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WORKING PAPER

The Impact of Incorporating Nurse-Specific Characteristics in a Cyclical Scheduling Approach

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ABSTRACT

Nursing staff is principally cyclically scheduled in various hospitals in Belgium. The employed cyclic schedules embody, however, only a weak reflection of the ultimate nurse rosters constructed for a specific month. In this paper we investigate the benefits of integrating nurse-specific characteristics in the cyclic scheduling approach. Moreover, we analyze to what extent these characteristics should be incorporated and compare this approach with a general and more robust cyclical scheduling approach and the flexible acyclical rostering of nursing personnel.

Keywords: Manpower planning; Healthcare

1 Introduction

The healthcare industry is faced with an increasing pressure of work due to the increasing elder population and the corresponding increasing demand for care and caring personnel. A hospital needs to assure that suitably qualified staff fulfils the required duties ensuring the delivery of high-quality care while controlling the costs. However, since the performance and quality of a health system ultimately depend on the quality and motivation of health human resources, the organizational support to employees should be appropriately addressed (Martinez and Martineau, 1998; Zurn et al., 2005). This support is especially revealed in the scheduling policies and practices conducted by the health organizations. Unattractive schedules and high workloads are likely to be avoided as these two factors typically lead to nurse discontentment and a high nursing turnover (Thompson, 1995; Felici and Gentile, 2004; Cline et al., 2003). More and more, hospitals adopt scheduling policies that increasingly accommodate preferences and requests of their nursing staff and abandon the more traditional cyclic scheduling. Cyclic scheduling provides fairness between the nurses but is acquainted with different discomforts when dealing with illnesses, vacations and personal concerns. The development of better nurse scheduling support systems should enable health care managers to deal with all these challenges and employ resources more effectively and efficiently. Hence, the management has interests such as minimizing overtime, maintaining continuity of care, maximizing morale, and minimizing turnover and absenteeism. Solving the nurse scheduling problem properly has a positive impact on the nurses' working conditions, which are strongly related to the quality level of health care (Bard and Purnomo, 2005a; Berrada et al., 1996; Burke et al., 2004a).

The presented approach focuses on the nurse rostering problem, which decides on the assignment of nurses to work days and/or daily work shifts across a typical planning horizon of 1 to 8 weeks for a

particular nursing unit. An individual schedule should be generated for each employee of the available nursing staff according to the applicable nurse scheduling policies. For the remainder of the paper we will denote a line-of-work for an individual nurse as a nurse schedule and the compound of all nurse schedules as the nurse roster. This problem aims to maximize the quality of the constructed timetable satisfying the hospital staffing demand coverage and meeting legal, union, hospital, and personal constraints imposed on the nurses' individual schedules. Roster quality is typically characterized by various (conflicting) goals complying with different priority levels, which represent the hospital's policies and the nurses' preferences (Randhawa and Sitompul, 1993; Burke et al., 2004b). The priorities given to these objectives may differ per health care organization, nursing unit and even per nurse scheduler. A part of the problem data, such as the quantity and mix of nursing resources (i.e., the ward's budget), the required qualifications, and the definition of shift types is determined at the strategic level (i.e., the staffing phase). Constructing timetables of work for personnel in healthcare institutions is a highly constrained and difficult problem to solve and is known to be NP-hard (Osogami and Imai, 2000).

Although we have developed a general approach, we investigate the nurse scheduling process and the effects of incorporating nurse-specific characteristics in a cyclical scheduling approach in a specific real-life environment. The problem case consists of generating an appropriate (non-)cyclical nurse roster for a ward in the department of internal medicine in the university hospital of Ghent (UZ). In this department cyclical scheduling is exercised. The cyclical individual nurse schedules are drawn up centrally in the hospital. Based on these schedules, the monthly rosters are constructed consulting the nurses and, hence, based on the incidental nurses' preferences. We want to explore the advantages and disadvantages of incorporating nurse-specific characteristics into this cyclical roster at the ward level. Nurses typically distinguish themselves by having different skill competencies, contract types, work stipulations and regulations, and/or scheduling preferences. Incorporating these nurse characteristics leads to a cyclical roster having a certain degree of nurse- and/or period-specificity because of staff retention and turnover and changing nurses' characteristics (e.g., altered general nurse preferences over time). Leaving these characteristics out of the problem formulation leads to a more general cyclical schedule providing a well-established footing for the nurse scheduler but neglects the nurse-specific information of a problem case possibly leading to job dissatisfaction, increased work for the nurse scheduler, bad reflection of the monthly nurse roster, and/or the need for more costly provision of care.

The remainder of the paper is organized as follows. In section 2, we provide a concise overview of the nurse scheduling literature. In section 3, we describe and analyze the real-world problem case. In section 4, we discuss the implications for the nurse scheduler and the nurses when incorporating nurse-specific characteristics in the cyclical schedule. Moreover, we conduct extensive computational

experiments on artificial problem instances generated under controlled design in order to demonstrate the generality of our findings. In section 5, conclusions are drawn and directions for future research are given.

2 Literature Overview

In this section, we provide an overview of the different modes the nurse scheduling process can be organized in real world environments, i.e., centralized scheduling, unit scheduling, and self-scheduling, and of the different approaches to nurse rostering, i.e., cyclical and acyclical scheduling. Moreover, we give a literature overview of the relevant solution procedures solving real-world cyclical and acyclical scheduling problems.

2.1 Organizational structure

Centralized scheduling describes the situation when one administrative department in a hospital carries out all the personnel scheduling activities (Easton et al., 1992; Siferd and Benton, 1992; Smith-Daniels et al., 1988; Warner, 1976). In this structure the head nurses are not burdened with the time consuming task of constructing schedules on a very regular basis. Two major advantages of centralized scheduling are fairness to employees through consistent, objective, and impartial application of policies and opportunities for cost containment through better use of resources. However, centralized scheduling suffers from a number of limitations, e.g., personnel can feel that local ward desires are not prompted into the procedure (Silvestro and Silvestro, 2000).

When head nurses or unit managers are given the responsibility to generate the schedules locally, the process is called unit scheduling (Sitompul and Randhawa, 1990). In this approach nurses receive more personalized attention.

Self-scheduling or interactive scheduling is applied when the personnel roster is generated manually by the staff themselves. Manually creating schedules has been generally adopted in hospital wards. In this environment, nurses collectively develop their schedules taking coverage and case-specific time-related constraints into account coordinated by the head nurse of the ward. While the individual personnel members express their preferences for schedules, the head nurse ensures that the hospital requirements are met. It is a very time consuming procedure in which the nurses indicate their preferences and negotiate among each other. Silvestro and Silvestro (2000) indicated that this approach easily leads to under- and overstaffing, that the schedule is made for the convenience of staff, that there are no formal procedures for conflict solving, and that there is a danger of generating unbalanced and inappropriate schedules leading to the perception of ‘unfair’ rosters. Miller (1984) and Hung (1992) identified the benefits of this operation mode, i.e., increased perception of autonomy of

the nurses, reduction of head nurse's scheduling time, greater staff satisfaction and commitment, improved cooperation and team work, and reduced turnover.

2.2 Nurse rostering approaches

The construction of cyclical schedules implies that each nurse works a cyclic schedule of n weeks, which is repeated over time. In a (pure) cyclic roster all employees of the same class perform exactly the same line of work, but with different starting times for the first shift or duty. Sometimes a complete cyclic roster, for all staff, is not feasible, but it may be possible to have cyclic rosters within subgroups of the workforce or over subperiods of the rostering horizon. This type of schedule is common if the day is partitioned in distinct shifts and if the personnel requirements per day and per shift obey a cyclical schedule. Cyclical scheduling is referred to as fixed scheduling (Silvestro and Silvestro, 2000). According to Warner (1976), cyclical schedules offer several advantages, i.e., personnel know their schedules a long time in advance, the same blocks are used repeatedly, the work is divided evenly, and unhealthy work rotations are avoided. However, according to Burke et al. (2004b), this approach has some serious drawbacks for practical applications. Cyclical schedules do not provide high levels of flexibility, i.e., they cannot easily address flexible work regulations, fluctuating personnel demands, and personal preferences. Burke et al. (2004b) argue that cyclical rostering does not provide sufficient flexibility in case of changes in personnel demands or when expressing personnel preferences. Pure cyclical scheduling is only applicable in very rare cases and is not suited to modern real nurse rostering applications.

