Using Integer Programming to Solve the Crew Scheduling Problem in the Taipei Rapid Transit Corporation

Chui-Yen, Chen [1,2]

[1]Department of Industrial Engineering and Management
University of Yuan-Ze, Ph.D. student
[2]Department of Tourism and Leisure Management
Chin-Min Institute of Technology, Instructor
110, Hsue-Fu Rd., Tou-Fen, Miao-Li 351, Taiwan, R.O.C.
Tel: 886-37-605670 Fax: 886-37-605674
s919507@mail.yzu.edu.tw

ABSTRACT: The transport operation volume has reached millions of people since the Taipei Rapid Transit Corporation (TRTC) started operating 28 March 1996. TRTC has become the key public transportation in Taipei city. Crew scheduling of station employees has become one of the basic costs of operating the Public Rapid Transit System. During the planning stage of the project, a mathematical model of planning phases was established and used to find answers to crew scheduling and reduce costs. In general, the crew scheduling problems relate to the "set covering" problem or "set partitioning" problem; therefore, it is often described by the methods of 0-1 Integer Programming. Hence, this study will adopt the methods of integer programming for mathematical programming to establish a crew scheduling program. The Target-based formula of using integer programming to solve the crew shift scheduling problem is meant to meet the interests of station employees. Furthermore, this study will use comparison analysis to research (1) common shift scheduling; (2) employee's preferred working hours; and (3) specified work day for employees to help solve day off or other problems. We hope to provide this method to the TRTC in a rapid and convenient timetable to improve the efficiency of operations and business competition.

Key-words: Crew scheduling problem (CSP), 0-1 Integer programming, Taipei Rapid Transit Corporation (TRTC)

1. Introduction

Human resource management is one of the major issues for services industries. Recently, awakening labor interests have included law enforcement of limitations on working hours and labor's efforts to establish a union to protect laborers. These and other limitations, therefore, push us to use the shortage of human resources to arrange an optimistic shifting schedule. This section will discuss the Taipei Rapid Transit Corporation (TRTC) station employee's crew scheduling problem.

Since the TRTC starting operating on 28 March 1996, the transport operation volume has reached millions of people. Therefore, the TRTC has become the key public transportation in Taipei, Taiwan. Because the TRTC is a year-round operation and it offers long service hours, staff working regulations differ from those of the common business employee. Currently, staff schedules for TRTC are divided into three shifts. In addition, the shifting schedules must comply with requirements set by the Labor Standards Law during each scheduled shift. Traditionally, shift scheduling is completed manually. This manual shift scheduling not only causes inefficiencies in employee operations, but also wastes time and costs. We expect that we can establish a convenient and rapid timetable via this research institute.

Because Integer Planning is categorized into NP-Completeness, the model variations may be excessive; however, it might address the issue of efficiency. Although it might be difficult to find an optimistic solution to crew scheduling, this study proposes that we can build a model to use as a trial. This model would test crew scheduling for the most employee stations in the TRTC of the Taipei main station (Ban-Nan line). For example, to search for the largest interest among station employees, this study might solve the model via LINGO.

2. Literature Review

The crew shift scheduling problem is the most common issue in mathematical science. Related studies are too numerous to enumerate, and they vary widely. For the crew shift scheduling problem, whether it be crew shift scheduling or crew allotment, both are related to multi-specifications and become an issue for 0-1 round number or complex Integer Planning. In addition, Bartholdi [12] suggested that the crew shift scheduling problem is related to NP-Complete's problem. Therefore, we are focused on large-scale problems and find it difficult to discover an optimum solution under reasonable algorithms. We always adopt a heuristic method solution to find the most efficiency and nearly optimum solution within a short time. Table 1 summarizes the major literature on this issue.

