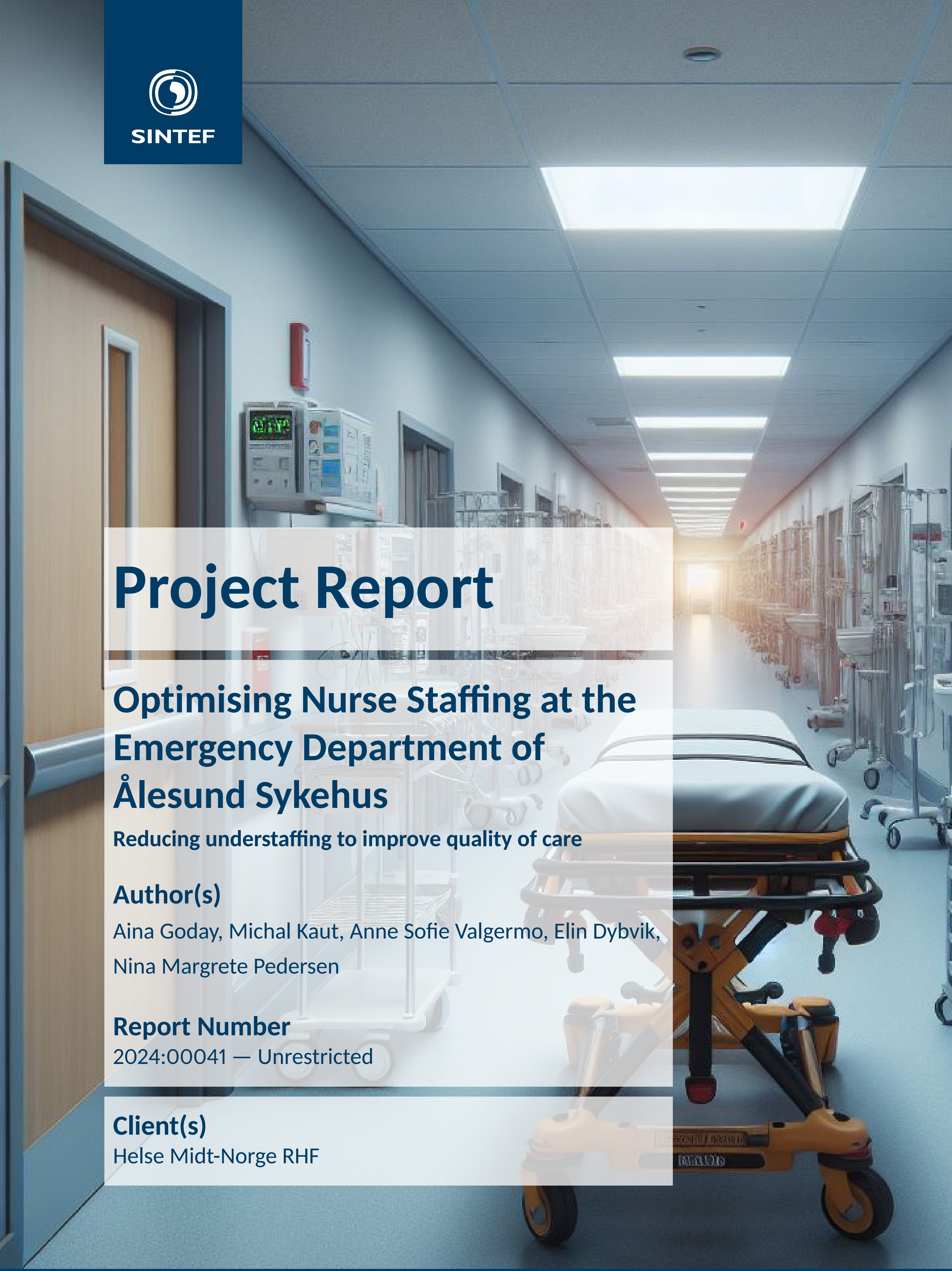

SINTEF

Project Report

Optimising Nurse Staffing at the Emergency Department of Ålesund Sykehus

Reducing understaffing to improve quality of care

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ABSTRACT
This report summarises the initiatives undertaken in the Emergency Department (ED) of Ålesund sykehus to enhance patient care and the workday for nurses. The objective was two-fold and involved addressing nurse understaffing and optimising rostering efficiency. We analysed care demand and nurse capacity and identified a misalignment. Based on this, we designed a new shift schedule, which was then used as input together with legal requirements and staff wishes to make an optimal roster. The ED leader devised a roster plan from the optimal roster, which was then further adjusted and implemented. The performance of the realised rosters in 2022 and 2023 appears to be very similar. Based solely on the data, it is difficult to attribute the entire coping of the increase in workload to the initiatives taken, but they have certainly contributed. The ED leader's experience is that the introduction of the new shifts has helped managing the workload in the afternoon and evening, and that the situation would have been considerably worse without the implemented measures.

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Contents

Management Summary

This report provides an overview of the initiatives undertaken as part of the iCope follow-up at the Emergency Department (ED) of Ålesund sykehus, where we investigate how to better use the existing resources in order to improve both the patient care quality and the workday for the nurses.

The dual objective involved 1) addressing nurse understaffing by better matching nurse capacity with demand for care, and 2) generating an optimal roster within minutes to save time for the ED leader.

We started the process by analysing care demand and nurse capacity, which we translated into workload and nurse hours. Our analysis revealed a misalignment, with surplus nurses during nights and morning and a shortage during afternoons and evenings.

In response, we together with ED management designed several shift schedules to redistribute nurse hours, trying to minimise understaffing while using a similar amount of hours per week. Additionally, we introduced new shifts that would help better fit nurse hours to the workload curve. The selected shift schedule outperformed the reference schedule in terms of understaffing and total nurse hours allocated. Although nurses were initially hesitant, they acknowledged the value of the proposed changes.

The chosen shift schedule together with nurses' preferences and contracts served as input for making the optimised roster, covering the 12-week period from 28-08-2023 to 19-11-2023. Rostering was a complex task. Only after starting the process did we realise that the chosen structure of the shift schedule made it difficult to create a roster for it. Due to the available staff, their contracts and the weekend rules, it was not possible to cover the shift schedule requirements exactly. Despite the optimisation tool facing difficulties in finding improvements that required multiple simultaneous changes, it efficiently provided a solution within minutes. To overcome this challenge, we made some manual adjustments to the final roster.

The optimised roster was then sent to the ED leader, who devised a plan based on it. Nurses made further adjustments to the plan, including the removal of the new T12 shift (worked Friday to Sunday from 18:00 to 6:00). The realised roster, while presenting significantly fewer hours than the optimal and planned rosters, effectively aligned demand for care and nurse capacity compared to the reference shift schedule, maintaining a similar weekly nurse hours count.

Comparing 2022 and 2023 posed a challenge, as autumn 2023 not only presented a higher workload (+12% compared to 2022) but also a higher nurse capacity (+6% in 2023). Overall, the performance remained similar in both periods, with a consistent frequency of understaffing of 17% and a total nurse hours shortage of approximately 400 hours. Based only on the data, it is difficult to attribute the coping of the increase in workload solely to the new shift schedule and roster, as there has also been an increase in capacity. However, they have certainly been a contributing factor. After the ED leader's experience in this period, there is a strong conviction that the late day and evening shifts (D7 and T9) have definitely helped better managing the workload in the afternoon and evening, and they are confident the situation would have been considerably worse without the implemented measures.

1 Introduction

1.1 Background

This report summarises the work carried out by SINTEF for Helse-Midt Norge during 2023 as a follow-up of the iCope project (2020-2023). iCope was a 3-year project funded by NFR which sought to implement Integral Capacity Management in Norwegian hospitals. The objective was to break through the silo-ed organization of hospital departments to establish integral planning and control of care chains.

The assignment of the follow-up study was to investigate how to better use the existing resources in the Emergency Department (ED) of Ålesund Sykehus in order to improve both the quality of care for the patient and the workday for the nurses.

1.2 Problem definition

The leader and nurses of the ED reported feeling very busy at certain times while experiencing periods of relative calm at others. This is quite common in the ED due to the natural variability that comes intrinsically from the patient care needs and the stochasticity of patient arrivals. However, this experience of "stop-and-go" operations is often mostly generated by human planning practices that generate peaks and valleys in demand and capacity. For example, nurse and physician rosters which might not be aligned with demand and therefore generate long waiting times for the patients, or planning of surgeries which affect the capacity in the wards and can block discharges in the ED, etc. Not managing the variability leads to over- and understaffing at different times. Particularly concerning for the ED is the understaffing, as it increases the risk for patient safety and leads to a high workload and high stress levels for the nurses. Therefore, the ED wants to investigate how to reduce the understaffing without hiring extra nurses.

Furthermore, the leader of the ED highlighted how time-consuming and effort demanding it is to generate nurse rosters that satisfy the desired staff levels, legal requirements and personnel wishes. For this reason, the ED wants to try a rostering tool that generates optimal schedules in less time, thereby freeing up valuable time for the leader to focus on other critical tasks while ensuring high adherence to rules and staff preferences.

1.3 Objective

The objective of this study is two-fold:

1. To reduce the current understaffing in the ED by better matching patient demand and nurse capacity, without adding extra resources.
2. To generate an optimal nurse roster, in a matter of minutes, that minimises the breach of personnel wishes and rules.

1.4 Methods

To reduce the understaffing, we first analyse whether there are any misalignments in the demand for care and nurse capacity. This is done by comparing the workload generated by the patients against the current shift schedules in the ED. We then proceed to determine what shifts are to be worked and how many nurses should be assigned per shift and day of the week. The objective of this shift design is to generate shifts that minimise the number of nurse hours required to cover the workload. This is known in the literature as *staff-shift scheduling* (Hulshof et al., 2012).

Afterwards, we proceed to generate nurse rosters, or the so-called *staff-to-shift assignment* (Hulshof et al., 2012). This is where a date and time are given to a nurse to perform a particular shift. We do the staff-to-shift assignment with "Scoop Roster", a rostering tool developed by SINTEF Digital (SINTEF). This tool optimises the rosters, in a matter of minutes, by ensuring the best coverage of the shifts (defined in the staff-shift scheduling), while minimising the breach of personnel wishes and rules.

As described in Hulshof et al. (2012), staff-shift scheduling is a decision made at the tactical level, whereas staff-to-shift assignment is done at the off-line operational level (see Hulshof et al. (2012) and Hans et al. (2011) for details of the hierarchical levels of planning and control). This means that staff-shift scheduling translates the strategical decision of "how many nurses are hired in the ED" into the tactical decision of "what shifts are to be worked" in order to facilitate the operational planning decision made by staff-to-shift scheduling of "who has to work and when". Therefore, the shifts defined in staff-shift scheduling are input for generating the rosters in staff-to-shift assignment. Not only have we followed a bottom-down approach but we have also done a bottom-up integration to use the results of the nurse roster optimisation as input to choose what shift alternatives are best given the nurses and contracts in the ED.

1.5 Structure of the report

The report is structured as follows. In Section 2 we analyse the demand for care and nurse capacity and identify misalignments. In Section 3 we use these findings to design nurse shift schedules based on the workload. In Section 4 we explain how we create an optimised roster based on the selected shift schedule, regulations and personnel wishes. Section 5 presents the optimised roster, the implementation of the actual roster and the comparison of autumn 2022 with autumn 2023. Finally, in Section 6 we point out future work and we conclude the report in Section 7.

2 Analysis of demand for care and nurse capacity

We start by analysing historical data from 2022 of the demand for care and nurse capacity, in order to identify inefficiencies caused by misalignments between the two.

2.1 Input data and data cleaning

The input for the analysis performed in this report consist of three datasets:

- **Nurse capacity realised**: an Excel file that captures the actual events of how the ED was staffed. It provides detail on the type of employee, date, shift, hour of the day, and the fraction of time the staff is present during the hour. The dataset spans from 01-01-2021 to 11-10-2023.
- **Nurse capacity planned**: an Excel file containing the same columns as the file above, but instead of realised hours it only contains planned hours, i.e., how they expected to staff the ED. This dataset is used in Section 5.2 to see the evolution from optimised roster to realised roster. It contains data from 29-08-2022 to 30-10-2022 and from 28-08-2023 to 29-10-2023.[1]
- **Demand for care**: an Excel file containing patient information such as id, admission and discharge times, admission group and admission triage colour. Each row contains a single patient stay. The dataset covers the period from 01-01-2018 to 10-11-2023.

Both staff datasets contained roles that were not relevant for the analysis and were hence removed. The ones included were “Medisinstudent m/lisens”, “Sykepleier”, “Spesialsykepleier”, “Assistant”, “Lærling/student”, “Seksjonsleder”, and “Ukjent kode”[2]. Additionally, shifts categorized as office time (“TD”, “DF”, “DHP”, “DK”, “DA”, “DP”) were filtered out. Finally, we removed any negative present time.

[1]This dataset may show nuances since it only contains hours categorized in the system as "planned" and does not include those classified as "overtime" ("mertid").

[2]Ukjent kode identifies a specific person that the system does not classify properly but we know is a nurse.

For the patient dataset, we removed any patients who had discharge timestamps earlier than their admission. We only took into account patients who are present in the ED for more than one minute and less than a day.

2.2 Calculation of workload and nurse hours

To compare nurse capacity against demand for care, we translated nurse capacity into "nurse hours" and demand for care into "workload", thus, ensuring that both metrics are expressed in the same unit, namely, hours.

To determine the nurse capacity in hours (and not number of individual nurses), we simply added up the time present from all the shifts per date and hour.

We employ the concept of "workload" to translate demand for care into a measurable metric. Workload is interpreted as "hours of nurse work generated by patients", which directly determines the nurse hours required at each moment. The calculation of workload not only considers patient arrivals at each moment but also the delayed congestion effects from previous hours. This is done by taking into account when patients arrive and are discharged, as well as how much care they need at each point in time throughout their stay depending on their triage colour and admission group. For more details on these calculations see Appendix A.