Burke et al. (2004b) advocate the construction of 'ad hoc' rosters, which comply better with the nurses' preferences. In these acyclic rosters, the lines of work for individual employees are completely independent. Acyclical or flexible scheduling is able to address fluctuating hospital demands in addition to flexibility with respect to the private preferences of the personnel.

However, according to Bard and Purnomo (2007) the disadvantages of both approaches can be eliminated when developing cyclical schedules for nurses while taking the quality of individual nurse schedules into account. In this way, individual schedules come towards the needs and wishes of the nurses and the inherent inconsistency of acyclic scheduling implying that nurses have noticeably different shift assignments from week to week and from month to month is removed.

2.3 Nurse rostering solution procedures

Problem descriptions and models vary drastically and depend on the characteristics and policies of the particular business environment. Hence, in literature many objective function possibilities subject to a huge variety of constraint combinations are explored. Since personnel scheduling problems have this

multitude of formulations, many procedures have been proposed to solve personnel scheduling problems in general and the nurse scheduling problem in particular. An extensive overview of personnel shift scheduling problems can be found in Ernst et al. (2004a, 2004b) and for the nurse scheduling problem specifically in Cheang et al. (2003) and Burke et al. (2004a). Exact procedures and mathematical programming techniques have been frequently proposed for both the cyclical and acyclical scheduling of nursing personnel (e.g., Burns and Koop, 1987; Hung, 1991; Muslija et al., 2000; Arthur and Ravindran, 1981; Azaiez and Al Sharif, 2005; Berrada et al., 1996; Brusco and Johns, 1995; Musa and Saxena, 1984; Ozkarahan and Bailey, 1988; Bard and Purnomo, 2005a, 2005b, 2007; Jaumard et al., 1998; Mehrotra et al., 2000; Maenhout and Vanhoucke, 2007c). In practice, the size of nurse rostering problems, the specific nurse and workplace characteristics, and the appropriate scheduling policies and practices, hinders the applicability of most developed exact optimization methods, which endorses the development of heuristic procedures. Many (meta-)heuristics have been developed to obtain high quality cyclical and acyclical schedules for real world problems in an acceptable computation time (e.g., Blau and Sear, 1983; Kostreva and Jennings, 1991; Brusco and Jacobs, 1995; Dowsland, 1998; Burke et al., 1999; Aickelin and Dowsland, 2000; Burke et al., 2001; Maenhout and Vanhoucke, 2005, 2006a, 2006b).

3 Problem description

In this section we describe the characteristics of the real-world nurse scheduling problem of a ward in the department of internal medicine. The hospital that participated in this study is a non-for-profit university hospital located in Ghent accounting for 1,069 beds divided over 35 departments. The hospital is one of the most prominent hospitals in Belgium with activities in medical care, teaching, scientific research, and providing services to the population. The hospital treats 365,000 outpatients and 33,000 inpatients a year and employs nearly 1,700 nurses comprising a vast share of the hospital's operational costs.

In order to map the nurse scheduling process the specific department provided us with information in order to assess the scheduling organization, the nurse characteristics, the scheduling objectives, and the scheduling policies and practices.

3.1 Organization of the scheduling process

The hospital provided us with information about the structural organization of the personnel scheduling process and data related to shift lengths, shift times, and the planning period.

The hospital is organized in wards with fixed activities with a permanent team of nurses. Although practical situations often allow people to be moved to another ward whenever a personnel shortage is unsolvable, the personnel rostering problem under study concerns a group of personnel belonging to

the same ward. As mentioned above, the nurse rostering for the permanent staff is cyclically organized. The cyclical roster is composed out of individual cyclical schedules, which have a length of 8 weeks and are composed centrally according to certain shift scheduling policies and objectives of the hospital, which are described in section 3.3. Based on this cyclical roster, the head nurse of the specific department is responsible for preparing a monthly nurse schedule. This process is done manually and is in dialogue with the nurses. The objectives and scheduling policies controlling the monthly construction of the actual nurse roster are described in section 3.4.

In the department, three shift types can be observed, i.e., an early, late, and a night shift. A shift type is a predefined period with a fixed start and end time. In the nurse roster, personnel members will be assigned to one of these three shifts or will be off duty. The codes, definition, and start and end times of the respective shifts are presented in table 1.

Table 1. Shift types in the department under study

Code	Shift	Start	End
E	Early	06:45	14:45
L	Late	14:15	22:15
N	Night	22:00	07:00

In order to guarantee the continuity of care, minimum coverage requirements are specified for each shift to meet the demand for care. Table 2 displays the minimum coverage requirements for a single week in the department under study. These coverage requirements are each week the same.

Table 2. Minimum coverage requirements

Minimum coverage requirements	Monday			Tuesday			Wednesday			Thursday			Friday			Saturday			Sunday		
Shift type	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N
# Minimum required	5	4	1	5	4	1	5	4	1	5	4	1	5	4	1	4	3	1	4	3	1

3.2 Nurse characteristics

Additionally, the head nurse provided information about the staff mix, the staff competences, and the nurses' scheduling preferences. The ward's personnel budget amounts 23.6 FTE. In the department under study several degrees of employment are encountered constituting the ward's budget, i.e., 16 personnel members are full-time, 3 are 90% part-time, 1 is 80% part-time, 2 are 75% part-time, 1 is 60% part-time, and 4 are 50% part-time. Additionally, certain stipulations are recorded in the nurses' work regulations or contracts for some employees having an impact on the rostering of nurses (e.g., no night shifts because of medical prescriptions).

The personnel members in the ward are characterized by having different skill competences. The staff of the department under study is composed out of a head nurse, an administrative secretary, 23 registered nurses, no nurse assistants, and 2 licensed practical nurses. Rather than employing strictly disjoint skill categories or hierarchical substitutability, alternative skill categories are additionally assigned to certain people in the department solving the problem of replacing people. This composition and assignment of (alternative) skill categories is based upon the particular level of qualification, responsibility, job description, and experience of the personnel. In constructing a cyclical nurse roster no substitutability is allowed. Also, when generating the monthly nurse rosters there is basically no substitutability taken into account. However, only in case of long-term absence (due to vacation, sickness, etc) some registered nurses are allowed to replace the head nurse and/or the secretary. Licensed practical nurses are never replaced when constructing the nurse roster. Because of this limited substitutability, we concentrate in the remainder of the paper only on the rostering of registered nurses for a regular month.

In order to construct appropriate nurse rosters complying with the nurses' preferences, the head nurse is acquainted with the nurses' general scheduling preferences. Additionally, the nurses communicate their incidental and period-specific wishes and requests to the head nurse, which takes these preferences into account when constructing the initial nurse roster for a particular month.

In table 3 we provide an overview of all nurse characteristics of the registered nursing staff in the department under study and of the nurses' scheduling preferences for a specific month.

Table 3. Overview of the nurse characeristics

Nurse characteristics	Cyclical roster type	Degree of employment	Skill categories(*)					General preferences/ Contract stipulations
			(1)	(2)	(3)	(4)	(5)	
1. Maarten Debackere	Basic	90%	0	1	1	1	0	Preference for early shifts
2. Merel Debrabandere	Basic	100%	0	1	1	1	0	Preference for night shifts
3. Pieter De Brandt	Basic	100%	1	1	1	1	0	No early shifts
4. Noor Decaluwé	Basic	100%	0	1	1	1	0	Preference for early shifts
5. Marie Dedecker	Basic	100%	0	1	1	1	0	Preference for late shifts
6. Peter De Jaegher	Basic	100%	0	1	1	1	0	/
7. Kenneth Denys	Basic (adapted)	75%	1	1	1	1	0	Preference for night shifts 14 night shift in cyclical schedule
8. Annelies Descamps	Supplementary	100%	0	1	1	1	0	/
9. Ruben De Schrijver	Supplementary	100%	0	1	1	1	0	Preference for Wednesday day off
10. Marieke De Smet	Supplementary	100%	1	1	1	1	0	Preference Monday day off
11. Nele Devleesschauwer	Supplementary	100%	1	1	1	1	0	Preference for late shifts
12. Tine Dhondt	Supplementary	50%	1	1	1	1	0	/
13. Severien Dumoulin	Supplementary	100%	0	1	1	1	0	/
14. Kelly D'haese	Supplementary	100%	1	1	1	1	0	Preference for weekend day off
15. Mathias D'hoore	Supplementary	75%	0	1	1	1	0	/
16. Joke Naudts	Supplementary	100%	0	1	1	1	0	Preference for weekend shifts
17. Katrien Rummes	Supplementary	90%	1	1	1	1	0	/
18. Louis Ryckaert	Supplementary	100%	1	1	1	1	0	Preference for late shifts
19. Eveline Vandeweghe	Supplementary	90%	1	1	1	1	0	/
20. Griet Vanhollebeke	Supplementary	100%	1	1	1	1	0	Only late shifts
21. Pauline Verhaeghe	Supplementary	60%	0	1	1	1	0	No weekend shifts
22. Melina Verstraete	Supplementary	100%	0	1	1	1	0	/
23. Stefanie Vlaeminck	Supplementary	50%	0	1	1	1	0	Preference for early shifts