Table 1. Literature review of crew shift scheduling

Author	Subjects	Methods	Key issue
Browmell and Lowerre [2]	Cyclic scheduling	Method of mathematics	Uses the method of mathematics to perform the periodic shift scheduling operations. Used to probe into how the shift scheduling policy affects human resources requirements.
Chuang, Shuo ping [3]	Service employee	Fuzzy theory	Uses the concept of triangular fuzzy function to select the evaluation criterion, and also arrange existing evaluation methods to analyze the adoption and advantages or disadvantages. Uses the methods of AHP giving weight to build the evaluation construction of unity quantification, and induce the clustering analysis as the decision of group framework, under fuzzy number.
Su, Chao-Ming, Chang, Ching [10]	Taipei Rapid Transit System (TRTS)'s station employee	Mathematical programming	Establishes two stages of shift scheduling models: the first stage determines the day off and working day for each station employee; the second stage decides the working hours for the station employee. Through the two stages, the authors build a model and use LINDO software to solve the problem.
Kuo, Wei -Yin [8]	Registered nurse	Integer planning	Uses the methods of mathematical programming to perform the shift scheduling program for Registered Nurses and builds the shift scheduling model, as well as using the Linear Programming Software Package LINDO to find a solution.
Wang, Pao-Chih [11]	Tank truck driver	Mathematical programming decision support system(DSS)	This study suggests that the decision support system (DSS) is under the goal of outsourcing un-transportable mileage and driver's un-transportable mirage. By comparison with a Chinese petroleum company (CPC) in Taiwan, the original shift scheduling has improved from 66.2% to 77.3%; thus the effect is excellent.
Huang, Jung-Hua, Tsai, Chih- Hao [5]	Paramedic	Mathematical programming	This study first focuses on the employer's problem of paramedics in hospital and developing algorithms, then under the conditions of cost-saving and complementing human resources to search for an optimum employee hiring range. After that, the study focuses on the crew shift scheduling problem, establishing the model of mathematical programming. In order to improve the goal of work-satisfaction for the paramedic, and also under the condition of regulations, the operation's policies and a variety of environmental requirements are used to search for optimum off day and in-shift timetable. For the application of software solution, this study used the LINDO as the crucial part.
Liu, Shuang- Huo [9]	Passenger Transportation Service Staff for Taiwan railway	Combined Genetic Algorithm with An Ant Colony Optimization System	While you account for the condition for train schedule/manpower factors and limitations, you can adopt the genetic algorithms to solve between the human workload balance and minimum overall work hours problem for train transportation. In doing so, you build the Passenger Transportation allocation model, and then combine the shift scheduling within each shift's problem. Finally, you use the Ant Colony Algorithms to search for the optimum solution in the shift's model of total shift periods.
Huang, Jen- Yu [4]	Timetable for MRT	Ant Colony Optimization Algorithms	Uses the methods of Ant Colony Optimization as its basis, and uses the characteristic of Ant Colony Optimization Algorithms easily running the parallel-process. After combined with the parallel-process technology, you can use the Taipei MRT Route Map and related stations, combining this information with time and convert it into the internet pattern. At the same time, you take the characteristics of off-peak/rush hours for train scheduling, conflict time adjustment as well as the variety of depot's drive in-out hour into account, in order to build a combined basic shift scheduling with conflict adjustment over two stage's shift produce algorithms.

This study is based on the industry's crew shift scheduling differences, thus producing different solutions. Beasely and Cao [1] suggested that the problem of crew shift scheduling lies within three categories by industry: 1) airliner's crew shift scheduling; 2) public transportation service employee's shift scheduling; and 3) official employee's shift scheduling. Because the public transportation service employee's crew shift scheduling is similar to airliner's crew shift scheduling, portions of this study used the steps to solving airliner crew shift scheduling as the solving process. The TRTC's shift scheduling is a smaller-scale problem than airliners, due to official employee's shift scheduling problem and the in-shift hours or rest regulations, which are mostly known or fixed. When compared with the massive level of airliner crew shift scheduling problems, the time to find the question's solution is smaller and more unified. The complexity of the problem is also lower than that for the airline industry. Therefore, some studies adopted LINDO or LINGO directly to solve the problem.