2.3 Comparison of workload and nurse hours

We start the comparison by analysing the total nurse and workload hours per day in 2022. This is shown in Fig. 1 with the use of boxplots.[3]

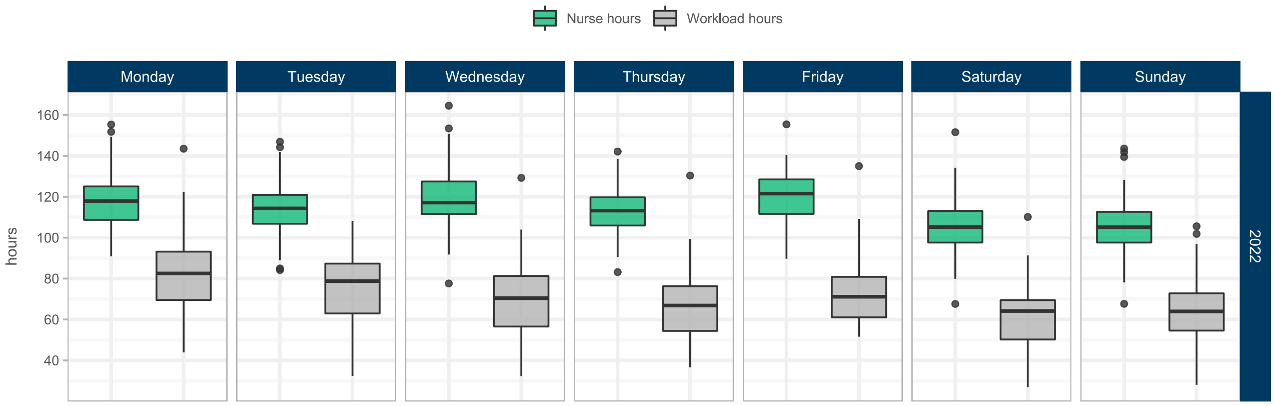

Figure 1: Total workload vs nurse hours per day of the week in 2022

Starting with the workload, we can see that Mondays and Tuesdays are the busiest days of the week, whereas Thursdays and weekends are comparably less busy. Regarding nurse capacity, Wednesdays and Fridays seem to have slightly more nurse hours than the rest of the days. This is probably caused by a training meeting on Wednesdays, and more scheduled hours on Friday mornings, which makes it easier to adjust if someone gets sick.[4] The days with the least amount of nurse hours are the weekends, followed by Tuesdays and Thursdays.

[3]A boxplot visually represents the distribution of a dataset. It consists of a box which contains 50% of the observations in the data, the whiskers, showing the spread to the minimum and maximum values, and dots representing outliers. The middle line in the box is the median, which divides the entire dataset into two halves. For instance, the grey boxplot for Monday in Fig. 1 shows that 50% of Mondays in 2022 (26 out of the 52 Mondays) had a total workload between 70 and 93 hours, with the median being 82. From the remaining Mondays, 25% (13) had more than 93 hours of workload, whereas the other 25% (13) had less than 70.

[4]The ED employs the concept of "forskyving". This implies scheduling the full contractual hours with a heavier allocation on Friday mornings. By ensuring an increased nurse presence on Fridays, the ED mitigates the challenge of finding staff to cover unexpected absences, as nurses are reluctant to take on additional shifts on Fridays. If the extra scheduled nurses are not required, it is easier to reschedule them to other days of the week than to persuade them to work on a Friday.

Concerning the alignment between demand and supply, a first indication of misalignment could be the fact that Mondays are similarly staffed as the rest of the days despite having considerably more workload.

Fig. 2 provides a visual overview of the nurse hours and workload per hour and day of the week in 2022. The green line represents the median of nurse hours, meaning the middle value of nurse hours per hour and day. The grey band represents the workload, with the lower and upper edges indicating that, 50% and 90% of the time respectively, the workload was below those levels. In other words, if the green line is above the top edge of the grey band, at least 90% of the workload was covered.

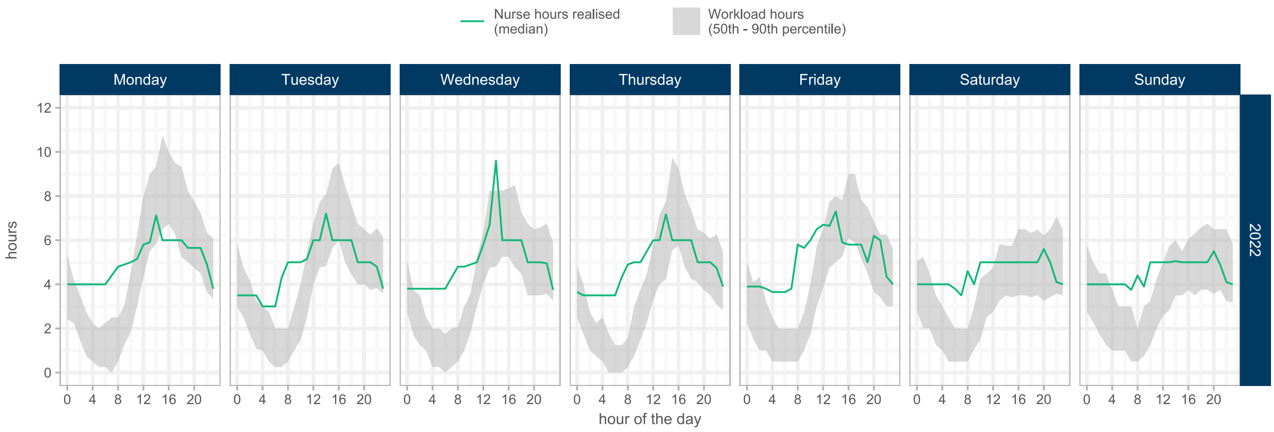

Figure 2: Workload vs nurse hours per day of the week and hour in 2022

We can see that the workload follows a clear pattern. At 8:00, the levels are quite low, at around 2 hours of work. As the morning progresses, the workload rises significantly, peaking in the afternoon between 14:00 and 17:00 at above 8 hours of work. Following the peak, there is a gradual decline, occasionally with a secondary increase around 22:00. From 22:00 to 4:00, the workload decreases, reaching a particular low level of around 2 or less hours of work between 5:00 and 6:00. While this holds true for weekdays, weekends do not have such a marked peak in the middle of the day, resulting in a similar workload during the afternoon and evening hours.

We can also observe a variation in the number of nurse hours throughout the day, with more nurse hours during the late morning and afternoon, and less during the evening and night. Even though the nurse capacity also varies, there are some clear misalignments with the workload. While the late night and morning (from 4:00 to 11:00) have far more nurse hours scheduled than needed, the afternoon and evening (from 12:00 to 00:00) lack nurse hours to cope with the peaks of workload. This is particularly worse on Monday, as it is the day with the highest workload and yet has similar nurse hours than the rest.

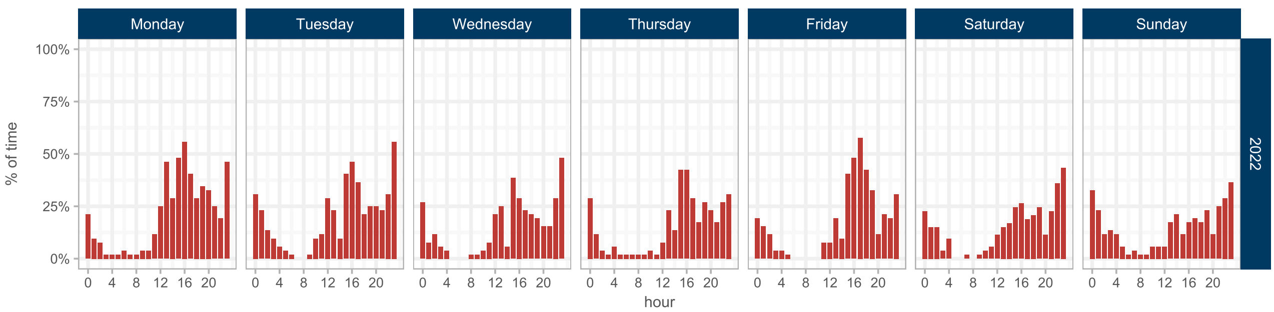

Figure 3: Frequency of understaffing per day of the week and hour in 2022

To quantify the frequency and magnitude of the understaffing generated by the misalignment, we calculate the difference between nurse hours and the weighted average of the workload per date and hour.

Fig. 3 shows how often each hour is understaffed. We classify an hour as understaffed when the workload is 5% higher than the nurse capacity. As we can see in the figure, most hours are understaffed less than 25% of the time, meaning that less than 13 days in the year of a certain day and hour combination missed nurse hours to cover the workload. Nevertheless, several days of the week are understaffed around 50% of the time between 12:00 and 16:00 and at 23:00.

Besides the frequency of understaffing we can also see how big the understaffing was. Fig. 4 illustrates the distribution of the difference between nurse and workload hours. In this plot we focus on the understaffing, hence only negative hours are depicted. We can see that Mondays and Tuesdays have a bigger understaffing than the rest of the days, with a total of -535 and -392 hours respectively in the year. When understaffed, all days mostly miss between 0 and 2 hours of nurse time [5]. Mondays and Thursdays have a longer tail, meaning that at some hours the understaffing was severe missing up to 8 and 9 hours of nurse time respectively. Nevertheless, the count for these bins is very low, implying it only happened a couple of times.

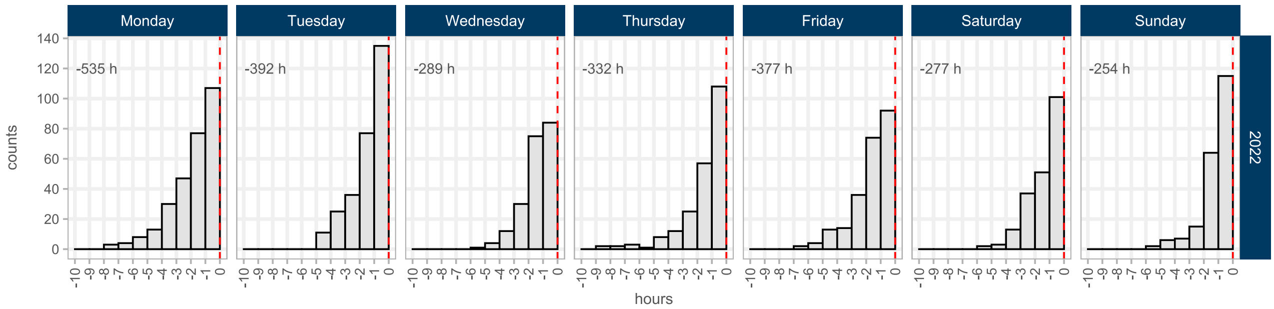

Figure 4: Distribution of the difference in hours between nurse capacity and workload per day of the week in 2022. Histogram bins are closed on the left. Only negative differences, indicating understaffing, are shown. The text label in each plot is the total sum of negative hours for the year.

3 Designing nurse shifts

Nurse shift scheduling, or *staff-shift scheduling*, is the process of determining the shifts to be worked along with the number of nurses per shift and day of the week. Based on the misalignments found in the previous section, we designed new shift schedules that better fit the workload pattern observed in historical data.

3.1 Reference shift schedule

Our reference schedule is derived from the actual working plan. It consists of 9 distinct shift types (3 day, 3 evening, and 3 night types), and allocates a total of 865.7 nurse hours per week. This value is intentionally lower than the total available workforce (approximately 1033 hours a week) as they plan according to the expected available workforce accounting for different types of leave. The structure of the reference shift schedule is displayed in Table 1.

[5]Note that the bins in the histogram in Fig. 4 are closed on the left and therefore 0 hours of difference does not count as understaffing.

Table 1: Structure of the reference shift schedule

	Shift times			Number of nurses								Hours
Shift	Start	End	Dur (h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun	week	week
D1	07:30	15:00	7.5	5	5	5	5	4			24	180
D10	10:00	22:10	12.2					1	1	1	3	36.5
D12	08:00	20:10	12.2					4	4	4	12	146
K1	14:45	22:15	7.5	6	5	0	5	1			17	127.5
K2	11:30	19:00	7.5	1	1	1	1	1			5	37.5
K5	13:45	22:15	8.5			5					5	42.5
N11	20:00	07:35	11.6							4	4	46.3
N12	20:00	08:10	12.2					4	4		8	97.3
N3	22:05	07:35	9.5	4	4	4	4				16	152
Total				16	15	15	15	15	9	9	94	865.7

In Fig. 5 we can see that the nurse hours curve from the reference schedule is very similar to the one in from the 2022 realised data in Fig. 2. During week days, there is normally overstaffing during the night and morning, and understaffing in the afternoon and evening. The main difference is that Monday afternoons and Friday mornings have more staff.

Fig. 6 shows how often each our is understaffed with the reference shift schedule. This is again similar to the one of Fig. 3, however, with less peaks and the noticeable difference that Fridays are not understaffed between 11:00 and 14:00.