(*) (1) Head nurse; (2) Secretary; (3) Registered nurse; (4) Nurse assistant; (5) Licensed Practical Nurse

3.3 Cyclic rostering

Basically, the personnel members in the department can be cyclically rostered according to two different cyclical schedules. The hospital composed a basic cyclical schedule, which assigns the personnel members to early, late, and night shifts over the planning horizon, and a supplementary cyclical schedule, which assigns the personnel member only to early or late shifts. Exploiting these two kinds of cyclical schedules, the hospital offers its nursing staff the choice to work or work not the unpopular but financially more attractive night shifts. Both cyclical schedules incorporate a high number of hard case-specific time related constraints, which are presented in table 4 for a single month.

As cyclical schedules are per definition repeated each n weeks, additional constraints are imposed allowing cyclical schedules to be repetitive, i.e., constraints accounting for the feasible succession of shift assignments, weekend assignments, and the minimum and maximum work stretches in the transition and repetition of cyclical schedules. Both types of cyclical schedules comprising each 8 weeks applied in the department under study are displayed in figure 1. It is clear that not all nurses

working the basic or supplementary cyclical schedule start their cyclical schedule in the same single week. For a particular week, some nurses have to work according to the cyclical schedule of week 1, others according to the schedule of week 2, etc in a way some coverage is provided for all shifts on each day. The current cyclical start working week of a particular month for each staff member is depicted in figure 2.

Table 4. Time related constraints incorporated in the cyclical schedules

Description	Basic cyclical schedule			Supplementary cyclical schedule		
	Policy	Min	Max	Policy	Min	Max
Number of working hours	Y	136	180	Y	136	160
Number of working days	Y	17	20	Y	17	20
Number of early shifts	Y	7	12	Y	9	10
Number of late shifts	Y	5	7	Y	9	10
Number of night shifts	Y	3	4	N	NA	NA
Number of working weekends	Y	1	3	Y	2	2
Number of free days after series of night shifts	Y	3	4	N	NA	NA
Consecutive number of working days	Y	2	7	Y	2	7
Consecutive number of assigned early shifts	Y	2	7	Y	2	7
Consecutive number of assigned late shifts	Y	3	5	Y	3	5
Consecutive number of assigned night shifts	Y	3	4	N	NA	NA
Consecutive number of rest periods	Y	1	3	Y	1	3
Consecutive number of working weekends	Y	1	2	Y	1	1
Working a complete weekend	Y	NA	NA	Y	NA	NA
Working an identical weekend	Y	NA	NA	Y	NA	NA
A rest of 11 hours between working shifts	Y	NA	NA	Y	NA	NA
Maximal one assignment per day	Y	NA	NA	Y	NA	NA

Basic cyclical schedule	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 1	E	E	E	-	N	N	N
Week 2	N	-	-	-	L	L	L
Week 3	L	L	-	E	E	-	-
Week 4	E	E	E	E	E	E	E
Week 5	-	N	N	N	-	-	-
Week 6	L	L	L	L	-	E	E
Week 7	-	-	L	L	L	-	-
Week 8	E	E	E	E	E	-	-
Supplementary cyclical schedule	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 1	L	L	L	L	L	-	-
Week 2	E	E	E	-	L	L	L
Week 3	L	-	E	E	E	-	-
Week 4	-	L	L	L	-	E	E
Week 5	E	E	E	E	E	-	-
Week 6	L	L	-	-	E	E	E
Week 7	E	-	L	L	L	-	-
Week 8	-	E	E	E	-	L	L

Figure 1. Applied cyclical schedules in the department under study

The displayed cyclical rosters in figure 1 are only valid for full-time personnel. For each category of part-time personnel (e.g., 75%, 50%) the number of working assignments in the corresponding

cyclical roster is reduced according to their degree of employment. Based on each nurse's stipulated working contract one of these two kinds of cyclical rosters are assigned to the nurse according his/her degree of employment, which basically provides fairness between the nurses. However, although these cyclical schedules were constructed in order to obtain fairness among the nurses and some generality such that in case of personnel retention new personnel members can easily take over the schedules of old personnel members, some nurse-specific characteristics were introduced in these rosters. The prescribed days off because of seniority leave are incorporated and fixed in the cyclical roster of each nurse. The extra free days due to part-time employment of some nurses have been fixed according to the nurses' general scheduling preferences. Furthermore, for some nurses a modified cyclical roster that adopts some nurse-specific general preferences is granted. This leads to the fact that at the time of the study 8 different cyclical schedules are applied in the department, which comprises a great variety of schedules in a cyclical scheduling approach. Based on these cyclical schedules for each nurse, a cyclical roster is constructed for all nurses in such a way that the cyclical coverage requirements are met. These cyclical coverage requirements are set higher than the postulated minimum coverage requirements of table 2 to meet the actual patient demand since other forecasts are also taken into account, e.g., availability of nurses at different times during the forecast period, patterns of turnover and sick calls, and the timing of staffing and training activities. The degree these cyclical coverage requirements are higher is dependent of the service level the hospital postulates. The service level is typically defined as the probability of violating the minimum coverage requirements below a certain critical level (e.g., 5%). More specifically, in the ward under study the head nurse claims three extra nurses for the early shift and three extra nurses for the late shift on top of the minimum required staff on each day. No extra nurses are postulated to constitute the cyclical coverage requirements of the night shifts. The cyclical roster in the department at the time of the study is displayed in figure 2 for four weeks.