Because the crew scheduling literature review is arranged by years, we can identify trends for crew shift scheduling and also understand some of the previous/current methods of crew scheduling. In early studies, crew scheduling almost always uses the fixed pattern, such as periodic. With variations, solutions gradually become multi-property, primarily for the purpose of enhancing the employee's affect factor (such as fairness, reasonability, employee's anticipation). For the shift scheduling pattern, we take the in-shifts and days-off problem into account. Furthermore, the computer has innovated rapidly and has become universal for arranging shift scheduling or auxiliary shift scheduling. Thus, the computer has increased the convenience and the efficiency of scheduling and has become one of the important tools for the universe of business.

Through the scholars' suggested methods of shift scheduling procedures, we can understand the implementation of the shift scheduling procedures under various situations. In early studies, the scholar always uses mathematical methods to perform periodic shift scheduling procedures; thus the consideration factors and the methods are easier. With increasing tools and methods, later scholars have coordinated mathematical programming methods with applying Computer Programming Languages or heuristic algorithms, for example. The consideration factors are embedded not only in the consideration of periodic shift scheduling, but also in the increased number of shift systems for shift scheduling performance for specific occupations or contractors (such as the nurse, full-time teacher school scheduling, 104 operator's shift scheduling in Taiwan, and stewardess, etc). For each different career's requirements, we take special situations into account in order to obtain more accurate and efficient shift scheduling.

3. Model Construction and Evaluation

We first follow the limitation condition, subject and hypothesis, to build the station employee's shift scheduling model. We then convert the collected data into the analysis practice, and investigate the applications of this model. We hereby use the following symbols and follow the alphabetical order to define the meaning, as below:

i : Station employee number, $i = 1...m...n$, Deputy Station Master: m ,station employee: n .

j : In shifts, $j = 1...p$

k : Work days

d_j : In shift's employee requirement

t_i^{UB} : The maxima limitation working days of ***i***th station employee

t_i^{LB} : The minimum limitation working days of ***i***th station employee

w_{ij} : The station employee's preference for in shift hour or day

x_{ij} : {0, 1} Decision variables

y_{ik} : The working shift is 0 or 1 of ***i***th station employee on day ***k***

This study is completed knowing daily shifting conditions to create the shift scheduling for TRTC's station employees. The Target-based formula is to meet the largest interest of station employees, as follows:

$$Max \quad \sum_{i=1}^{m}\sum_{j=1}^{p} w_{ij}x_{ij} \tag{1}$$

subject to

$$\sum_{i=1}^{n} x_{ij} = d_j \qquad \forall j \tag{2}$$

$$t_i^{LB} \le \sum_{j=1}^{p} x_{ij} \le t_i^{UB} \qquad \forall i \tag{3}$$

$$\sum_{j=q}^{q+20} x_{ij} \le 6 \qquad \forall i \quad q = 1...p-6 \tag{4}$$

$$\sum_{j=q}^{q+2} x_{ij} \le 1 \qquad \forall i \quad q = 1...p-2 \tag{5}$$

$$\sum_{i=1}^{m} x_{ij} \ge 1 \qquad \forall j \quad i = 1...m \tag{6}$$

$$x_{ij} = 0 \qquad i \in female \quad j = 3,6,9,... \tag{7}$$

$$x_{ij} = \begin{cases} 0 \\ 1 \end{cases} \quad \forall i, j \tag{8}$$

The target formula (1) is focused on the preference weight of station employee's in shifts. In summary, the goal of this section is to figure out the maximum value.