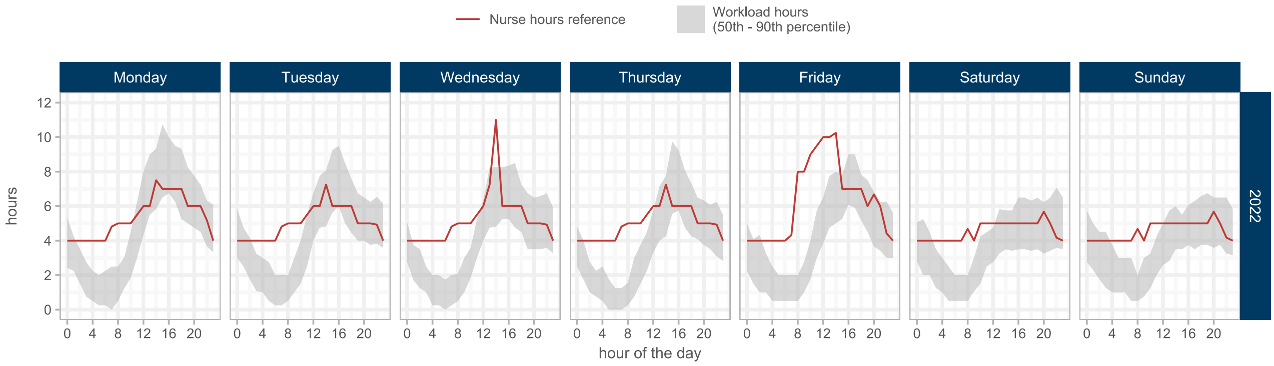

Figure 5: Reference shift schedule (in red) compared to historical workload in 2022

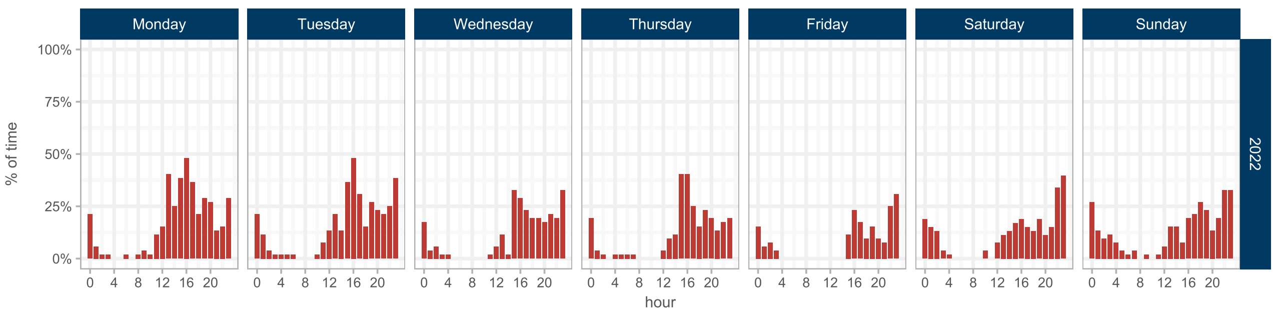

Figure 6: Frequency of understaffing generated by the reference shift schedule compared to 2022 workload

3.2 Design of shifts schedules that better fit the workload

To design a shift schedule that better fits the workload pattern observed in historical data, we decided to reduce the nurse hours at night and early morning, and increase them in the afternoon and evening. The intention is to minimise the understaffing while using approximately the same amount of working hours as in the reference schedule. With this premise in mind, the leaders in the ED designed 12 different alternatives by:

- modifying the number of nurses per day in the existing shifts
- adding new shifts
- changing the start and end times of the shifts

All 12 shift schedules were compared in terms of nurse hours, understaffing and expected acceptance by the nurses. Fig. 7 displays all the alternatives, including the reference, illustrating understaffing[6] and nurse hours per week. Most alternatives allocate less hours than the reference and yet they are less understaffed.

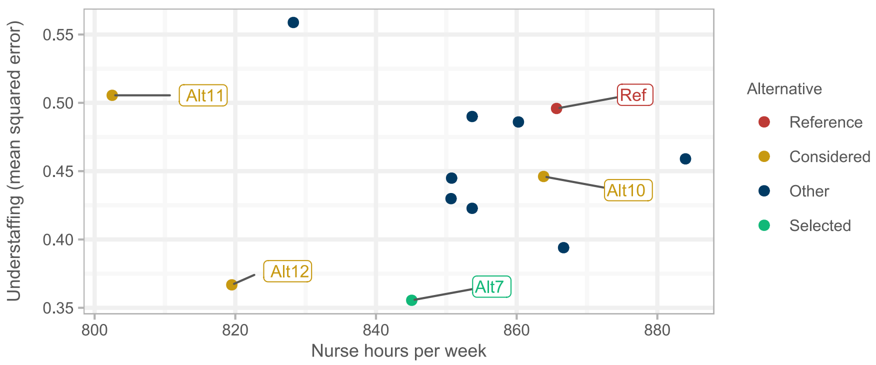

Figure 7: Comparison of the 12 different alternatives (and reference) suggested by the ED

Alternatives 7, 10, 11 and 12 were interesting to management for various reasons, and therefore were considered (see Appendix B for more details):

- Alternative 10: while being particularly interesting to management as it only considers 12h-shifts, like nurses desire, it does not provide enough flexibility to cover peaks and valleys in the the demand.
- Alternative 11: in contrast to Alternative 10, this one only contains short shifts ranging from 7.5 to 9.5 hours (including newly defined shifts). It uses considerably less hours than the reference and is slightly more understaffed. The undersaffing could have probably been reduced by increasing the nurse hours. Nevertheless, this alternative is not feasible as nurses want to work 12h-shifts.
- Alternative 7: this alternative consists of both short and long shifts (including newly defined shifts). It successfully follows the workload curve, and therefore is less understaffed than the reference, while also employing less hours.
- Alternative 12: this one has the exact same structure as alternative 7 with the exception that it does not use long shifts in the weekend. Even though it follows the workload curve better than alternative 7, 12h-shift have to be allocated in the weekend to satisfy the nurses' preferences.

[6] In this case, understaffing is measured with the mean squared error. To calculate this, we first work out the error, which is the difference between workload and nurse hours caped at 0 for positive differences (thereby, excluding all overstaffing). We then square the error to give a higher penalty to those hours that have been severely understaffed. Finally, we calculate the average of all the squared errors per alternative.

3.3 Selection of the best shift schedule

Based on the reasoning above, alternative 7 was chosen, presented in Table 2.[7] It uses the same shifts as the reference with the addition of 3 new ones: D7, T9 and T12. These extra shifts were designed to reinforce the hours with high workload and lack of nurses. Table 2 was used as input to make the rosters in the next section.

Table 2: Structure of the selected work schedule (alternative 7)

	Shift times			Number of nurses								Hours
Shift	Start	End	Dur (h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun	week	week
D1	07:30	15:00	7.5	3	3	3	3	2	0	0	14	105
D10	10:00	22:10	12.2					1	1	1	3	36.5
D12	08:00	20:10	12.2					3	4	4	11	133.8
K1	14:45	22:15	7.5	5	4		4	1	0	0	14	105
K2	11:30	19:00	7.5	2	2	2	2	2			10	75
K5	13:45	22:15	8.5			4					4	34
N11	20:00	07:35	11.6							3	3	34.8
N12	20:00	08:10	12.2					3	3		6	73
N3	22:05	07:35	9.5	3	3	3	3	0	0	0	12	114
D7	10:00	17:30	7.5	2	2	2	2				8	60
T9	18:00	03:30	9.5	1	1	1	1				4	38
T12	18:00	06:00	12.0					1	1	1	3	36
Total				16	15	15	15	13	9	9	92	845.1

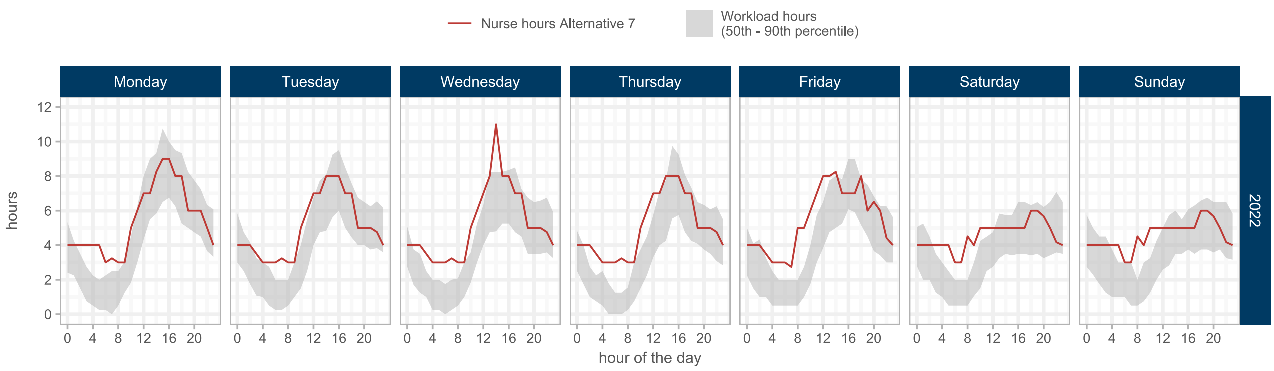

Figure 8: The selected shift schedule (alternative 7) (in red) compared to historical workload in 2022

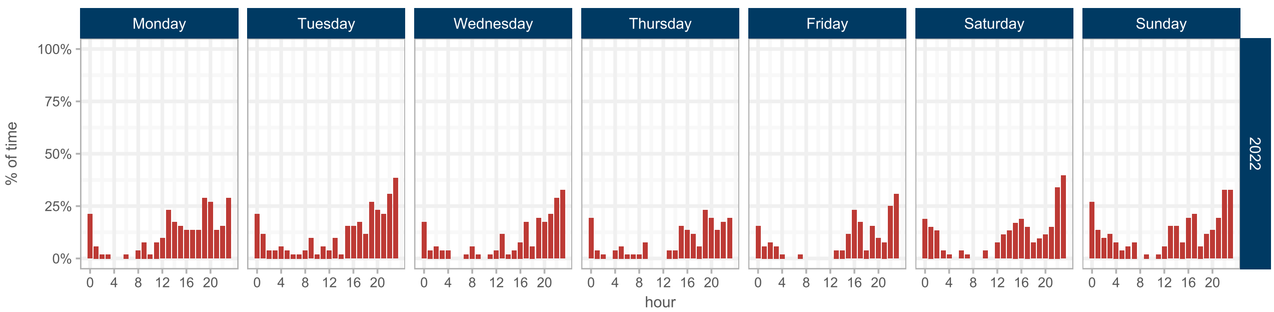

Figure 9: Frequency of understaffing generated by alternative 7 compared to 2022 workload

[7]The zeros in Table 2 indicate the possibility of rostering nurses on those shifts. For more details on the reasons see Section 5.1.1

Alternative 7 is overlayed to historical workload in Fig. 8 and the frequency of understaffing is depicted in Fig. 9. We can see that the schedule follows the workload more closely than the reference, significantly reducing both the under- and over-staffing while using less nurse hours a week.

It is important to note that this shift schedule establishes the minimum number of nurses required per shift to effectively manage the workload with the expected available resources. However, considering the higher workforce, additional nurses will be added to the numbers presented in Table 2 when rostering.

Regarding the introduction of new shifts, we organized a workshop in the ED to update the nurses on our progress and involve them in the design and selection of the new shift schedule. Although they were not particularly enthusiastic about the new shifts suggested by management, they recognized the positive impact on workload coverage. They agreed to implement them as long as the shifts were equally distributed among employees and not consistently assigned on the same day.

4 Making nurse rosters

Rostering, or *staff-to-shift assignment*, is the process of creating work schedules for personnel, based on a given shift schedule. This is typically done for several weeks or months ahead. Rostering is a complex optimization problem and we use the "Scoop Roster" tool developed by SINTEF Digital to solve it.

The tool takes the following input:

- list of shift types, with start- and end-times
- weekly shift schedule, i.e., number of nursers per shift type for each week day
- list of employees and their *contracts*

There, the contracts specify both legal limits on working hours and employees' personal contract agreements and preferences. Each contract clause can be either *absolute*, i.e., not allowed to break, or include a *penalty* for breaking it. The tool then searches for a roster that satisfies the absolute contract clauses and has the smallest possible sum of penalties. Note that Scoop Roster uses heuristics to solve the problem and therefore does not guarantee to find the optimal solution.

4.1 Input specifications – work schedule requirements

Due to available staff and their contracts and preferences, it is not possible to cover the schedule requirements exactly: we may not have enough staff for some hours and have more employees needing work than the schedule requires at other times. On the other hand, covering the schedule is the main goal of the rostering problem, so the penalties for under-staffing are set an order of magnitude higher than the rest.

We also attach a very small penalty for over-staffing of shifts, mostly because it makes it easy to quantify the over-staffing. We do not allow staffing of unscheduled shifts, i.e., all over-staffing must happen on shifts that had been scheduled for the day.

4.2 Input specifications - per employee

This section describes input specifications per employee, divided between contractual requirements, work-time rules and personal preferences.

4.2.1 "Absolute" requirements

Theses are mostly legal requirements, except for the last one which is contractual. As such, they apply to all employees.

- There must be at least 9 hours break between two consecutive shifts.
- Work at most 54 hours per week.
- Each nurse must have 35 hours consecutive free at least once each week.
- Work at most 5 days in a row.

4.2.2 Requirements with penalties for being broken

Some of these requirements are actually meant to be absolute, but the Scoop Roster struggled if they were formulated as such. Instead, we have assigned a sufficiently high penalty to ensure they will not be broken.

Note that in the following rules, "weekend" means a period from Friday afternoon til early Monday morning.

The following is list sorted by the requirements' penalties, from the most to the least important:

- During weekends, either work all three shifts or not at all.
- When working night shifts, do at least two in a row.
- During weekends, do either three day shifts or three night shifts.
- Each employee should have at least one free "long weekend" (Friday–Monday) during the planning horizon.
- Penalise unpopular shifts, such as late afternoon shifts during weekends.
  - In this case, we use *quadratic penalties*, to spread the burden evenly between employees.
- Penalise some unpopular shift combinations – typically combinations where the second shift starts earlier than the preceding one, implying a short break between the two shifts.
- Work at most 51.5 hours per week.