Cyclical roster Week 23 - Week 26	Type(*)	Adjusted(**)	Week 23							Week 24							Week 25							Week 26						
			5/jun	6/jun	7/jun	8/jun	9/jun	10/jun	11/jun	12/jun	13/jun	14/jun	15/jun	16/jun	17/jun	18/jun	19/jun	20/jun	21/jun	22/jun	23/jun	24/jun	25/jun	26/jun	27/jun	28/jun	29/jun	30/jun	1/jul	2/jul
1. Maarten Debackere	B3	×	L	L	-	-	E	-	-	E	E	E	E	E	E	E	-	N	N	N	-	-	-	L	L	L	L	-	E	E
2. Merel Debrabandere	B4	-	E	E	E	E	E	E	E	-	N	N	N	-	-	-	L	L	L	L	-	E	E	-	-	L	L	L	-	-
3. Pieter De Brandt	B5	-	-	N	N	N	-	-	-	L	L	L	L	-	E	E	-	-	L	L	L	-	-	E	E	E	E	E	-	-
4. Noor Decaluwé	B6	-	L	L	L	L	-	E	E	-	-	L	L	L	-	-	E	E	E	E	E	-	-	E	E	E	-	N	N	N
5. Marie Dedecker	B7	-	-	-	L	L	L	-	-	E	E	E	E	E	-	-	E	E	E	-	N	N	N	N	-	-	-	L	L	L
6. Peter De Jaegher	B1	-	E	E	E	-	N	N	N	N	-	-	-	L	L	L	L	L	-	E	E	-	-	E	E	E	E	E	E	E
7. Kenneth Denys	B'6	×	N	-	-	-	-	-	-	-	-	L	L	N	N	N	N	-	-	-	-	-	-	L	N	N	N	-	-	-
8. Annelies Descamps	S4	-	-	L	L	L	-	E	E	E	E	E	E	E	-	-	L	L	-	-	E	E	E	E	-	L	L	L	-	-
9. Ruben De Schrijver	S8	-	-	E	E	E	-	L	L	L	L	L	L	L	-	-	E	E	E	-	L	L	L	L	-	E	E	E	-	-
10. Marieke De Smet	S2	-	E	E	E	-	L	L	L	L	-	E	E	E	-	-	-	L	L	L	-	E	E	E	E	E	E	E	-	-
11. Nele Devleesschauwer	S3	-	L	-	E	E	E	-	-	-	L	L	L	-	E	E	E	E	E	E	E	-	-	L	L	-	-	E	E	E
12. Tine Dhondt	S4	×	-	L	L	L	L	-	-	-	-	-	-	-	-	-	L	L	-	E	E	E	E	-	-	-	-	-	-	-
13. Severien Dumoulin	S5	-	E	E	E	E	E	-	-	L	L	-	-	E	E	E	E	-	L	L	L	-	-	-	E	E	E	-	L	L
14. Kelly D'haese	S7	-	E	-	L	L	L	-	-	-	E	E	E	-	L	L	L	L	L	L	L	-	-	E	E	E	-	L	L	L
15. Mathias D'hoore	S8	×	-	-	E	E	-	L	L	L	-	L	L	L	-	-	-	E	E	-	L	L	L	-	-	E	E	E	-	-
16. Joke Naudts	S2	-	E	E	E	-	L	L	L	L	-	E	E	E	-	-	-	L	L	L	-	E	E	E	E	E	E	E	-	-
17. Katrien Rummes	S2	×	E	E	E	-	L	L	L	L	-	E	E	E	-	-	-	-	L	L	-	E	E	E	-	-	E	E	-	-
18. Louis Ryckaert	S3	-	L	-	E	E	E	-	-	-	L	L	L	-	E	E	E	E	E	E	E	-	-	L	L	-	-	E	E	E
19. Eveline Vandeweghe	S5	×	E	E	-	E	E	-	-	L	L	-	-	E	E	E	E	-	-	L	L	-	-	-	-	E	E	-	L	L
20. Griet Vanhollebeke	S6	-	L	L	-	-	E	E	E	E	-	L	L	L	-	-	-	E	E	E	-	L	L	L	L	L	L	L	-	-
21. Pauline Verhaeghe	S4	×	-	-	-	E	-	E	E	E	E	-	-	L	-	-	L	L	L	-	-	-	-	E	E	E	-	-	-	-
22. Melina Verstraete	S7	-	E	-	L	L	L	-	-	-	E	E	E	-	L	L	L	L	L	L	L	-	-	E	E	E	-	L	L	L
23. Stefanie Vlaeminck	S4	×	-	-	-	-	-	E	E	E	-	-	E	E	-	-	-	-	-	-	-	-	-	E	E	L	L	L	-	-
# Scheduled E			9	8	10	8	7	6	6	6	6	8	9	9	6	6	7	7	7	6	6	6	6	11	10	12	9	9	4	4
# Scheduled L			5	5	6	6	7	5	5	8	6	8	8	6	3	3	7	9	9	9	7	3	3	6	4	5	5	7	5	5
# Scheduled N			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
# Minimum Required E			5	5	5	5	5	4	4	5	5	5	5	5	4	4	5	5	5	5	5	4	4	5	5	5	5	5	4	4
# Minimum Required L			4	4	4	4	4	3	3	4	4	4	4	4	3	3	4	4	4	4	4	3	3	4	4	4	4	4	3	3
# Minimum Required N			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

(*) The column 'Type' indicates the specific cyclical schedule of each nurse using an XY code, i.e.,

X: specifies whether the nurse works the basic (B) or supplementary (S) cyclical schedule displayed in figure 1. Note that nurse 7 works a special cyclical schedule (B') containing more night shifts than the basic cyclical roster.

Y: specifies the week number of figure 1 scheduled in week 23 (and, hence, is sequenced by Y+1 in week 24, etc).

(**) The column 'Adjusted' indicates whether the cyclical schedule of the nurse deviates from the postulated cyclical schedules of figure 1.

Figure 2. The current cyclical roster for four weeks for all nurses

Figure 2 reveals that the number of scheduled nurses for each shift type is not levelled over the days of the scheduling horizon. The number of scheduled nurses for each shift is above, on, or below the cyclical coverage requirements. Hence, in constructing a monthly roster the degree of freedom of scheduling the nursing personnel is higher for some shifts than for other shifts. Moreover, for some shifts we observe that the number of scheduled nurses is even equal to the minimum coverage requirements, which implies that each time a scheduled nurse is absent or asks a day off a solution must be found for staffing the involved shifts correctly. These irregularities in the cyclical nurse roster are due to the history of the ward's nursing staff, e.g., changes in the employment rate of nurses, modifications of nurse cyclical schedules, personnel retention.

3.4 Monthly roster generation

In constructing a roster for a specific month the head nurse considers multiple objectives. More precisely, six objectives are taken into account, which are displayed in table 5 with a connotation of their importance to the nurse scheduler.

Table 5. Nurse rostering objectives

Objectives	Importance
Satisfy minimum coverage requirements	××××××××
Satisfy nurses' incidental wishes and requests	××××
Fairness among the nurses	×××
Satisfy time-related constraints	××
Strive for efficient staffing	××××
Comply with the cyclical roster(*)	×

(*) In the experimental analysis (section 4) the relative importance of this objective function component is varied (cf table 8).

Table 5 indicates that the nurse scheduler primarily wants to guarantee the continuity of care by satisfying the minimum coverage requirements. Besides this primary objective, the nurse scheduler aims to fulfill the nurses' incidental wishes and requests with a relative high priority. This implies that working shifts or free days scheduled in the cyclical roster can change according to the nurses' preferences. Furthermore, the shifts need to be staffed efficiently, which imply that no extra nurses above the minimum coverage requirements are likely to be scheduled. When constructing the monthly roster the nurse scheduler is only slightly interested in complying with the cyclical roster. Despite the fact that a lot of case-specific time-related constraints are taken into account when generating the cyclical roster, only little constraints are taken into account when constructing the monthly nurse roster as the fairness among nurses, the healthiness of work patterns, etc are estimated by the head nurse to be controlled by complying with the composed cyclical schedule. Table 6 gives an overview

of these monthly time-related constraints. In the table the normal and extreme values are displayed for the maximum work stretches. The nurse scheduler tries to comply with the normal values for these constraints. However, extreme circumstances can lead to the violation of these normal constraints. In that case the nurse scheduler considers the extreme values as maximum values which cannot be violated.

Table 6. Monthly nurse rostering time-related constraints

Time-related constraints	Normal	Extreme
Minimum number of working days	12	10
Maximum number of working days	20	20
Maximum work stretch of working days	7	9
Maximum work stretch of early shifts	7	9
Maximum work stretch of late shifts	7	9
Minimum work stretch of night shifts	3	3
Maximum work stretch of night shifts	5	7
Conceding extra free days due to seniority	NA	NA
Forward rotation	NA	NA
Maximum one assignment per day	NA	NA

Other time-related constraints (e.g., the minimum / maximum number of weekends, the minimum / maximum number of working days / early shifts / late shifts / night shifts), which need to be complied with in the cyclical roster, are only taken into account to guarantee fairness between the nurses. No minimum or maximum values are imposed on the monthly rosters. Instead, deviations from average values, corrected for holiday periods or periods of long-term illness absences, are likely to be avoided. Hence, the real-world situation addressed in this research incorporates a high number of soft constraints on the personal schedules in order to provide fairness between the employees. The soft constraints will be preferably satisfied, but violations can be accepted to a certain extent.

4 Experimental Analysis

Experience learns that the postulated cyclical rosters provide a good footing but that the current practices lead to the fact that they are totally not a good projection of the eventual constructed month rosters. This has several causes. On the one hand, the current cyclical roster does not correspond well to the cyclical and minimum coverage requirements as indicated above (cf table 2). On the other hand, the head nurse mainly takes the general and incidental requests into account when constructing monthly rosters while the cyclical roster is often overlooked. In this section, we compare various cyclical rosters on a continuum having a varying degree in which nurse-specific characteristics are taken into account. On the one side, we encounter nurse-specific cyclical rosters that incorporate the general nurse preferences, nurse work regulations, etc. Acyclic personnel rostering is the extreme case

where also the incidental nurse preferences and requests are taken into account. On the other side, we have very general cyclical rosters in which all nurses are assigned to one of the two cyclical rosters of figure 1. In extreme circumstances all nurses are assigned to one and the same cyclical roster and, hence, no distinction is made between nurses. These rosters are conceived as very fair and no problems are encountered in case of personnel retention. In the following we examine to which degree nurse-specific characteristics are best taken into account for the specific case study. In section 4.1, we elaborate on the test design used to uncover the best cyclical roster for the department under study. We suggest different cyclical rostering approaches and propose different scenarios exploring different circumstances in order to verify the roster robustness. In section 4.2, we compare the robustness of the cyclical rosters for the nursing staff of the department under study and suggest the most appropriate approach based on the obtained solution quality and the degree to which these cyclical rosters are an adequate representation of a monthly nurse roster of a specific month.