The limit formula above (2), is the on-duty employee number=the requirement value of on-duty's station employee. Formula (3) is the maximum/minimum limitations of a station employee's working hour, and also the condition for any station employee's special working conditions. Formula (4) is the continuous working days (no more than six days). After the employee has worked continuously for six days they should have one day off. Formula (5) is when the station employee performs the shift; in the case of continuous working for two-three days, they must take two shifts off. For example, when the employee works on a day shift, he can work on any shift the next day. If he works on the Swing shift, he can only work on the Swing shift the next day. Formula (6) is for complying with the regulation that each employee in shift must have a supervisor or deputy station master. Formula (7) is for the female employee's shift scheduling regulations. Formula (8) is the 0-1 limitation of decision variables x_{ij} .

$$\sum_{i=1}^{m}\sum_{k=1}^{n}\left|y_{ik+1}-y_{ik}\right| \tag{9}$$

For the evaluation model, this study focuses on evaluating the differences among station employees' continuous work situations, such as formula (9). If the station employee works continuously for two days ($y_{ik+1}=1$ and $y_{ik}=1$) or took two days off ($y_{ik+1}=0$ and $y_{ik}=0$), then formula (9) is zero (0). If the station employee works continuously for one day and took one day off (the y_{ik+1} and y_{ik} value, one is zero (0), the other value is one (1)), the $\left|y_{ik+1}-y_{ik}\right|$ value is one (1), as is shown in Table 2, Example 1, the value is three (3) (=|1-1|+|0-1|+|1-0|+|1-1|+|0-1|). In Table 1, Example 2, the value is one (1) 1(=|1-1|+|1-1|+|1-1|+|0-1|+|0-0|). The lower the value, the difference for continuous working shift is lower, therefore, it implies that each work shift is closer.

Table 2. the description of shift scheduling model's evaluation

Example	In shifts scheduling	$\left\|y_{ik+1}-y_{ik}\right\|$
I	DDRDDR	3
II	EEEERR	1

Note: We used four of six working days for this example, with D being the day shift, E the Swing shift, and R is a day off.

The Intel Pentium D 3.4GHz CPU, the memory is DDR-II 800 2,048MB, hard disk is 250GB, 7200rpm, and the processing software is mathematical programming software: LINGO 8.0 was used to perform the testing of this study models.

4. Scenario Analysis and Testing Results

The example of this study is TRTC's station employee. It uses the requirement of a daily in-shift employee, under known conditions. It focuses on the shift scheduling planning of the station employee, and investigates whether the station employee's assignment is a problem. For theoretical analysis, we used the most crowded operating station of the TRTC, the Taipei main station (Ban-Nan line) as an example and to perform the testing (see Figure 1).

For the employee requirements of the TRTC-Taipei main station (Ban-Nan line), the station's employee requirement is current the largest. The station's in-shift employee requirement is now 17 shift, the female employee is 8 shifts, and deputy station master is 5s. In every station, however, we only deploy a Station Master, whose on-duty hour is fixed. The in-shift time is 08:30-17:30; he doesn't in-shift with other station employees. Hence, this study does not include this factor. In addition, the in-shift scheduling is three shifts: the day shift time is 06:30~14:30 (D); swing shift time is: 14:15~22:15 (E) and night shift time is: 22:00~06:45(N). The on-duty employees required for the day shift and swing shift is 5s daily, and we also deploy a deputy station master on every on-duty shift. The night shift requires two employees, one is the deputy station master, and the other is a station service employee. To estimate manpower, TRTC focuses on the hardware facility, and does not concern itself with the number of passengers; therefore, there is no issue with rush/off peak commuting hours. After the employee finishes an on-duty shift, he must take a break of two shifts. The employee's continuous working days cannot exceed more than six days; therefore, they must take one day off after working continuously for six days. In addition, by regulation of Labor Standards Law in Taiwan, the employee must take eight days off in one month. If they have an extra day off, their off days will exceed eight days. We also respect female employees' rights, so the female employee of the TRTC is only on duty during the day shift and swing shift. This study used the example of the monthly shift hours; the shift scheduling monthly is 90 shifts.