4.2.3 Contract types

At the particular emergency department, there are two contract variants concerning working during weekends:

every 4th weekend, 12h, the most common contract

- Working every 4th weekend
- During the weekend, work only long shifts (11.5–12.2 hours)[8]

every 3rd weekend, short, worked by a small number of nurses

- Working every 3rd weekend
- During the weekend, work only short shifts (7.5–10 hours)

In addition, there is one person working every second weekend (and not otherwise) and one every fifth weekend, both working long shifts during the weekends.

[8]Note that this gives a full week's worth of work (36 hours).

4.2.4 Personal preferences

These requirements represent personal preferences, with varying penalties for being broken.

- Wants to work 4 nights in a row.
- Wants to work 5 nights in a row.
- Working only during weekends – only possible for employees with fractional contracts.
- Works only day shifts (no nights).
- Prefers night shifts.

4.2.5 Working hours

In addition to the above requirements, we have to make sure that each person works the appropriate amount of hours during the scheduled period. In our case, a full (100 %) contract means 35.5 hours per week, but there are employees with fractional contracts going as low as 20 %.[9] In the model, we have penalties for working both more and less than the contracted time, with the former being penalised more.

4.3 Experience with Scoop Roster

Our experience shows that Scoop Roster can provide good solutions in a manner of minutes, provided the requirements are formulated in a particular way. This is connected to the way the tool works. Simply said, it starts from an empty roster which is filled step-by-step, keeping the solution *feasible*, i.e., satisfying all the absolute constraints. Once the roster is filled, the solver will try improving the solution (decrease the penalty) by swapping some of the assignments.

With that in mind, here are some observations we have made while formulating the requirements:

4.3.1 Feasible empty roster

An empty roster should be *feasible*, i.e., it should not violate any of the absolute constrains. Otherwise, the tool struggles to find an initial feasible solution.

This is why have to use under-staffing penalties – if we formulated schedule covering as absolute constraints, the empty initial roster would be infeasible.

4.3.2 Problem with complex patterns

Since the solver improves solutions by swapping assignments, it struggles finding improvements that require multiple simultaneous changes. As an extreme example, consider the "every 4th weekend, 12h" contract type and a situation where one nurse is currently working weekends 1, 5, 9, ... If we are scheduling for 12 weeks, then moving the nurse to working weekends 2, 6, 10, . . . requires changes of the following assignments:

- clear the nurses' assignments for weekends $(1, 5, 9) \ldots 3 \times 3 = 9$ shifts
- assign the nurse to some shifts in weekends $(2, 6, 10) \ldots 3 \times 3 = 9$ shifts
- clear the nurse's assignments from week days in weeks $(2, 6, 10)$ (to prevent breaking max-work rules) . . . up to $3 \times 5 = 15$ shifts

In other words, we need to change ca. 30 shifts, just to make the weekend switch and then make the roster feasible again. To make the roster good, one would also have to:

[9] This is mostly due to them spending some fraction of their work time on additional duties.

SINTEF

- assign the nurse to some week-day shifts in weeks $(1, 5, 9)\ldots$ up to $3 \times 5 = 15$ shifts
- re-assign shifts that now break rules due the above changes.

This means that to make the switch of one person to another weekend schedule, one needs to move on the order of 50 shifts before the new roster has a chance to be better than the previous one. As a result, no neighbourhood algorithm we are aware of will be able to make such a switch, unless there is an explicit support for this in the optimization algorithm.

Fortunately for us, the weekend assignments are mostly repeated from previous roster (for existing employees) and can be assigned and fixed manually prior to optimisation for the rest, eliminating the issue altogether.

However, there are still rules that require many coordinated shift changes, for example the rule (actually, a preference) for working four nights in a row: one needs to move all the night shifts to avoid a penalty for breaking the rule, involving 4 shifts at the original position, 4 shifts at the destination, and probably several additional shifts to avoid breaking other rules.

Another example is a situation from our actual roster, where we have four nurses working (D12, D12, D12) during one particular weekend, while the required amount of D12 for the three days is (3, 4, 4). At the same time, there is an uncovered sequence of (T12, T12, T12) in the same weekend. This means that if we move one nurse from D12 to T12, we decrease the number of uncovered shifts from three to two (since we would still have enough coverage for D12 on Friday). However, the solver is not able to find this improvement, possibly because the shift has to be done as one move: the improvement comes from a change on Friday, but the sequence (T12, D12, D12) is not allowed as there would be only two hours of break between T12 and D12.

4.3.3 Balance between days and weeks

Ideally, the total nurse hours required by the shift schedule would be equal to the total available workforce. In reality, there will usually be a difference. In addition, the different contract conditions can make it impossible to staff all shifts required by the schedule.

All this means that we may have nurses that need extra shifts, at least on some days. Currently, we allow these to be assigned to any planned shift, without further conditions or penalties. In particular, we do not control the total number of nurses available at any time, which can result in uneven staffing both between days and between weeks – since we plan for several weeks at a time, the total staffing for any particular week day can differ between the planned weeks (Fig. 10).

This could be at least partially alleviated by additional soft constraints on the total number of nursers present at given time periods - this could be selected hours or longer time intervals like "morning" or "night". Unfortunately, the current version of the optimiser does not allow using quadratic penalties for over- or under-staffing, which would ensure an even spread of the extra hours between days. While these could be approximated by multiple sets of linear penalties, it would increase the number of rules considerably. Finding the right balance is left for further research.

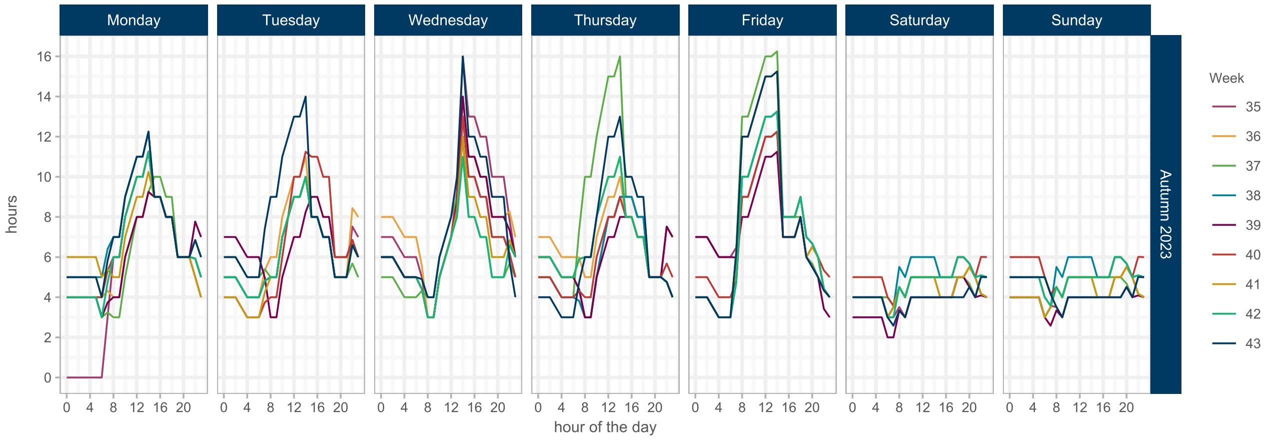

Figure 10: Nurse hours allocated per week, day and hour showing uneven staffing between days and weeks in the optimised roster. Monday of week 35 starts at 0 nurse hours as it does not take into account the previous roster (week 34).

5 Test case - new schedule and roster for autumn 2023

5.1 Optimised roster for autumn 2023

In Section 3 we designed a new shift schedule that betters fits the workload pattern observed in historical data. The structure in Table 2 served as input in Section 4 for generating a 12-week roster covering the period from 28-08-2023 to 19-11-2023. The output of Scoop Roster is shown in Fig. 11.

5.1.1 Problems with the selected schedule

While the selected shift schedule presents a clear improvement in terms of understaffing, it turned out that its structure makes it difficult to create a roster for it. This is caused by the weekend rules, discussed in Section 4.2.3.

As mentioned there, most employees work every 4th weekend and then they work long shifts all three days (Friday to Sunday). In our schedule, this means day shifts D10 and D12 and night shifts N11, N12, and T12. Looking at Table 2, we see that there is an imbalance in D12, with 3 nurses on Friday and 4 on Saturday and Sunday. Since nurses working on Saturday and Sunday have to work on Friday as well, and since they only work long shifts, there will always be one nurse extra on D10 or D12 on Friday.

Another issue is the K1 shift on Friday - since it ends late in the evening, it triggers the weekend-rule for the nurse.[10] In other words, the nurse should work the rest of the weekend as well. However, since K1 is a short shift, this nurse should continue on short shifts - but there are no such shifts scheduled for Saturday and Sunday. This is the reason there are shifts with zero scheduled nurses – since we do not allow assigning shifts that are not planned for the day, there would otherwise be no feasible assignment for the nurse taking K1 on Friday.

Moreover, there turned out to be four nurses working every 3rd weekend, short shifts. This means that even if we spread them evenly, there would be two such nurses every third weekend – but the only available short shift being one K1 on Friday. In other words, the contracts force us to make 5 un-required assignments of short shifts during those weekends (in addition to the one un-required assignment of a long shift mentioned above.)

[10] Shifts D1 and K2, on the other hand, end earlier on Friday and therefore do not count as weekend work.

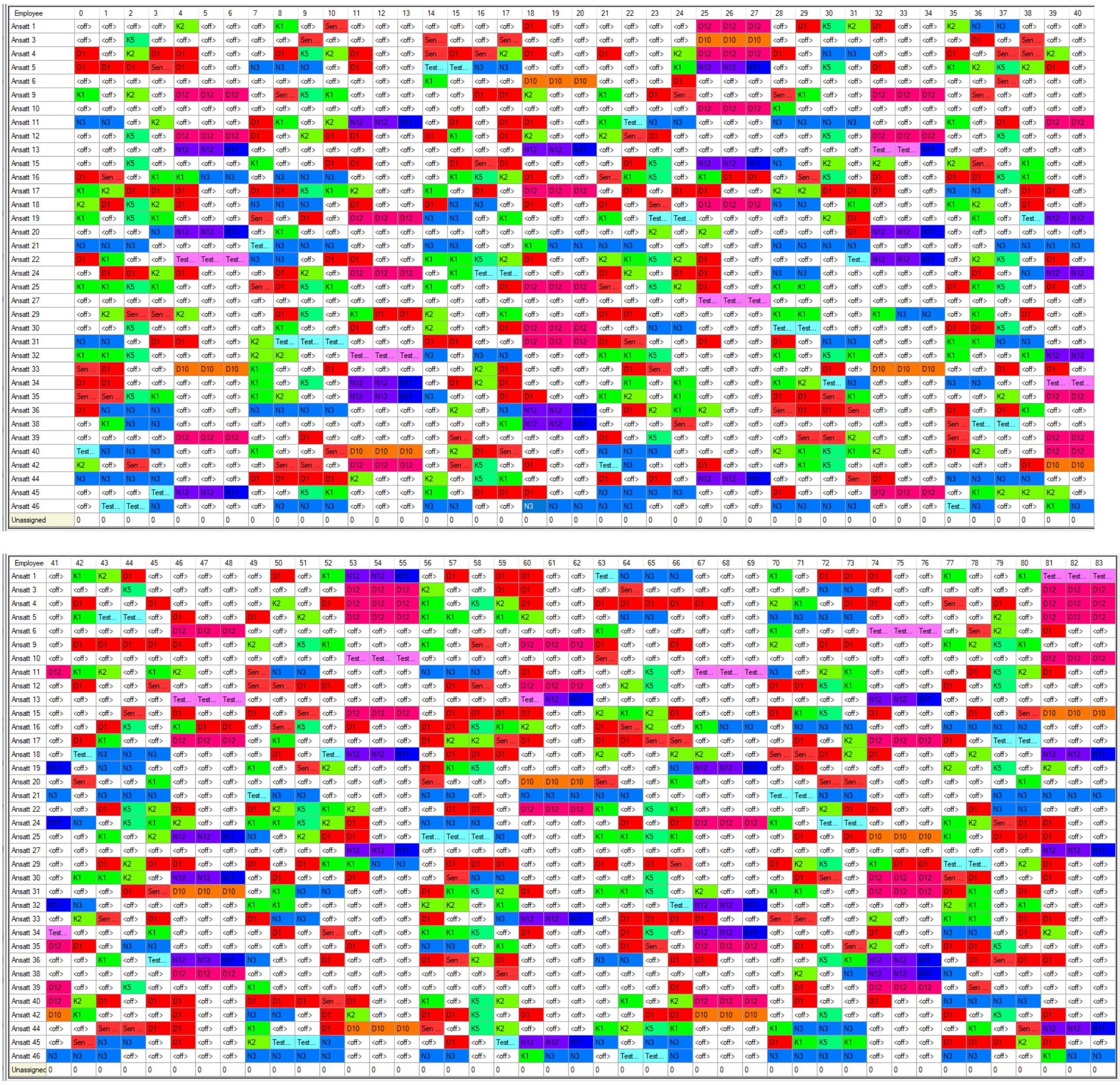

Figure 11: Final roster generated by Scoop Roster. Columns represent days starting on 28-08-2023 and finishing on 19-11-2023. Shifts "Sen...", "Test..." (in blue) and "Test..." (in pink) correspond to D7, T9 and T12 respectively. Shifts going overnight are placed on the day they start, not on the day where most hours at worked (for example, an N3 on Monday starts on Monday at 22:05).

These issues could probably be at least partially mitigated if we were aware of the weekend contracts at the time we designed and selected the schedules.