4.1 Test design

4.1.1 Different scheduling methods

In this section we develop several cyclical rosters for the nursing staff of the department under study. Based on these cyclical rosters we construct a (acyclical) monthly nurse roster for a specific month. We also suggest the pure acyclical rostering to the problem case producing a monthly roster starting from an empty schedule as an alternative to organize the ward's scheduling process. All the proposed approaches are devised in collaboration with the head nurse of the involved ward. An overview of the diverse features of the different approaches according to which a cyclical roster is constructed is provided in table 7. In the table there is information provided concerning the type of the individual cyclical nurse schedules as point of departure, the construction of the cyclical roster, and the construction of a monthly roster.

The suggested approaches can depart from different types of individual cyclical nurse schedules, i.e.,

- All nurses are assigned to the basic or to the supplementary cyclical schedule displayed in figure 1.
- All nurses are assigned to their individual cyclical nurse schedule as displayed in figure 2 (i.e., the cyclical schedule as employed in the involved ward).
- New individual cyclical nurse schedules are built for all nurses during the cyclical roster construction starting from scratch based on the scheduling policies displayed in table 4.

During the construction of the cyclical roster different items can be considered, i.e.,

- Contract Stipulations (CS): The individual cyclical nurse schedules can be adjusted/generated according to the stipulated work contract regulations (e.g., part-time employment, no night shifts).

- General Preferences (GP): The individual cyclical nurse schedules can be generated/adjusted/shifted taking the nurses' general preferences into account.
- Shifting: The individual cyclical nurse schedules can be shifted in time with periods of one week in order to meet the cyclical coverage requirements and/or the nurses' general preferences as best as possible.

In order to construct a monthly roster, changes are made to the cyclical roster in order to meet the postulated minimum coverage requirements and the nurses' incidental preferences as best as possible. In some scenarios the nurses' stipulated contract regulations have to be additionally taken into account (e.g., part-time employment, no early shifts).

Table 7. Features of the different scheduling methods

Approach	Individual nurse cyclical schedule	Cyclical roster construction			Monthly roster construction
		CS	GP	Shifting	
1	cf figure 1.	N	N	Y	Incorporate incidental preferences and work contract stipulations
2	cf figure 1.	Y	2a: N 2b: Y	Y	Incorporate incidental preferences
3	cf figure 2.	NA	NA	Y	Incorporate incidental preferences
4	cf figure 2.	NA	NA	N	Incorporate incidental preferences
5	New based on table 4.	Y	5a: N 5b: Y	Y	Incorporate incidental preferences
6	NA	NA	NA	NA	Incorporate incidental preferences and work contract stipulations

In the following the different approaches are described in detail, i.e.,

Approach 1: In this approach, we construct a cyclical roster based on cyclical schedules incorporating the least as possible nurse-specific characteristics. All nurses are assigned to working the basic or the supplementary cyclical roster (cf figure 1). These schedules are re-positioned in time according to the postulated objectives. Hence, for each nurse we determine in which week his/her cyclical schedule begins, i.e., the nurse's cyclical schedule can begin in week 1, week 2, ..., week 8 of the cyclical schedule displayed in figure 1. Nurse-specific elements (e.g., free days due to seniority leave, free days due to part-time employment) are only taking into account in the construction of the monthly rosters.

Approach 2: In this approach, all nurses are assigned to the basic or the supplementary cyclical roster according to their degree of employment. We re-positioned these schedules in time by determining

their begin week in such a way the cyclical coverage requirements are adequately met. Moreover, we re-construct the nurses' cyclical schedules by introducing nurse-specific work contract stipulations. For part-time employed nurses, e.g., we add extra free days due to their part-time employment and, hence, delete some working shifts in their cyclical nurse schedule. When nurses are not allowed to work a certain shift type (e.g., early shifts), these shifts are replaced by other assignments. Moreover, a distinction is made between approach 2a and approach 2b. In approach 2b the nurses' general scheduling preferences are also considered during the construction of the cyclical roster, in contrast to approach 2b.

Approach 3: We generate a monthly roster based on the current cyclical schedules of the nurses for the department under study (cf figure 2), which are re-scheduled over time such that the cyclical coverage requirements are adequately met. Hence, this approach retains each nurse's current cyclical schedule entirely and determines the week the cyclical schedule begins with. In approach 3 and 4, the individual cyclical nurse schedules are directly copied from the involved ward. These schedules are designed according to the discretion of the nurse scheduler whether or not taking the nurses' general preferences into account. Basically, the nurses' contract stipulations are taken into account as the general cyclical schedules are adapted to each nurse's degree of employment (cf figure 2). However, as we consider these individual schedules as input (and hence fixed), the nurses' preferences and other specific contract stipulations cannot be considered during the construction of the cyclical roster.

Approach 4: In this approach, we produce a monthly roster based on the current cyclical roster for the department under study (cf figure 2).

Approach 5: In this approach, new cyclical schedules are build for each nurse during the construction of the cyclical roster taking the case-specific time-related constraints displayed in table 4 and each nurse's contract stipulations into account. In approach 5a a cyclical roster is constructed in such a way the cyclical coverage requirements are adequately met. Approach 5b incorporates the nurses' general preferences on top.

Approach 6: In this approach we exercise the pure acyclical rostering to the problem case. Hence, we build a monthly roster starting from an empty schedule taking the nurses' contract stipulations and incidental preferences into account.

A close examination of the different approaches reveals that these approaches are ordered from a more general rostering organization (in which the same individual schedule is assigned to all nurses) (approach 1) to more nurse-specific methods of organizing the scheduling process (in which all nurses are assigned a singular nurse roster) (approach 5) or even to a nurse-specific and period-specific

scheduling method (approach 6). Based on these different methods we construct a nurse roster for a specific month based on the gathered data (cf section 3). Moreover, in approach 1 to 5 the nurse rosters for a specific month are constructed according to four different settings with corresponding penalty costs varying the relative importance of complying with the postulated cyclical roster in the objective function. These settings of relative importance in the objective function are displayed in table 8. Furthermore, we generate several additional problem instances supposing different circumstances presented in section 4.1.2 for which nurse rosters need to be generated in order to verify the robustness of the different scheduling methods.

Table 8. Different degrees of complying with the cyclical roster

Comply with the cyclical roster(*)	Importance
Setting 1: High importance	×××××××
Setting 2: Moderate importance	×××××
Setting 3: Low importance	×××
Setting 4: Very low importance	×

(*) Objective function component in constructing monthly rosters (see table 5).

The computational performance and evaluation of these different approaches is provided in section 4.2.1.

4.1.2 Robustness of the cyclical roster

In this section we propose different scenarios to check the robustness of the constructed cyclical rosters. To that purpose we construct a nurse roster for another month when the nurse scheduler has typically to deal with different circumstances, e.g., different sets of incidental nurse preferences, altered general nurse preferences, changed nurse work regulations and nurse retention, and adapted coverage requirements. The cyclical and monthly shift scheduling policies are not varied and are implemented as at the time of the case study. Changing the cyclical shift scheduling policies would require new cyclical schedules for all nurses. In the following we describe the different circumstances under which a roster needs to be constructed.

Scenario 1: A nurse roster needs to be constructed for 3 other periods (i.e., situation 1.1, situation 1.2, and situation 1.3). We assume that the main nursing staff characteristics are the same. Only the incidental nurse preferences are modified.

Scenario 2: A nurse roster needs to be constructed for the period under study. We assume that the general scheduling preferences of a few nurses have changed. The changes are displayed in table 9. The other nurse characteristics remain the same.