Fig.1 Taipei MRT Route Map

To account for the interests of the station employee, this study asked the station employees and deputy station masters to fill out a questionnaire, weighing their interests monthly. The maximum weight of an interest in a working day is (50), with the minimum weight of a less interesting working day is (10). To avoid the station employee or deputy station master filling out the same shift of the interest working day, and also result in some shift where no one is on duty, this study has setup the maxima weight into 10, but 0, meaning that the station employee still has chance to work on a special shift, and therefore, it would lower the requirements of employee. In addition, the night shift of female station employee's weight is zero(0), $x_{ij} = 0$,the reason for doing this is due to we must meet the limitation formula (7), which regulates that female employee do not work the night shift.

Therefore, under normal model operations of shift scheduling, we can distinguish if it with the interest of station employee's testing or not. Model A shows the station employee's interest as "common;" meaning that the station employee doesn't have the right to choose working days and in-shift schedules. Model B is based on the interest of station employee by adding up the weight factors, where the station employee can choose his/her interest in shift scheduling. Because one of the goals is to satisfy of the preferences of station employee, model B allows them to search for the best interest to work with the shift scheduling. Model C is to test for the employee's most interest in a working day. The three kinds of shift scheduling models, A, B and C, are shown in Table 3.

Table 3. The shift scheduling arrangement of model A

Employee number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Day off(days)	8	9	9	8	9	8	9	8	9	8	9	9	9	10	9	11	8
Day shift	8	8	6	9	6	8	12	10	15	13	12	8	2	8	8	11	6
Swing shift	5	6	7	6	15	14	9	12	6	9	9	13	9	4	9	5	12
Night shift	9	7	8	7	0	0	0	0	0	0	0	0	10	8	4	3	4

Table 4. The shift scheduling arrangement of model B

Employee number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Day off(days)	8	9	8	8	8	9	9	8	10	8	10	9	9	8	10	9	10
Day shift	6	8	5	7	13	11	6	14	7	13	10	13	8	8	9	9	3
Swing shift	3	6	8	9	9	10	15	8	13	9	10	8	9	7	7	7	12
Night shift	13	7	9	6	0	0	0	0	0	0	0	0	4	7	4	5	5

Table 5. The shift scheduling arrangement of model C

Employee number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Day off(days)	8	9	8	8	8	9	8	10	9	8	9	9	10	8	11	9	9
Day shift	5	6	5	9	12	14	6	11	8	16	12	6	8	13	9	4	6
Swing shift	3	12	8	5	10	7	16	9	13	6	9	15	8	6	4	10	9
Night shift	14	3	9	8	0	0	0	0	0	0	0	0	4	3	6	7	6

After collecting the data above, and arranging it into the table we arrived at the following: the employee number, 1-5 are deputy station masters, and the employee number, 5-12 are female employees. They do not work during the night shift. Generally, the station employee's days off amounted to more than 8-11 days, so it would comply with the Labor Standards Law in Taiwan. By comparing the shift scheduling attachment, you can see there is a deputy station master on duty between each shift. Therefore, the three-models all comply with the shift scheduling of TRTC.

If you need to further investigate which model is optimum, you can use this study model's evaluation index to investigate the working frequency of each station employee. As Table 6 shows, we set the evaluation value of Model C into less, because this model is better than both Model A and Model B. In addition, by comparing the frequency of continuous days off, Model A and Model B both focus on continuous two days off. For the Model C, because the employee can fill the schedule taking into account personal working interests, the frequency of two or three continuous two days off is more even.

Table 6. The comparison of each model

Evaluation subject	Model A	Model B	Model C
Model evaluation value	200 *	220 *	186 *
The sum up of continuous two days off	20	21	13
The sum up of continuous three days off	10	7	16
The sum up of continuous four days off	1	0	1
Solution	Optimal	Optimal	Feasible
Object Value	3,600	15,170	15,630(15,640) **
Time	9 sec	11sec	7min 07sec
Iterations	11,788	18,174	456,380

*the model's evaluation value is the summary for 17s employee
**The target value is 15,640, but we can find the Feasible Solution on target value 15,630.