Table 3: Amount of nurses on long shifts during weekends

weekend rule	1	2	3	4	5	6	7	8	9	10	11	12
every 4th	6	8	7	9	6	8	7	9	6	8	7	9
every 2nd	1	0	1	0	1	0	1	0	1	0	1	0
sub-total	7	8	8	9	7	8	8	9	7	8	8	9
every 5th	1	0	0	0	0	1	0	0	0	0	1	0
total	8	8	8	9	7	9	8	9	7	8	9	9

While there is not enough shifts for nurses working short shifts during the weekend, we do not have enough nurses for the required weekend long shifts. In particular, we have 30 nurses on the "every 4th weekend" contract, with the following distribution between the four patterns: (6, 8, 7, 9).[11] In addition, we have one nurse working every second- and one every fifth weekend, resulting in the number of available nurses presented in Table 3.

Since the number of long shifts during the three weekend days is (8,9,9), having 8 nurses results in 2 uncovered shifts, while having only 7 nurses increases this number to 5. It follows that there will always be at least $5 \times 2 + 2 \times 5 = 20$ uncovered long weekend shifts in the course of the 12 weeks. Again, this suggests that the shift schedules should be adjusted to the available task force.

Note that the understaffing could also be decreased by moving one of the nurses one "every 4th weekend" contract that start at weekend 4 to weekend 1, which would change the "sub-total" line of Table 3 to (8,8,8,8,...) and the total number of missed shifts to $9 \times 2 = 18$.[12]

5.1.2 Inconsistency in specified contracts

It is also possible to specify contradictory contract requirements for a given nurse, irrespective of the schedule. For example, we have a nurse on the "every 4th weekend" contract, which on itself requires $3 \times 12/4 = 9$ hours per week, corresponding to $25.3\,\%$ of a full position. At the same time, the nurse is said to have only $20\,\%$ position. Since the penalties for breaking the weekend-rule contract are set higher than those for working more than specified (up to a limit), the nurse always ends up working "overtime", i.e., more than the specified $20\,\%$.

5.2 From optimised to realised roster

Once the optimised roster was made and adjusted under the supervision of ED management, the ED leader used it as the basis for creating the initial roster plan. After publishing the plan, nurses were allowed to make changes to further fit their preferences. One main adjustment was the substitution of all T12 shifts by other shifts, as nurses disliked it. The plan was then implemented, with deviations due to unforeseen events such as sick leave. This lead to the realised roster, which reflects the actual staffing in the ED during the studied period. Fig. 12 gives and overview of the steps in the process for turning data insights into rosters.

[11]In other words, there are 6 nurses working on weekends (1,5,9), 8 nursers working on weekends (2,6,10), etc.

[12]However, this exploits the fact that the nurse working on every 5th weekend starts in weekend 1 and therefore works in three weekends during the scheduled period. If we repeat the same pattern for another 12 weeks, then this nurse will only have two working weekends and the number of missed shifts will be 20 again.

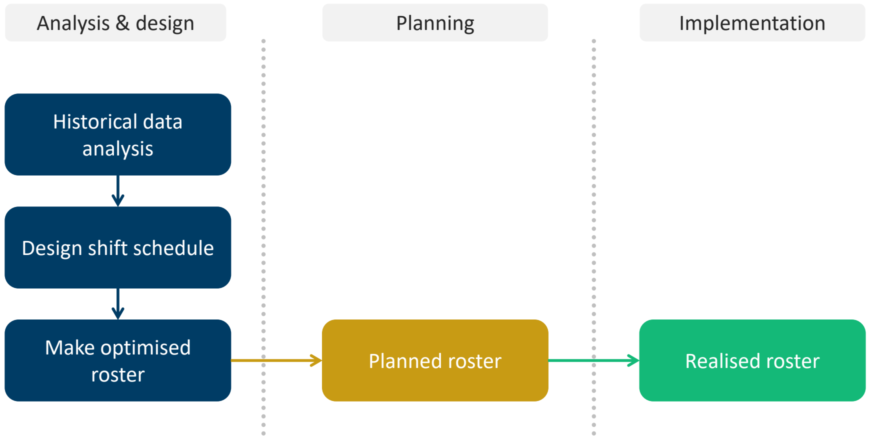

Figure 12: Steps followed to turn data insights into real-life rosters with smart planning and optimisation

In the following figures we analyse the first 9 weeks of the period we made the roster for. This is from 28-08-2023 to 29-10-2023.

Fig. 13 depicts the weekly distribution of hours assigned by the optimised, planned, and realised rosters. The optimised roster schedules on average around 77 and 188 more hours a week than the planned and realised rosters respectively, and the planned roster allocates 111 more hours than the realised one. The reasons for the difference between the planned and optimised rosters remain unclear to us.[13] The reduction in hours from the realised roster is expected considering the high sick leave reported by the ED leader during this period.

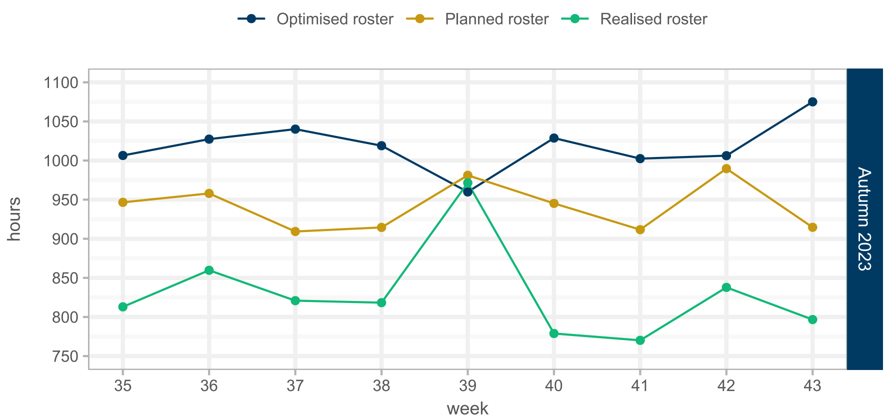

Figure 13: Total hours per week in the optimised, planned and realised rosters in Autumn 2023

Week 39 of the optimised roster is one of the weeks with 2 missing nurses on long shifts on the weekends (as explained in Section 5.1.1 and shown in weekend rule 5 of Table 3). This justifies why it schedules less hours than in other weeks. On the contrary, week 43 has a lot more hours scheduled as the optimisation tool allocated quite some extra D1 shifts during the week. Week 39 of the realised roster shows a dramatic increase in nurse hours caused by a planning meeting in the evening of 27-09-2023, and a course during the day on 28-09-2023 and 29-09-2023. These hours were classified as patient time, although it was not intended to be. In the future a new shift code will be generated for this kind of events.

[13] As mentioned in Section 2.1 the planned data might present some nuances that might not make it entirely correct.

When examining how the three rosters compare to each other, as well as with the workload, in Fig. 14, several observations arise. First is how the realised roster closely mirrors the planned roster but shifted downwards. In contrast, there are differences between the optimised and planned roster, showing that adjustments were made.

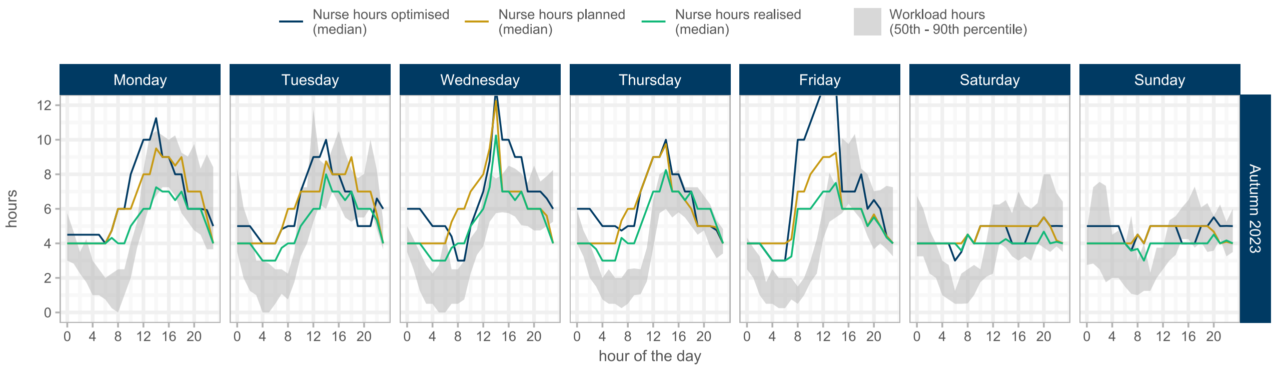

Figure 14: Workload vs nurse hours from the optimised, planned, and realised rosters in autumn 2023

Another observation is how the realised roster tends to allocate fewer nurses during night hours, aligning more closely with the workload curve than the planned roster does. Determining whether this reduction is intentional or a result of staffing shortages due to sick leave is challenging. Another potential reason for the difference between the realised and planned rosters could be attributed to the need to still schedule those individuals on long-term leave into shifts like D1, D12, N3, etc. in the planned roster. This practice ensures that their rotation remains consistent upon their return. However, as we have already mentioned, there could also be some inaccuracies in the planned data.

Monday still stands out as the busiest day. Yet, the nurse time during peak hours is lower than those in peak hours on other days. An explanation to this could be the general feeling in the ED that Mondays have a higher sick leave, the fact that the ED leader was not able to replace some of the staff, and that there are also more activities to perform. While this could be a plausible explanation, it needs to be verified.

Furthermore, we continue to observe a misalignment between nurse hours and workload on Fridays. This is caused by a) the increase in scheduled nurse hours in the morning, designed for ease of adjustment (as explained in Footnote 4 on Page 8), and b) the weekend rules, which force the allocation of nurses into day shifts, as rostering them in evening shifts triggers working on the weekend. We later learned that the ED hires extra staff to reinforce those hours that are not properly staffed because of the above-mentioned reasons.

Regarding the weekends, the realised roster consistently allocates 4 nurse hours throughout the day. This value is a median. A couple of days had up to 6 nurse hours, and a couple others had barely 2 nurse hours, but mostly 4 nurse hours seem to be usual (see Fig. 29 in Appendix C for more details). The ED leader reported an unusual high sick leave on weekends during autumn 2023, where a lot of nurses had to be replaced. This, together with the fact that the realised nurse hours is a median, explains why the weekends look so flat.

Notably, when comparing the realised roster to the reference shift schedule in Fig. 15, we can clearly observe how the realised roster successfully shifts nurse hours from the night and morning (when they are not required), to the afternoon and evenings (when there are peaks of workload). The reference shift schedule and the realised roster are comparable as they use approximately the same nurse hours per week (865.7 and an average of 830, respectively).

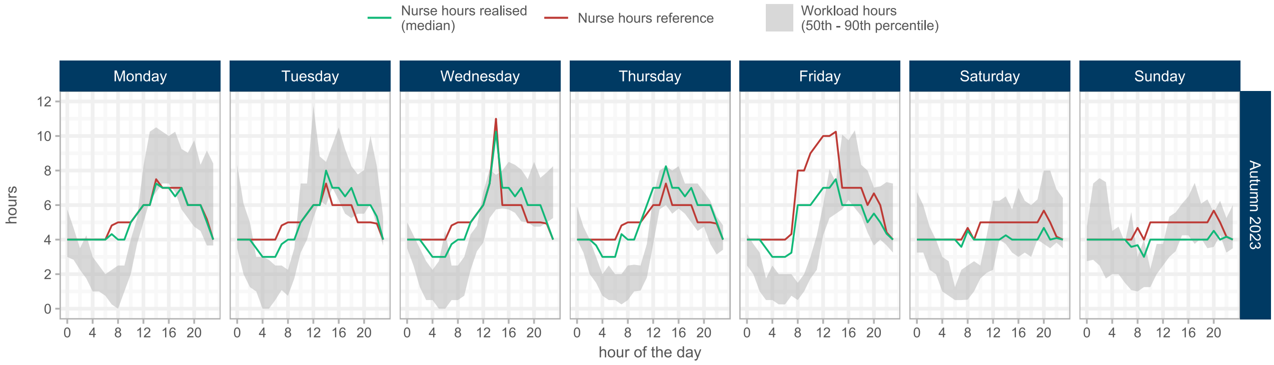

Figure 15: Workload vs nurse hours from realised data in autumn 2023 (green line) and the reference shift schedule from 2022 (red line)

Back to the comparison of the three rosters, the understaffing is expected to be the highest in the realised roster and the lowest in the optimised roster as the optimised roster has more allocated hours than the planned roster, which in turn has more hours than the realised roster. Table 4 summarises the frequency and magnitude of understaffing for each roster for the studied period.

Table 4: Frequency and magnitude of understaffing per roster type. The magnitude is the sum of hours understaffed in the autumn 2023.

	Optimised	Plan	Realised
Frequency (%)	10	14	17
Magnitude (h)	-263	-363	-465

5.3 Comparison of autumn 2022 and 2023

In this section we compare 9 weeks of autumn 2022 (from 29-08-2022 to 30-10-2022) with autumn 2023 (from 28-08-2023 to 29-10-2023).

We start by examining the cumulative hours throughout the analysed period. In 2023, nurse hours and workload increased by 6% and 12%, respectively. When looking at the figures per day of the week, as depicted in Fig. 16, we observe a workload increase for all days of the week, especially on Tuesdays due to unusual peaks in weeks 37, 40 and 42 for a typical Tuesday (for more details on autumn 2023 per date see Fig. 29, and for autumn 2022 see Fig. 28 in Appendix C). Nurse capacity in 2023 was higher than in 2022 on weekdays, but lower on weekends.