Table 9. Situations with altered general nurses' preferences

	Nurse characteristics	General preferences/ Contract stipulations
Situation 2.1	**2. Merel Debrabandere**	Preference for late shifts
	6. Peter De Jaegher	Preference for night shifts
	13. Severien Dumoulin	Preference for early shifts
	18. Louis Ryckaert	Preference for early shifts
Situation 2.2	**6. Peter De Jaegher**	Preference for weekend day off
	13. Severien Dumoulin	Preference for late shifts
	17. Katrien Rummes	Preference for weekend shifts
	19. Eveline Vandeweghe	Preference for Friday day off
Situation 2.3	**6. Peter De Jaegher**	No weekend shifts
	13. Severien Dumoulin	Preference for late shifts
	15. Mathias D'hoore	Only early shifts
	22. Melina Verstraete	Preference for early shifts

Scenario 3: The work regulations of a few nurses have changed. In a first step we construct the cyclical schedules of those nurses with nursing contract regulations by adding or removing working shifts. In a second step, the monthly roster construction is performed. The particularities of the generated problem instances are displayed in table 10.

Table 10. Situations with altered nurse work regulations

	Nurse characteristics	Cyclical roster type	Degree of employment
Situation 3.1	**9. Ruben De Schrijver**	Supplementary	75%
	16. Joke Naudts	Supplementary	75%
	23. Stefanie Vlaeminck	Supplementary	100%
Situation 3.2	**6. Peter De Jaegher**	Supplementary	100%
	10. Marieke De Smet	Basic	100%
	19. Eveline Vandeweghe	Supplementary	50%
Situation 3.3	**10. Marieke De Smet**	Supplementary	75%
	11. Nele Devleesschauwer	Supplementary	75%
	12. Tine Dhondt	Supplementary	100%
	17. Katrien Rummes	Supplementary	50%
	21. Pauline Verhaeghe	Supplementary	100%

Scenario 4: A nurse roster needs to be constructed for the period under study. We assume that the coverage requirements have changed. In table 11 we display the altered minimum coverage requirements of three different situations. The characteristics of the nursing staff remain the same.

Table 11. Situations with altered coverage requirements

Minimum coverage requirements	Monday			Tuesday			Wednesday			Thursday			Friday			Saturday			Sunday		
Shift type	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N	E	L	N
Situation 4.1	5	4	1	5	4	1	5	4	1	5	4	1	5	4	1	5	4	1	5	4	1
Situation 4.2	6	5	1	6	5	1	6	5	1	6	5	1	6	5	1	4	3	1	4	3	1
Situation 4.3	4	4	1	4	4	1	4	4	1	4	4	1	4	4	1	4	3	1	4	3	1

Hence, in total we have 52 observations, i.e., 4 settings x (4 scenarios x 3 situations + 1 original problem instance), per rostering approach in order to determine the best cyclical roster for the department under study. The computational results and the evaluation of the robustness of the different approaches towards these different circumstances are provided in section 4.2.2.

4.2 Computational results

In this section we discuss the results of incorporating nurse-specific characteristics in a cyclical roster. We rely on the (adapted) exact procedure of Maenhout and Vanhoucke (2007) to compose the cyclical and acyclical rosters. Figure 3 represents a schematic overview of the scheduling process.

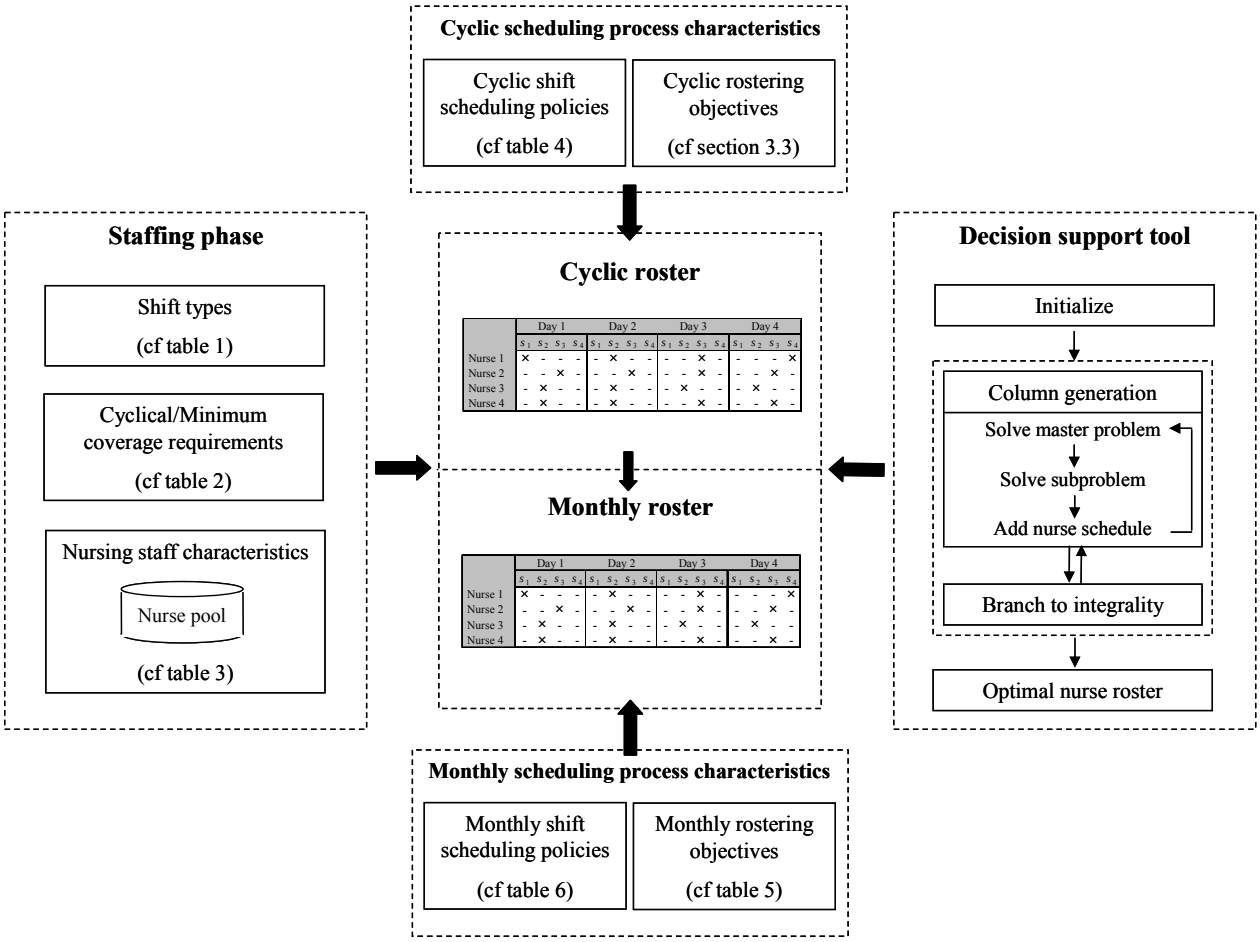

Figure 3. Schematic overview of the scheduling process

Several rostering and ward characteristics are already determined in the strategic staffing phase, i.e., the shift types, the required number of staff, and the nursing staff characteristics. These serve typically as input for the scheduling phase. The cyclic and monthly rosters are composed using an exact branch-and-price procedure, which basically relies on column generation to solve the LP relaxation of the problem and a branching process to thrive the LP optimal solution to integrality if necessary. Moreover, the cyclic and monthly roster construction is guided by the respective shift scheduling policies and roster objectives. The monthly roster is also determined by the postulated cyclic roster.

All tests were carried out on a Dell computer with a Dual Core processor 2.8 Ghz and 2 Gb RAM. The procedure has been linked with the industrial LINDO optimization library version 5.3 (Schrage, 1995). The cyclical rosters are generated using a stop criterion of 3 hours. Table 12 presents the computational results for generating monthly rosters based on the cyclical rosters or starting from an empty schedule. Table 12 describes the performance of the procedure of Maenhout and Vanhoucke (2007) in a real-life problem environment using the following parameters, i.e., the number of problem instances (# instances), the number of column generation iterations (# iter), the number of columns generated (# columns), the required CPU time (s) to solve the master problem (CPU_{MP}), the required CPU time (s) to solve the subproblem (CPU_{SP}), the total required time (s) to solve the problem instance (CPU), the total number of nodes (# nodes), and the percentage of solutions whose optimal solution is obtained within a time limit of 1800s (% optimal). Table 12 reveals that 75% of the problem instances are solved to optimality. The table provides information involving all instances, also those files whose search is interrupted at 1800s.