In addition, if you work on the model process procedure of LINGO, then Model A and Model B both all with the solution methods. You can with Feasible Solution only on Model C. For process time consumption, Model C took longer than the others. In contrast to Models A and B, Model C's process frequency was higher than the others because it was restricted by the working interest day value of the employee.

5. Conclusion and Suggestions

This study's conclusions and suggestions are:

1. This study established a crew shift scheduling model of TRTC through mathematical programming, and used the LINGO to search for the applicable solution model. The result show how this model is applied for the current crew shift scheduling of TRTC's employee.
2. Currently, the TRTC's crew shift scheduling process is done manually, so rapidly changing the crew shift scheduling is inefficient. This study is done through the mathematical programming software LINDO for the solution to this issue.
3. For complying with manpower requirements, station employee's working days and days off, this model does not only provide the common shift scheduling for TRTC, but also deals with the interests of employees for working day and days off for through preference weighting, in order to solve the actual situation of shift scheduling.
4. In addition, TRTC's day-off regulations must comply with Labor Standards Law, and female employees do not work the night shift. You can use the restrictions of this model to find the solution.
5. Using the evaluation model's index, you can obtain crew shift scheduling from each model, station employee's working frequency. Then you can use the working frequency's figure to determine equitable shift scheduling. Using the case study, you can see that the result of Model C is better than others.
6. For Model C, the target of this model's value is 15,640. While using LINGO, you could only find the Feasible Solution of target value is 15,630. This section suggested that you could use the method of mathematical programming or heuristic method algorithms to resolve this.
7. In the case study, this study only focuses on the most needed employees of TRTC operation station, currently (Taipei main station [Ban-Nan line]). While the variation could not use LINGO to find the solution, you could use the heuristic method algorithms to find the solution for TRTC station employee's shift scheduling problem. We expected that the requirement of solution process frequency would be lower than the current crew shift scheduling, and could also improve the efficiency of shift scheduling.
8. Currently, the structure of this study can only arrange the shift scheduling for a single station. We hope to extend this model to the whole shift scheduling in the future in order to comply with the shift scheduling process for TRTC and improve the efficiency of crew shift scheduling.