The comparison between 2022 and 2023 is challenging due to the rise in both workload and nurse capacity. In an ideal scenario, where workload and capacity grow proportionally, there could be a plausible link between improvements in understaffing and the changes caused by the new shift schedule and roster optimisation. However, when the increase in nurse capacity exceeds that of the workload, improvements in performance might be attributed to the increased nurse capacity rather than the efficiency of the schedule. Therefore, a careful examination is necessary to identify days for meaningful comparisons. From Fig. 17, which shows the percentage increase in workload and nurse hours in 2023 compared to 2022, we can deduce that the comparison between years would be fair for all days except for Mondays and Thursdays.

Fig. 18 and Fig. 19 show the frequency and magnitude of understaffing for autumn 2022 and 2023. The text labels in each individual plot summarise the frequency and total magnitude of understaffing for the corresponding day.

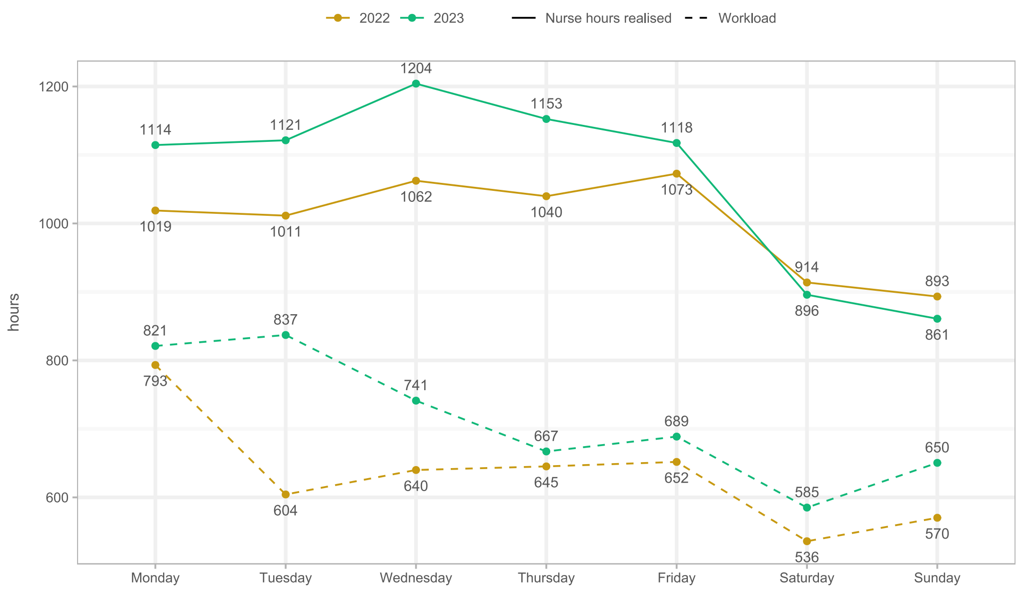

Figure 16: Sum total workload and nurse hours per day in autumn 2022 and 2023

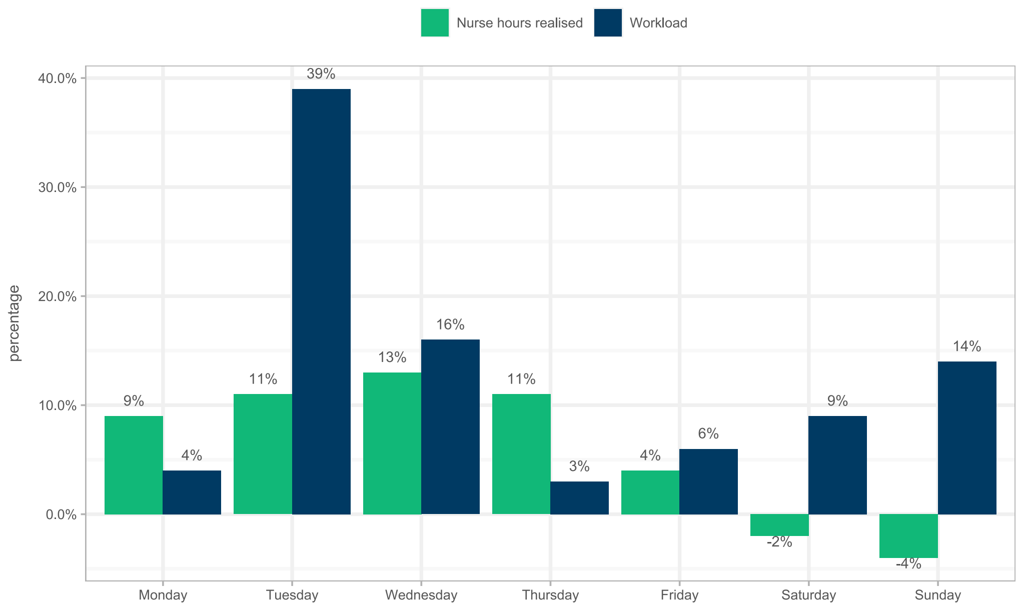

Figure 17: Percentage increase in workload and nurse hours in 2023 compared to 2022

Taking into account the fairness of comparison explained earlier and both graphs, we can examine the performance of each day:

- Tuesday: While Tuesday had a much higher rise in workload than staff, the frequency of understaffing remained the same, at 19%. Nevertheless, the magnitude of understaffing was more severe in 2023, as the shortage of nurse hours raised up to 7h at some times, and 30 more hours of nurse shortage in 2023 overall.
- Wednesday: Unlike Tuesday, Wednesday had a much more proportional increase between workload and nurse capacity (16% and 13% respectively). Both years have almost the same frequency and magnitude

of understaffing. It is interesting to see in Fig. 18 how the frequency of understaffing during afternoon hours in 2023 has decreased.

- Friday: It is not surprising the bad understaffing in the afternoon, which seems to have gotten worse in 2023 (Fig. 18). This is also shown in Fig. 19 with the fact that in 2023 there were more times with a shortage between 2 and 8 nurse hours, and between 0 and 2 hours.
- Saturday and Sunday: Not surprisingly both the frequency and magnitude of understaffing have increased in 2023 as both days have had a considerable increase in workload and a decrease in nurse capacity compared to 2022.

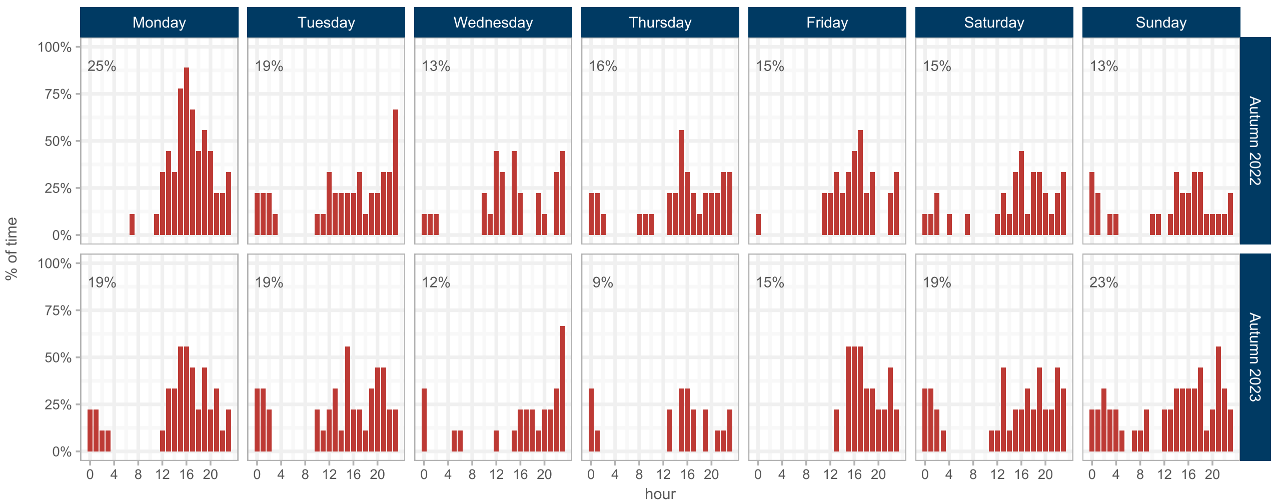

Figure 18: Frequency of understaffing per day of the week and hour in autumn 2022 and 2023. Text labels indicate total frequency of understaffing in the corresponding day.

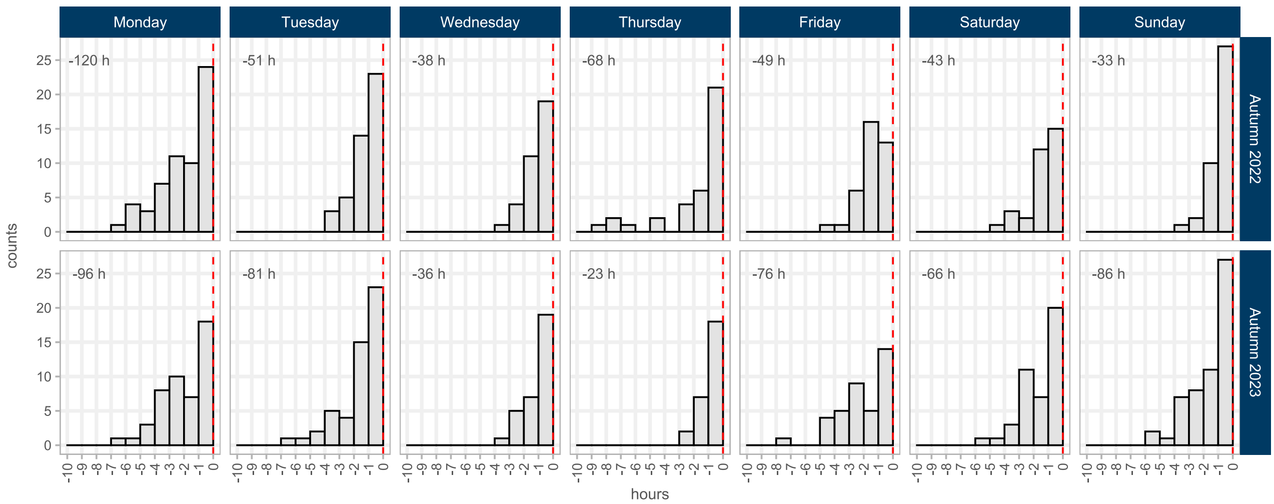

Figure 19: Magnitude of understaffing per day of the week in autumn 2022 and 2023. Text labels indicate total hours understaffed in the corresponding day.

We can also look at the overall performance of both periods in 2022 and 2023 (Table 5). The two have been understaffed 17% of the time with a total shortage of around 400 nurse hours, meaning that overall the performance has remained stable.

Table 5: Overall understaffing in autumn 2022 and 2023

Understaffing	Autumn 2022	Autumn 2023
Frequency (%)	17	17
Magnitude (h)	-402	-465

Based solely on this analysis, it is difficult to attribute the coping of the increase in workload to the new shift schedule and roster as there has also been an increase in staffing. Nevertheless, we can certainly say that the performance has remained stable and one of the causes, among others, has been the changes introduced. Furthermore, with the ED leader's firsthand experience during this period, there is a strong conviction that the introduction of the late-day and evening shifts played a crucial role in preventing the situation from becoming much worse.

5.4 Factors contributing to workload surge

In the previous section we identified a 12% workload increase in autumn 2023 compared to autumn 2022. Factors that can cause a raise in workload are:

a) More patients coming into the ED

b) A higher percentage of acute patients

c) Increased length of stay, caused by:

- Longer waiting times to see the doctor
- Blocked discharges due to unavailability of beds in the wards
- Leaving patients in the ED for extended monitoring, to avoid hospitalisation and ensure their well-being before being discharged home.
- Longer waiting times for lab tests or imaging results

Table 6 shows how there has been a consistent number of patients attending the ED in these two periods, with a minimal decline of 1% observed in 2023. It also shows that the percentages of acuteness degrees have remained unchanged.

Table 6: Total number of patient and acuteness degree distribution in autumn 2022 and 2023

	Autumn 2022		Autumn 2023	
Triage color	Total	Percentage	Total	Percentage
Rød	270	11.0	276	11.4
Orange	841	34.4	818	33.8
Gul	1210	49.5	1215	50.2
Grønn	125	5.1	111	4.6
Total	2446	100.0	2420	100.0

Last, we have looked at the distribution of the length of stay per triage color in both periods. We can observe a shift towards longer stays in 2023. In general, there are less patients staying between 0 and 3 hours and more staying slightly longer. From previous analysis in iCope we can say that this is not likely to be caused by delays in the lab and imaging departments.

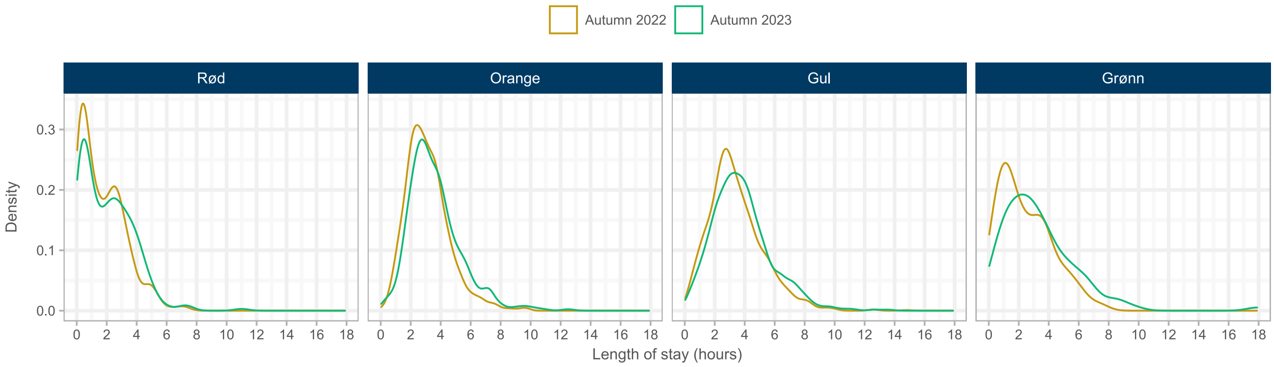

Figure 20: Distribution of the length of stay per triage color in autumn 2022 and 2023.