Table 12. Computational results for the monthly roster construction

Solution parameters	
# instances	377
# $columns_{IP}$	3919.78
# $iterations_{IP}$	209.32
# nodes	15.79
% $optimal_{IP}$	75.07%
CPU_{MP}	234.69
CPU_{SP}	1122.31
CPU	1356.99

4.2.1 Comparison of the solution quality of the different scheduling approaches

In order to determine the best approach we compare the solution quality of all these approaches and settings with the effort of the scheduler which is reflected in the number of schedule changes

necessary to construct the monthly nurse roster departing from a cyclical roster or from the empty roster. The experimental results of this roster construction averaged per setting (cf table 8) per rostering approach are presented in figure 4. The different approaches are represented the following symbols, i.e., (Δ) approach 1, (♦) approach 2a, (◊) approach 2b, (×) approach 3, (+) approach 4 , (●) approach 5a, (○) approach 5b, and (□) approach 6. On the X-axis the number of schedule changes are displayed, which is a measure how good the cyclical roster is a projection of monthly nurse rosters and the required effort of the nurse scheduler. On the Y-axis the roster quality is displayed (we consider a minimization problem, i.e., the lower, the better), which is a weighted average of the aforementioned objective function components.

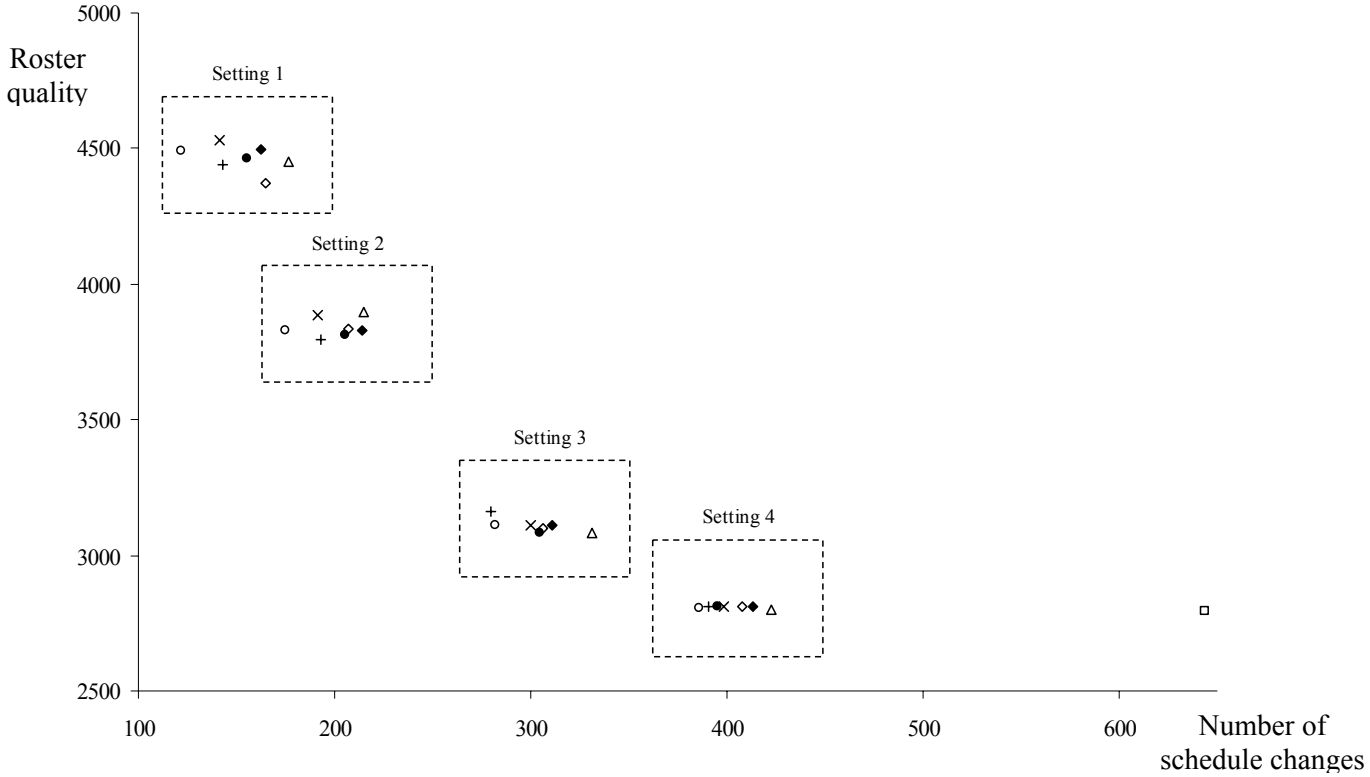

Figure 4. Average roster solution quality versus cyclical roster compliance

Figure 4 displays the trade-off between the compliance with the cyclical roster and the obtained roster quality. Since for all problem instances all shifts are efficiently staffed, no violations of the coverage requirements are encountered, the accounted fairness penalty costs are negligible, and all time-related constraints are properly satisfied, the obtained roster quality can be reduced in general to the compliance with the cyclical roster and the personnel job satisfaction. The higher the relative importance given to the objective of complying with the cyclical roster the more we pinpoint to the scheduled assignments of the cyclical roster. When the only objective is this compliance, the rostering task consists of cancelling some working shifts in such a way the minimum coverage requirements are met. Hence, in this case we preserve only the best roster assignments for each shift on each day. This rather rigid roster construction leads typically to a relative low score on the roster quality (particularly

the personnel job satisfaction) obtained with a minimum of effort of the nurse scheduler (see setting 1). When the penalty of non-compliance with the cyclical roster is set low, the personnel job satisfaction mainly determines the monthly nurse roster. This leads typically to a monthly nurse roster that strongly differs from the postulated cyclical roster which provides little or no footage (see setting 4). This very flexible roster construction will typically lead to a relative high score on the personnel job satisfaction but is confronted with inconsistency in assigning nurses to shifts. The decision to which degree monthly rosters comply with the cyclical roster is dependent of the hospital's policy. The same holds for the decision to organize the scheduling process cyclical or acyclical. The acyclical rostering approach (□) typically leads to the best results in terms of personnel job satisfaction but requires the highest scheduling effort starting from an empty schedule. However, when the postulated cyclical roster is moderately complied with (e.g., setting 3), we observe that still good quality rosters can be obtained having an important quality notion of consistency for the nurses and the nurse scheduler (which is not explicitly taken into account in the objective function). When comparing the different cyclical schedules for each setting of roster compliance we observe that scenario 5b (○), in which a new cyclical roster is constructed taking the shift scheduling policies and nurses' general preferences into account, leads to a comparable personnel job satisfaction with the other cyclical rosters but needs less changes on the average with respect to the involved cyclical roster. Moreover, we observe that both approaches copying the existing individual cyclical nurse schedules (i.e., approach 3 (×) and 4 (+)) perform on the average reasonably well. Approach 1 (Δ), incorporating no nurse-specific characteristics, performs on the average worst. Hence, in general, incorporating the nurse-specific characteristics to a higher extent leads to cyclical rosters that are a better representation of the monthly nurse rosters and reduces the (monthly) effort of the scheduler.

4.2.2 Comparison of the robustness of the different scheduling approaches

Apart from knowing the best approach it is also interesting to get notice of the robustness of the different scheduling approaches and to verify which approaches perform consistently well under different circumstances. In figure 5, the results are displayed for each approach separately described in section 4.1.1. For each approach and each setting, 13 different problem instances (i.e., the original problem instance and the different situations (3 x 4 problem instances) described in section 4.1.2) are solved resulting in 52 observations for scenario 1 to 5 and 13 observations for scenario 6 which employs only one setting. The exhibited charts have the same variables on the X-axis and Y-axis and are similarly scaled as figure 4. In order to examine the robustness of the proposed approaches we investigate to which degree the cyclical rosters are an adequate projection of the rosters constructed for a specific month. Hence, we consider the variability (i.e., expressed by the standard deviation $\sigma_{approach, setting}$) in the number of schedule changes of the monthly roster with respect to the cyclical roster encountered in different circumstances as a relevant measure. These standard deviations are averaged per approach and displayed in the upper right corner of each chart.