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Appendix

Table A.1 Model A: the crew shift schedule without any employee's performance

NO.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	MON	N	R	D	D	E	R	D	E	D	E	E	R	N	R	E	R	D
2	TUS	N	R	D	E	R	E	D	E	D	R	E	D	N	E	R	R	D
3	WEN	N	E	D	N	D	E	E	E	D	D	R	E	R	R	R	D	R
4	THUR	N	E	E	R	D	E	R	E	D	D	R	E	R	N	R	D	D
5	FRI	R	N	R	D	E	E	R	R	D	D	R	E	D	N	E	D	E
6	SAT	E	N	R	D	R	R	E	D	D	D	D	E	E	R	N	R	E
7	SUN	R	N	R	D	E	E	E	D	R	D	D	R	E	D	N	R	E
8	MON	D	N	D	R	E	E	E	R	D	R	D	R	E	D	N	R	E
9	TUS	D	R	N	R	E	E	E	R	D	D	R	R	E	D	N	D	E
10	WEN	D	E	N	R	E	E	R	R	D	D	D	D	E	N	R	E	R
11	THUR	D	R	N	E	E	R	D	D	E	E	D	R	R	N	D	E	R
12	FRI	D	D	R	N	E	D	E	E	R	E	D	D	R	N	R	R	E
13	SAT	E	D	D	N	R	D	R	E	R	E	R	D	N	R	D	E	E
14	SUN	R	D	E	N	R	E	D	E	E	R	D	E	N	D	D	R	R
15	MON	R	D	E	N	R	E	D	R	E	E	D	E	R	R	D	D	N
16	TUS	N	E	R	R	D	E	D	D	R	R	D	E	E	R	E	D	N
17	WEN	N	E	D	D	R	R	D	D	E	R	E	E	N	R	E	D	R
18	THUR	N	R	R	E	D	R	D	D	E	E	E	R	N	D	E	R	D
19	FRI	R	R	E	N	D	E	E	R	R	E	E	D	N	D	R	D	D
20	SAT	E	N	E	R	D	R	R	D	D	E	R	E	N	E	R	D	D
21	SUN	R	N	E	D	R	D	R	D	D	E	R	E	R	E	E	D	N
22	MON	E	N	R	D	E	D	R	D	D	R	E	E	D	N	R	E	R
23	TUS	N	R	R	D	E	D	R	D	R	D	E	E	E	N	D	R	E
24	WEN	N	R	E	D	E	R	D	E	D	D	E	R	N	R	D	R	E
25	THUR	R	D	N	E	E	E	D	R	D	R	R	R	N	D	D	E	E
26	FRI	D	D	N	R	E	E	D	R	D	D	R	E	R	R	E	N	E
27	SAT	E	D	N	R	R	R	D	E	E	D	D	R	E	D	E	N	R
28	SUN	R	D	N	E	E	D	R	E	R	D	D	D	R	E	E	N	R
29	MON	D	R	N	E	E	D	E	E	R	D	D	D	R	N	R	R	E
30	TUS	D	E	R	N	R	D	E	E	R	R	E	D	E	R	D	D	N

Table A.2 Model B: the crew shift schedule with employee's prefer hours

NO.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	MON	R	R	E	N	D	R	E	D	D	E	E	D	E	R	R	D	N
2	TUS	D	R	E	N	D	E	E	D	E	R	E	D	N	R	R	D	R
3	WEN	D	N	N	R	E	E	E	D	R	D	R	D	R	D	R	E	E
4	THUR	E	N	N	D	R	R	R	D	D	D	R	E	D	E	E	R	E
5	FRI	N	N	R	E	D	D	R	E	R	D	E	R	D	E	R	D	E
6	SAT	N	R	R	E	D	D	E	R	D	E	R	D	E	R	D	N	E
7	SUN	N	D	E	R	E	E	R	D	E	R	D	R	E	D	D	R	N
8	MON	R	E	N	D	E	R	D	R	E	D	E	R	E	D	D	R	N
9	TUS	D	R	N	R	E	D	E	R	E	D	R	E	N	D	D	E	R
10	WEN	E	D	N	R	R	D	R	E	E	D	D	E	R	N	D	E	R
11	THUR	N	D	R	E	D	D	D	E	R	E	D	E	R	R	E	N	R
12	FRI	N	D	D	E	D	E	D	E	R	R	E	E	R	D	R	R	N
13	SAT	R	N	D	E	R	E	E	E	R	D	E	R	N	D	D	D	R
14	SUN	R	R	E	N	D	R	E	R	E	D	R	D	N	E	D	E	D
15	MON	R	D	N	R	E	D	R	D	E	E	D	E	R	R	D	N	E
16	TUS	N	D	R	D	E	E	D	E	R	R	D	R	D	R	E	N	E
17	WEN	N	D	D	E	R	R	D	R	D	R	E	D	E	E	E	R	N
18	THUR	R	R	E	N	D	R	E	D	D	E	E	D	E	N	R	D	R
19	FRI	D	R	E	N	D	E	E	D	E	R	R	D	R	N	R	D	E
20	SAT	D	E	N	R	E	R	E	D	R	D	R	D	D	N	R	E	E
21	SUN	E	E	N	D	R	D	R	D	D	E	R	E	D	N	E	R	R
22	MON	N	E	R	D	D	E	R	E	E	R	E	R	D	N	R	D	D
23	TUS	N	N	R	E	D	R	E	R	E	D	R	D	E	R	E	D	D
24	WEN	R	N	E	R	D	D	R	D	E	D	D	R	E	E	N	R	E
25	THUR	D	N	R	D	E	D	D	D	E	E	E	R	R	N	R	R	E
26	FRI	N	R	D	R	E	E	E	D	R	E	R	D	D	R	D	N	E
27	SAT	N	E	N	D	R	E	E	R	D	R	D	E	D	D	E	R	R
28	SUN	N	E	R	E	D	R	E	E	E	D	D	R	R	D	N	D	R
29	MON	N	R	D	E	R	D	E	R	R	D	D	D	R	E	N	E	E
30	TUS	R	D	E	N	R	D	R	D	R	E	D	D	E	E	N	E	R