All in all, it looks like the increase in workload is the result of longer lengths of stay, and likely caused by factors that are not within the control of ED management and therefore out of scope in this project.

6 Next steps

The findings in Section 5 have shed light on critical challenges. Here is a list of topics that can enhance the performance in the ED.

- **Improve the shift schedule**: First, if the ED desires to keep the 12h shifts on weekends, it is key to design a structure that takes into account the weekends rules to ensure that a roster can be created from it. Second, it is worth considering adding an extra shift on Tuesdays, just like on Mondays, as the workload on Tuesdays has increased considerably. Finally, it would also be interesting to discuss extending the D7 shift to finish at 18:00 instead of 17:30 to ensure a continuity of nurses during high workload hours until the T9 shift starts.
- **Improve the rostering algorithm**: For a more optimal rostering of nurses, it is necessary to further develop the algorithm of Scoop Roster to include penalties that help balance the distribution of shifts throughout days and weeks.
- **Investigate sick leave and absence**: as we have seen, sick leave and absence have been big factors that have contributed to a reduced workforce. It would be interesting to study the incidence of both per day of the week as there is a feeling of a higher sick leave on Mondays. If this were the case, a further analysis on how to use flexibility to tackle this issue would be required.
- **Analyse reasons for increased length of stay**: so far, all the project adjustments have focused on factors under the control of ED management. However, the observed increase in workload, attributed to extended lengths of stay, suggests the need to address underlying causes. These causes are possibly related to blocked discharges due to bed unavailability, prolonged waits for doctors visits, or the intention to monitor the patient for a longer period to prevent hospitalisation. Addressing these issues could potentially reduce the overall workload and smoother peaks, thereby creating a more stable daily workflow, and subsequently, decreasing the required nurse hours.

7 Conclusions

This report summarises the initiatives undertaken at the emergency department of Ålesund sykehus to alleviate nurse understaffing. The focus was on aligning demand for care with nurse capacity and optimising nurse rosters to free up valuable time from the leader.

In Section 2, we have presented the alignment between patient demand and nurse capacity in 2022 and identified inefficiencies. Based on this, we have designed in Section 3 a shift schedule that tries to minimise understaffing while using the same amount of resources. In Section 4, we have introduced the optimisation tool we have used to create an efficient nurse roster considering the designed shift schedule, legal requirements and personnel wishes. In Section 5, we have presented the problems and challenges we have encountered when making the nurse roster for autumn 2023. We have also analysed the implementation of the optimised roster, as well as compared the performance of autumn 2022 with 2023. Finally, we have given pointers for future work in Section 6.

The first objective of the project was the reduce the current understaffing in the ED by better matching patient demand and nurse capacity without adding extra resources. In overall numbers, the undersataffing in autumn 2023 has remained very similar to the one in 2022. Based solely on the data, it is difficult to attribute the entire coping of the increase in workload to the new shift schedule and roster as there has also been an increase in capacity, but they have certainly contributed. After the ED leader's experience in this period, there is a strong conviction that the late day and evening shifts (D7 and T9) have definitely helped better managing the workload in the afternoon and evening, and they are confident the situation would have been considerably worse without the implemented measures.

The second objective was to generate an optimal nurse roster, in a matter of minutes, that minimises the breach of personnel wishes and rules. Scoop Roster, the chosen tool, demands high technical skills and formulating the use case requirements in a specific way. Since it was our first time using it, coding everything to get a proper result took a considerable amount of time. Once set up, Scoop roster has definitely been able to provide a solution, in a very short time, that has fewer breaches than the original roster we were given, though some manual changes afterwards were still necessary. While the tool has the potential to save leaders a considerable amount of time and provide efficient rosters, a user-friendly interface is essential for hospitals to adopt and utilise this tool.

Acknowledgements

This work has been done as a part of the iCope project, which was funded by the Research Council of Norway from 2020 to 2022 (project number 296219) and by Helse Midt-Norge RHF in 2023. We want to thank HMN-RHF for believing in the concept that iCope promoted and funding the follow-up of the project, to the staff in Ålesund sykehus who provided data, insights, and were enthusiastic about improving healthcare operations. We also want to thank SINTEF Digital for letting us use the Scoop Roster tool.

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SINTEF. Scoop roster - a software component for automatic optimization of rosters. `https://www.sintef.no/en/software/software-applied-mathematics/scoop-roster/` [Accessed: 2023-11-23].

A Appendix - Calculation of workload

As explained in Section 3, the calculation of workload takes into account patient arrivals, their length of stay and the care they need. In Table 7, ED management estimated the care required throughout the patient stay for each patient type.

Table 7: Estimation of the work generated by patient type

Colour	Admission group	Phase	Phase length (min)	Minutes of work generated in phase	Minutes of work per minute of real time
Red	All	Phase 1	60	120	2.00
		Phase 2	-	120/h	2.00
		Phase 3	-	120/h	2.00
Orange	All	Phase 1	60	60	1.00
		Phase 2	-	30/h	0.50
		Phase 3	30	30	1.00
Yellow	All	Phase 1	60	30	0.50
		Phase 2	-	15/h	0.25
		Phase 3	20	20	1.00
Yellow	KIR/ORT POL	Phase 1	60	15	0.25
		Phase 2	-	5/h	0.08
		Phase 3	15	15	1.00
Green	All	Phase 1	60	30	0.50
		Phase 2	-	15/h	0.25
		Phase 3	20	20	1.00
Green	KIR/ORT POL	Phase 1	60	15	0.25
		Phase 2	-	5/h	0.08
		Phase 3	15	15	1.00
Blue	All	Phase 1	60	3	0.05
		Phase 2	-	3/h	0.05
		Phase 3	3	3	1.00

The patient stay is divided into three phases:

- *Phase 1*: captures the work generated by the patient during the first hour of stay in the ED, involving admission, triage, and stabilization of the patient. This tends to be the most intense period.
- *Phase 2*: encompassing the period between the end of the first hour and the start of the discharge, this phase involves patient waiting, doctor consultations, lab and image test, etc. It requires nurses to prepare and monitor patients.
- *Phase 3*: estimates how long the discharge process for each patient type takes.

During phases 1 and 2, we do not know how care is distributed over time, so we spread the workload generated by the patient evenly over each hour. To do that, we use the minutes of work generated per minute of time (last column in Table 7).

Table 7 is read as follows. For instance, an orange patient requires 60 minutes of work during phase 1 (which lasts 60 minutes), therefore generating 1 minute of work per minute of stay. Afterwards, the patient requires 30 minutes of nurse care per hour until discharge. Since we do not know if this care takes place at the beginning, middle or end of the hour, we spread it evenly during the hour, hence the patient generates 0.5 minutes of work per minute of stay. Finally, the last 30 minutes of the patient's stay count as discharge. Since all the discharge minutes are worked by the nurse, this generates 1 minute of work per minute of stay.

We then wrote a code that takes as input the cleaned dataset of demand for care. The program goes through each patient in the dataset, calculates the amount of work they generate per minute during their stay based on Table 7, and then adds up the total workload generated by all patients for each minute. The result is shown in Figure 21.

When comparing the workload to nurse hours, our approach varies depending on the visualization goal. For assessing the magnitude or percentage of understaffing, or alignment for a specific date, we aggregate the workload by hour using a weighted average, which weighs each value of the workload by the number of minutes it has been present in the hour. The result is directly comparable to nurse hours per hour and date. On the other hand, if the aim is to provide a broad overview of the week, we calculate the 50th and 90th percentiles of all the workload minutes within each hour per day of the week and compare it to the median of nurse hours per hour and day of the week (like in Figure 2).

year	week	month	day	date	hour	timestamp	workload
2022	35	September	Thursday	2022-09-01	18	2022-09-01 18:57:00	6.57
2022	35	September	Thursday	2022-09-01	18	2022-09-01 18:58:00	6.57
2022	35	September	Thursday	2022-09-01	18	2022-09-01 18:59:00	7.32
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:00:00	7.32
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:01:00	7.32
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:02:00	7.32
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:03:00	6.82
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:04:00	6.82
2022	35	September	Thursday	2022-09-01	19	2022-09-01 19:05:00	6.82

Figure 21: Example of the dataset containing workload per minute

B Appendix - Alternatives considered

B.1 Alternative 10

Table 8: Structure of the shift schedule from alternative 10

	Shift times			Number of nurses								Hours
Shift	Start	End	Dur (h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun	week	week
D1	07:30	15:00	7.5								0	0
D10	10:00	22:10	12.2	4	3	2	2	2	1	1	15	182.5
D12	08:00	20:10	12.2	4	4	4	4	4	4	4	28	340.7
K1	14:45	22:15	7.5								0	0
K2	11:30	19:00	7.5								0	0
K5	13:45	22:15	8.5								0	0
N11	20:00	07:35	11.6								0	0
N12	20:00	08:10	12.2	4	4	4	4	4	4	4	28	340.7
N3	22:05	07:35	9.5								0	0
D7	10:00	17:30	7.5								0	0
T9	18:00	03:30	9.5								0	0
T12	18:00	06:00	12.0								0	0
Total				12	11	10	10	10	9	9	71	863.8

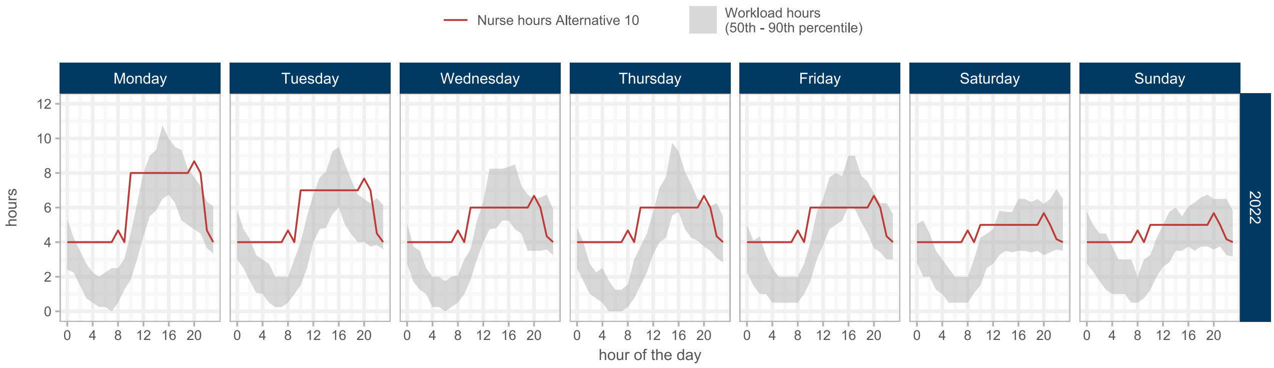

Figure 22: Shift schedule from alternative 10 (in red) compared to historical workload in 2022

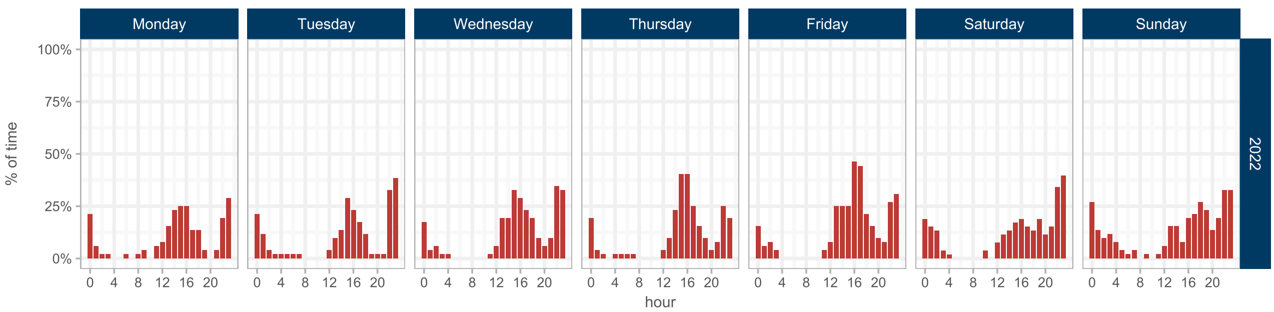

Figure 23: Frequency of understaffing generated by alternative 10 compared to 2022 workload

B.2 Alternative 11

Table 9: Structure of the shift schedule from alternative 11

	Shift times			**Number of nurses**								**Hours**
Shift	Start	End	Dur (h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun	week	week
D1	07:30	15:00	7.5	3	3	3	3	5	3	3	23	172.5
D10	10:00	22:10	12.2								0	0
D12	08:00	20:10	12.2								0	0
K1	14:45	22:15	7.5	5	4		4	4	4	4	25	187.5
K2	11:30	19:00	7.5	2	2	2	2	1	1	1	11	82.5
K5	13:45	22:15	8.5			4					4	34
N11	20:00	07:35	11.6								0	0
N12	20:00	08:10	12.2								0	0
N3	22:05	07:35	9.5	3	3	3	3	4	4	4	24	228
D7	10:00	17:30	7.5	2	2	2	2				8	60
T9	18:00	03:30	9.5	1	1	1	1				4	38
T12	18:00	06:00	12.0								0	0
Total				16	15	15	15	14	12	12	99	802.5