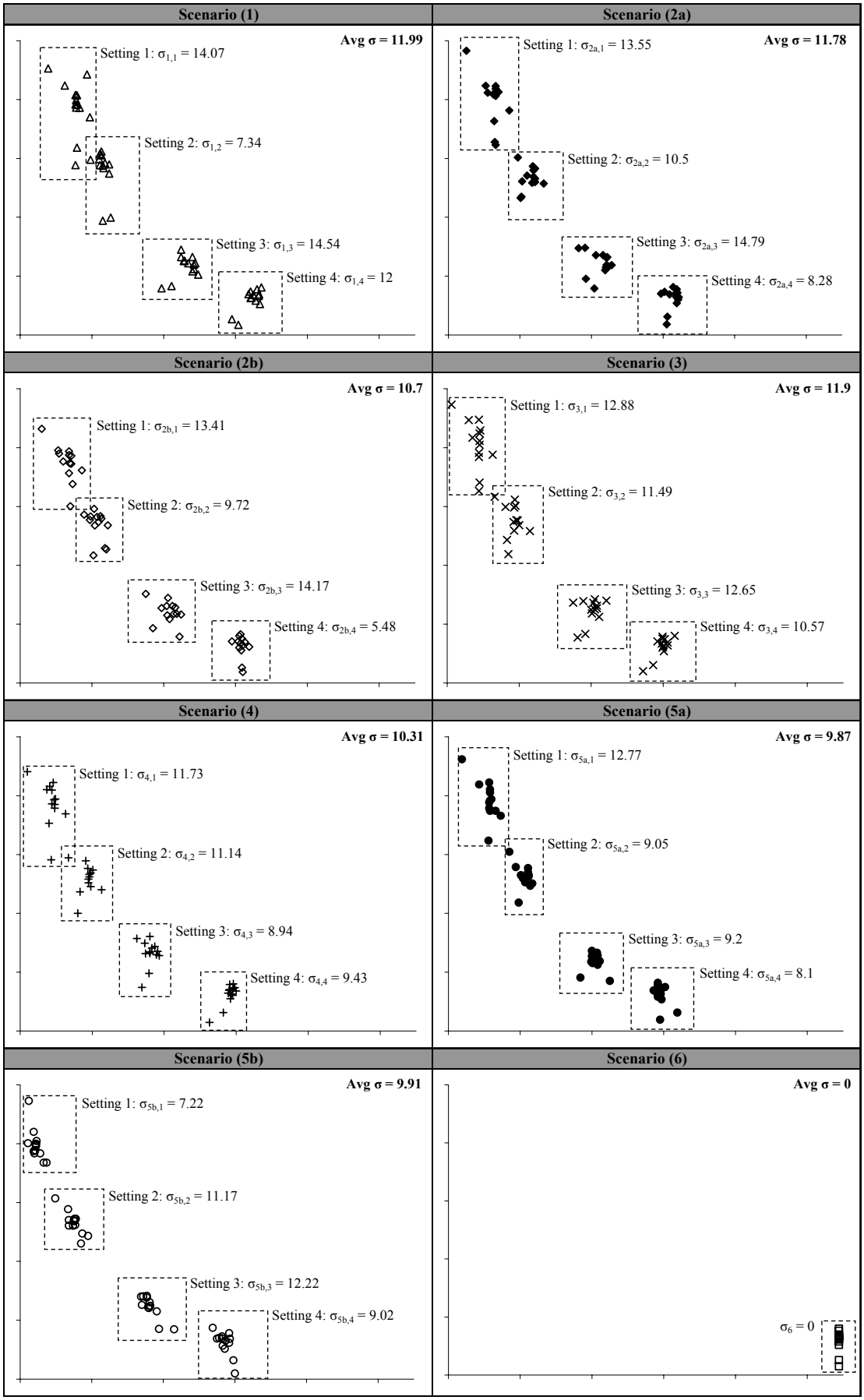
Scenario (1)
Avg σ = 11.99
Setting 1: σ1,1 = 14.07
Setting 2: σ1,2 = 7.34
Setting 3: σ1,3 = 14.54
Setting 4: σ1,4 = 12
Scenario (2a)
Avg σ = 11.78
Setting 1: σ2a,1 = 13.55
Setting 2: σ2a,2 = 10.5
Setting 3: σ2a,3 = 14.79
Setting 4: σ2a,4 = 8.28
Scenario (2b)
Avg σ = 10.7
Setting 1: σ2b,1 = 13.41
Setting 2: σ2b,2 = 9.72
Setting 3: σ2b,3 = 14.17
Setting 4: σ2b,4 = 5.48
Scenario (3)
Avg σ = 11.9
Setting 1: σ3,1 = 12.88
Setting 2: σ3,2 = 11.49
Setting 3: σ3,3 = 12.65
Setting 4: σ3,4 = 10.57
Scenario (4)
Avg σ = 10.31
Setting 1: σ4,1 = 11.73
Setting 2: σ4,2 = 11.14
Setting 3: σ4,3 = 8.94
Setting 4: σ4,4 = 9.43
Scenario (5a)
Avg σ = 9.87
Setting 1: σ5a,1 = 12.77
Setting 2: σ5a,2 = 9.05
Setting 3: σ5a,3 = 9.2
Setting 4: σ5a,4 = 8.1
Scenario (5b)
Avg σ = 9.91
Setting 1: σ5b,1 = 7.22
Setting 2: σ5b,2 = 11.17
Setting 3: σ5b,3 = 12.22
Setting 4: σ5b,4 = 9.02
Scenario (6)
Avg σ = 0
σ6 = 0

Figure 5. Robustness of the cyclical rosters

The results displayed in figure 5 indicate that no unambiguous conclusions can be drawn. In the following the different approaches are evaluated based on their average standard deviation. Figure 5 reveals that especially those cyclical approaches that construct new cyclical individual nurse schedules based on the shift scheduling policies displayed in table 4 (i.e., approach 5a and 5b) perform consistently well under different circumstances and, hence, are – on the average – more robust than others. These approaches account for a standard deviation in the number of schedule changes averaged over the different settings of respectively 9.78 and 9.91. Approach 1 leads to the highest variability with an average standard deviation of 11.99. Approach 4, which represents the current situation in the ward, is fairly robust against different circumstances with an average standard deviation of 10.31. The acyclical rostering organization (approach 6) starts from an empty schedule and, hence, leads to a fixed and known number of schedule changes. In this respect, acyclical rostering is most robust against different changed circumstances. However, combining the results described in sections 4.1.2 and 4.2.2, a monthly roster can be constructed with comparable solution quality and with (strongly) reduced scheduling effort when starting from a cyclical roster. Moreover, complying more with the cyclical roster still leads to a monthly roster with reasonable schedule quality. Additionally, a higher conformity results in a higher consistency in the nurses' individual schedules from month to month and better conveys the extra quality components incorporated in cyclical rosters. Approach 5b, which results in a single individual cyclical nurse schedule for each nurse taking different nurse-specific characteristics into account, embodies the best scheduling organization for the ward under study.

5 Conclusions

In this paper, we studied the nurse shift scheduling problem in a real-life environment. The scheduling process in the department under study is cyclically organized. The case implied the generation of the appropriate rostering approach and the exploration of the advantages and disadvantages of incorporating nurse-specific characteristics into a cyclical scheduling approach. We have shown that the current individual cyclical nurse schedules are outperformed in terms of robustness, scheduling effort, and solution quality by constructing new individual nurse schedules for each nurse separately incorporating nurse-specific characteristics (general preferences, work contract stipulations, etc.). This observation is independent of the choice of the nurse scheduler to comply with the cyclical nurse roster during the construction of monthly rosters.

As many hospitals in Belgium still exploit a cyclical scheduling approach, we aim to develop dedicated exact and/or heuristic algorithms to construct cyclical schedules while taking into account the quality of the nurse rosters. In this way, management can offer greater flexibility to its

nursing staff in constructing rosters by combining the principal components of cyclic rostering and acyclic rostering in a single model. Hence, as most hospitals refuse to switch over to acyclic scheduling because of its inconsistency over time, hospitals can benefit from the more flexible approach of acyclic rostering. Moreover, it would be a challenge for future research to encompass unexpected events (e.g., the demand for nursing services, absenteeism, days off) in the construction of monthly rosters. These unexpected changes render the initial schedule typically useless or raise the need to change the initial schedule dramatically. Further research is needed to develop methods that intelligently re-schedule the initial schedule in line with the constructed cyclical rosters with the least as possible number of schedule changes.

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