Table A.2 Model C: the crew shift schedule with employee's prefer days

NO.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	MON	E	R	N	D	D	R	D	D	E	R	E	E	N	R	R	D	E
2	TUS	N	R	R	D	E	R	D	D	E	D	R	E	N	D	R	E	E
3	WEN	N	E	D	D	E	D	E	D	R	D	R	E	R	E	R	N	R
4	THUR	N	R	E	D	R	D	R	E	D	D	R	E	D	E	E	N	R
5	FRI	N	D	R	E	D	E	R	E	D	E	E	R	D	N	R	R	D
6	SAT	R	E	R	N	D	E	E	R	D	E	R	E	D	N	D	R	D
7	SUN	N	E	E	R	D	E	R	E	D	R	D	R	E	N	D	R	D
8	MON	R	N	R	E	D	R	D	R	E	D	E	E	N	R	D	E	D
9	TUS	D	N	D	R	E	D	E	R	E	R	E	R	N	R	D	E	D
10	WEN	E	N	D	R	E	R	E	R	R	D	E	D	R	D	D	E	N
11	THUR	N	R	E	D	R	D	E	D	E	D	E	R	R	D	E	N	R
12	FRI	N	R	E	D	E	D	E	D	R	D	E	D	R	E	R	R	N
13	SAT	N	D	E	E	R	D	E	D	R	E	R	D	R	E	D	N	R
14	SUN	R	D	E	N	R	E	R	D	R	E	R	D	D	E	D	N	E
15	MON	R	E	R	N	D	E	E	D	D	E	D	R	D	R	N	R	E
16	TUS	R	E	N	N	D	E	E	R	D	R	D	D	E	R	R	D	E
17	WEN	E	E	N	R	D	R	R	D	E	R	D	D	E	R	D	E	N
18	THUR	N	R	R	D	E	R	D	D	E	R	D	E	E	D	R	E	N
19	FRI	N	R	D	N	E	R	D	E	E	D	D	E	R	D	R	E	R
20	SAT	N	R	D	R	E	D	E	E	R	D	E	E	D	R	R	N	D
21	SUN	N	D	E	D	R	D	R	E	D	R	R	E	R	D	E	N	E
22	MON	R	D	N	E	R	R	D	E	E	D	E	R	D	D	N	R	E
23	TUS	N	E	R	N	D	D	E	R	E	D	R	E	D	D	R	R	E
24	WEN	R	E	E	N	D	D	R	E	R	D	D	R	E	E	D	R	N
25	THUR	D	E	R	N	D	D	E	R	D	E	D	R	E	R	E	R	N
26	FRI	D	E	N	R	D	E	E	R	E	R	D	R	E	D	N	D	R
27	SAT	D	R	N	R	E	R	E	R	E	D	D	E	E	D	N	D	R
28	SUN	N	D	N	R	E	D	E	D	E	D	R	E	R	D	R	E	R
29	MON	R	E	N	D	R	D	E	E	R	D	D	E	R	D	N	E	R
30	TUS	D	E	N	E	R	D	R	R	R	D	D	E	R	D	N	E	E