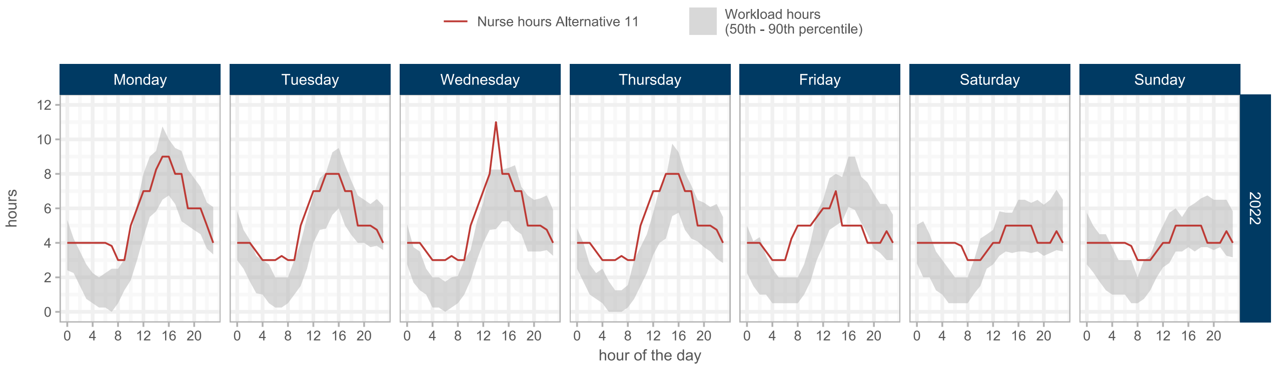

Figure 24: Shift schedule from alternative 11 (in red) compared to historical workload in 2022

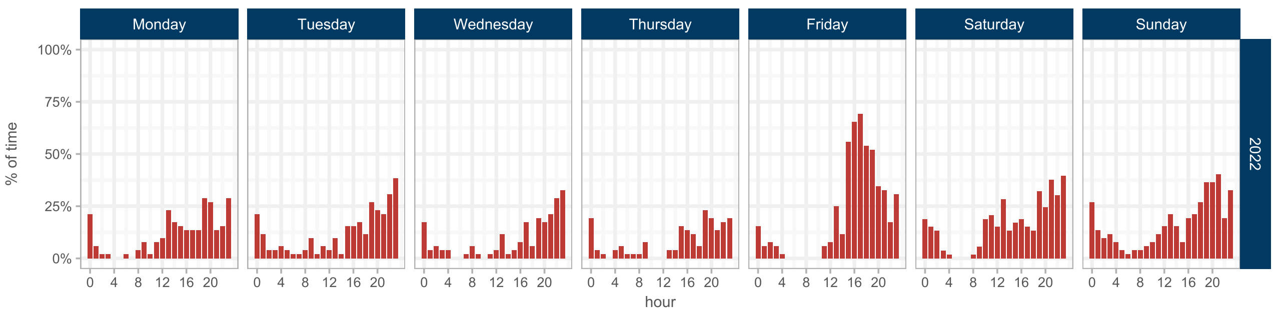

Figure 25: Frequency of understaffing generated by alternative 11 compared to 2022 workload

B.3 Alternative 12

Table 10: Structure of the shift schedule from alternative 12

	Shift times			Number of nurses								Hours
Shift	Start	End	Dur (h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun	week	week
D1	07:30	15:00	7.5	3	3	3	3	3	3	3	21	157.5
D10	10:00	22:10	12.2								0	0
D12	08:00	20:10	12.2								0	0
K1	14:45	22:15	7.5	5	4		4	4	4	4	25	187.5
K2	11:30	19:00	7.5	2	2	2	2	2	1	1	12	90
K5	13:45	22:15	8.5			4					4	34
N11	20:00	07:35	11.6								0	0
N12	20:00	08:10	12.2								0	0
N3	22:05	07:35	9.5	3	3	3	3	3	4	3	22	209
D7	10:00	17:30	7.5	2	2	2	2	2			10	75
T9	18:00	03:30	9.5	1	1	1	1	1	1	1	7	66.5
T12	18:00	06:00	12.0								0	0
Total				16	15	15	15	15	13	12	101	819.5

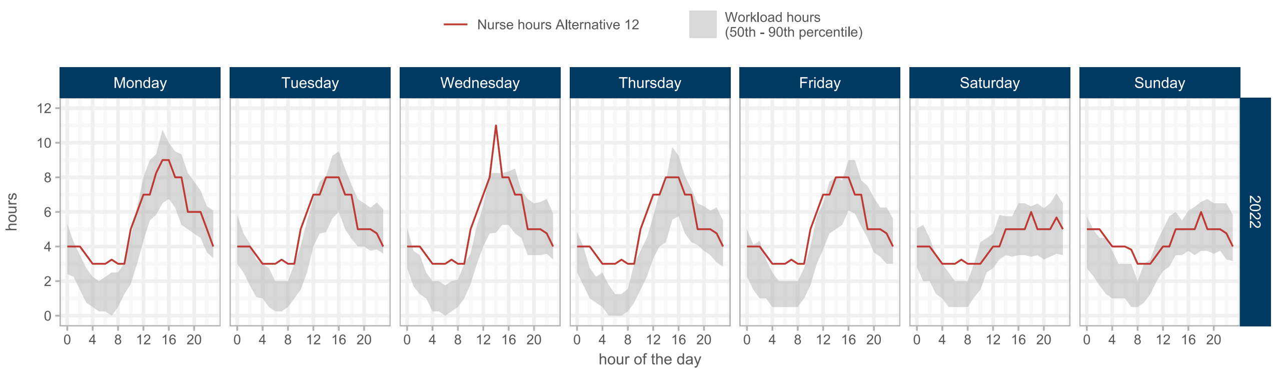

Figure 26: Shift schedule from alternative 12 (in red) compared to historical workload in 2022

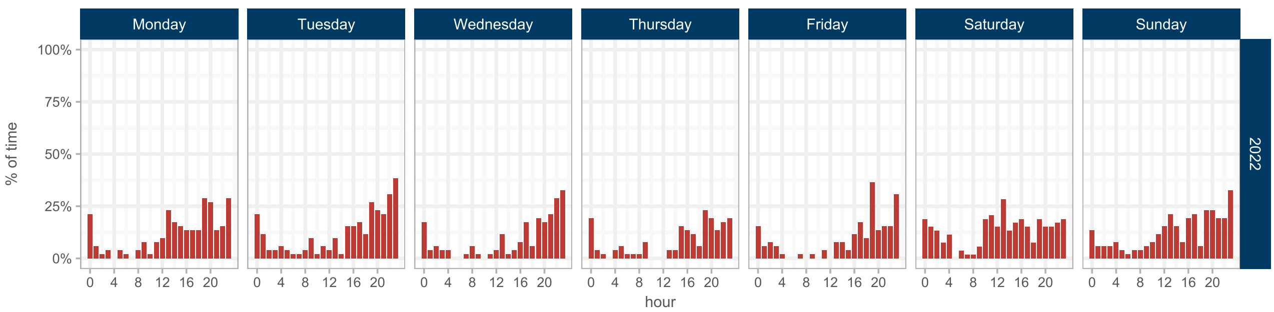

Figure 27: Frequency of understaffing generated by alternative 12 compared to 2022 workload

C Appendix - Workload vs nurse hours

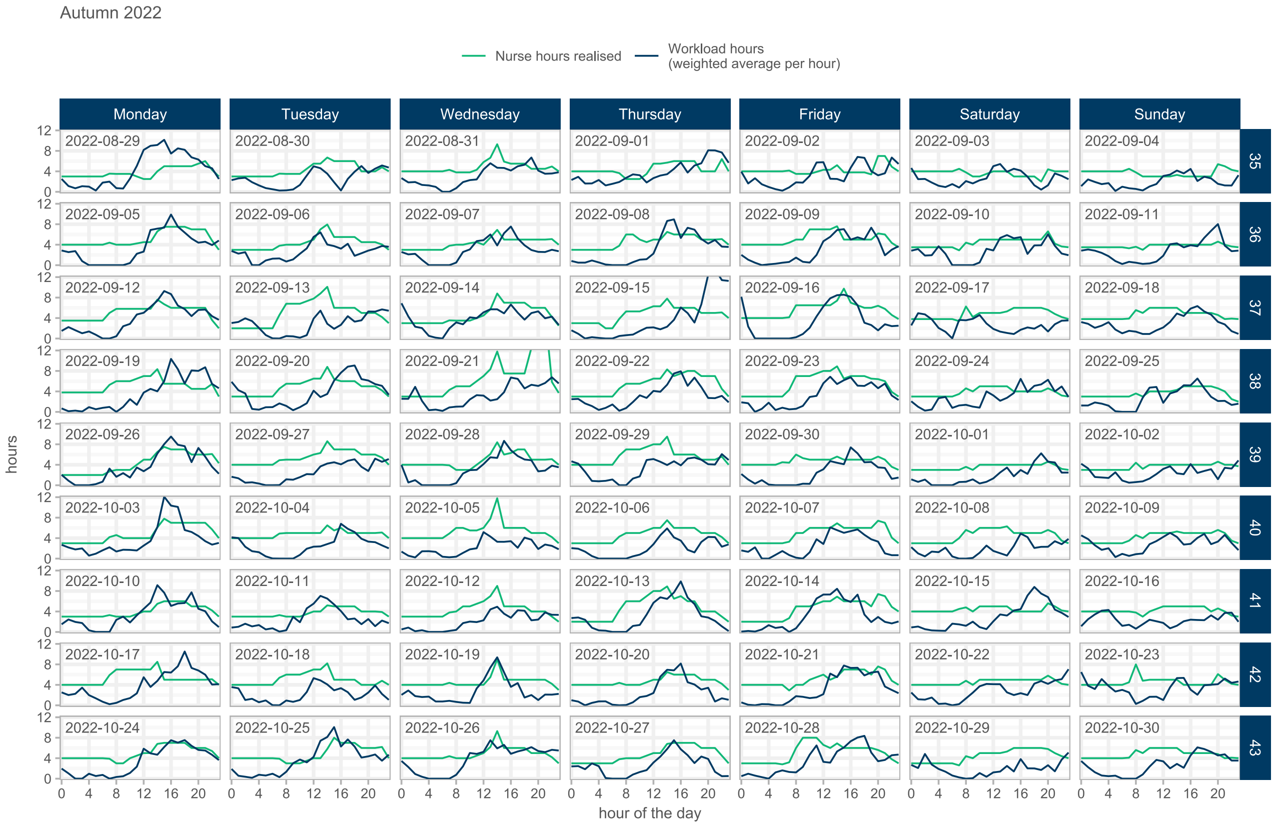

Figure 28: Daily workload vs nurse hours realised per hour from 29-08-2022 to 30-10-2022.

Autumn 2023

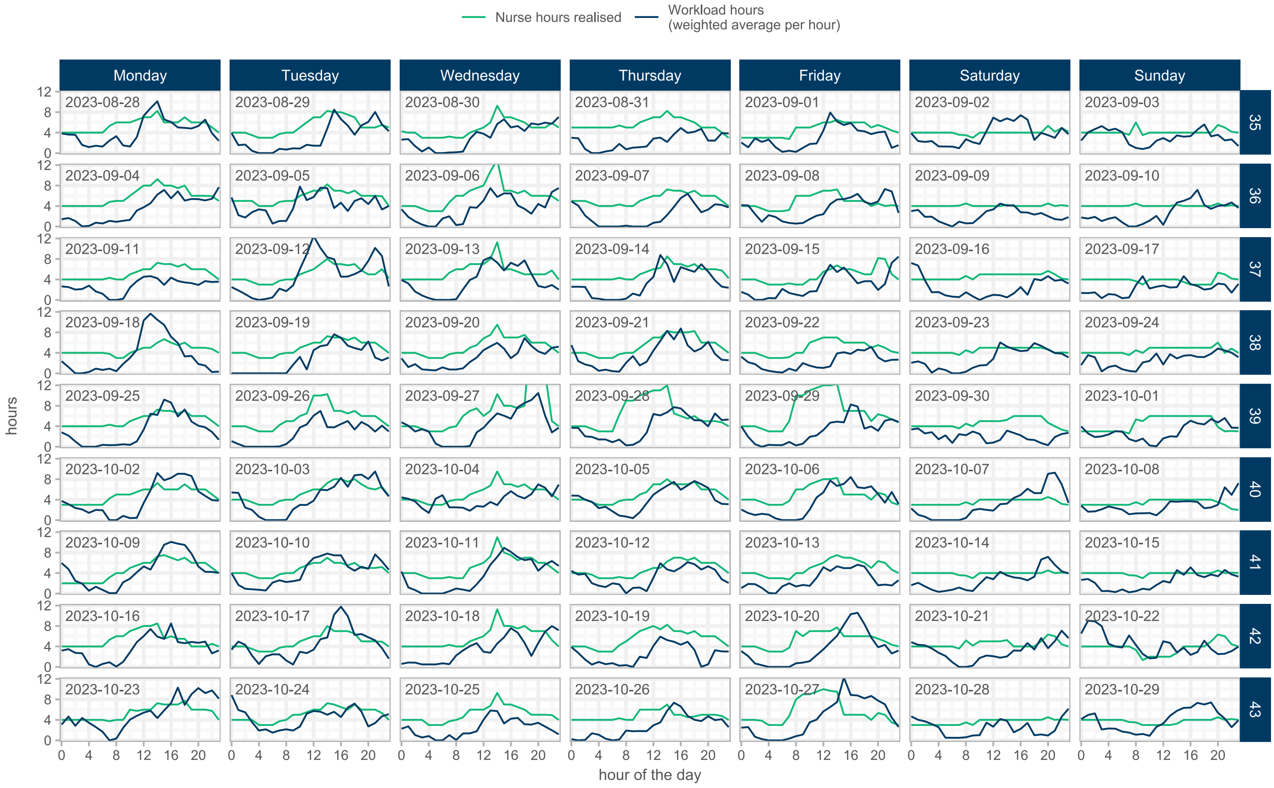

Figure 29: Daily workload vs nurse hours realised per hour from 28-08-2023 to 29-10-2023

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