# Improving the Quality of Personnel Scheduling by Incorporating Fairness

Gözde Alp and Ali Fuat Alkaya

***Abstract*—This paper deals with a real world personnel scheduling problem of a company that has large number of employees. In this problem, once given the number of workers needed for each day and shift, and the constraints emerging from the company and official regulations, the objective is to assign the shifts to workers in a fair manner. To solve this problem, we defined two sub problems, where the first one is the tour scheduling problem, and the second one is the employee assignment problem. We built the integer linear models of these problems by incorporating the constraints and implemented the models in a solver. Application results show that our results are much better in terms of schedule quality and fairness when it is compared with actual schedule. To our best, this is the first study that takes fairness into account.**

***Index Terms*—Tour scheduling, shift scheduling, shift assignment, personnel scheduling, fairness.**

## I. Introduction

Workforce scheduling is one of the most popular problems studied in scheduling and optimization research areas. Constructing efficient and balanced schedules is an enormous issue requiring time and labor cost for the companies with large number of employees. In the literature, workforce scheduling is also referred to as manpower scheduling and personnel scheduling and we will use these terms interchangeably throughout this manuscript.

Personnel scheduling includes a wide range of problems; some of those are shift scheduling, day off scheduling, tour scheduling, crew scheduling, task scheduling, demand scheduling etc. Shift scheduling involves selecting a set of the most suitable shifts from a set of candidate shifts on a single day by satisfying the personnel demand for each shift. The aim is to select most appropriate shifts satisfying employee requirements for each time slot. The main concern in days off scheduling is to determine the off-work days for each worker over the planning horizon, rather than to assign the worker particular shifts on working days. A tour is a weekly assignation, specifying the shifts for the working days and the days off. Tour scheduling composes a weekly schedule, involving both choosing the off days for the workers and allocating shifts for each of their working days over the planning horizon. If working hours for a day is 24 than the problem is called continuous tour scheduling.

The focus of this study is improving the personnel scheduling quality of a production company. Production factory operates 24 hours a day, seven days a week. Employee schedules must be prepared weekly by supplying personnel demand for each day and each shift. The main objectives of this study are (i) satisfying weekly personnel demand with the best preferable schemata (a schema is a weekly schedule, also referred as tour) and (ii) providing fair distribution during specified planning period among all employees. In our approach, we separated this real world personnel scheduling problem into tour scheduling problem and employee assignment problem. Satisfying employee requirement with best preferable schemata may be done by solving the problem as a tour scheduling problem. Tour scheduling presents a weekly solution that contains the tours and the number of their assignments. It is necessary to make a fair assignment distribution over a certain number of weeks period to ensure fairness. Therefore, we need an assignment model to provide a fair distribution throughout the planning period. Detailed information may be found in Section III. We have reduced the tour scheduling problem into the well-known weighted set covering problem. Then we have defined a fairness based assignment model that assigns schedules to employees for given number of weeks, which is a novel contribution to the literature, to our best.

The remainder of paper is organized as follows: the studies investigated in the literature are summarized in Section II. The detailed description of problem and solution techniques is presented in Section III. Experimental studies and result are demonstrated in Section IV. Section V concludes and comprises suggestions for future research.

## II. Literature Review

Computational methods for personnel scheduling has been a subject of continued research and commercial interest since the 1950s. The most detailed survey study, related with this problem prepared by Ernst *et al.* [1] . The study consists of an annotated bibliography of personnel scheduling compatible with the name of study. 700 studies about personnel scheduling is analyzed and summarized. Those 700 papers are classified according to the type of problem addressed, the application areas. Van den Bergh *et al.* [2] presents a review of the literature on personnel scheduling problems facilitates the tracing of published work in relevant fields of interest and it also gives beneficial ideas for the future studies about this topic. Another review study about staff scheduling proposed in 2004 by Ernst et.al [3]. Rostering problems in specific application areas, and the models and algorithms that have been reported in the literature for their solution are reviewed in the study.

Lau [4] considers a special tour scheduling problem in which off days for each worker are given and consecutive shifts in two consecutive working days follow some given rules. The aim is to assign shifts to workers such that

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The authors are with Marmara University, Engineering Faculty, Computer Engineering, Istanbul, Turkey (e-mail: gozde.alp@marmara.edu, trfalkaya@marmara.edu.tr).

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variable demands are met and shift transition rules are satisfied. It is proved that in the cyclic case, the problem is NP-hard in general, but can be solved in polynomial time if the transition rules are of special forms.

Alvarez-Valdes *et al*. deal with continuous tour scheduling problem. Reduced set covering tour scheduling formulation is selected as solution technique. Employees are assigned to suitable shifts with Hungarian method. Each employee has at least 36 hours off during a week and each employee has a weekend of during 4 weeks period. They've tried to provide balance between workers in number of weekend off and number of night shifts. Problem is solved with Tabu search and CPLEX and results are discussed. Stolletz also used set covering formulation [5]. Morris and Showalter presented a rewarding study in 1983 that clarifies the usage of set covering formulation for shift scheduling, days off scheduling and tour scheduling problems [6]. Top down heuristic is used to solve tour scheduling problem. Easton and Rossin (1991) offer solution for tour scheduling as reduced set covering problem including employee type property considering employee preferences [7]. Employee assignment problem is solved as General Assignment Problem. Easton and Rossin (1996) also defines tour scheduling problem as reduced set covering problem. Employee assignment part is done by a number of heuristics those are described in the study [8].

Morris and Showalter present a linear programming application that produces optimal solution to specific day-off and tour scheduling problems [9]. Chew formulated construction of cyclic duty line on in [10].

Brunner and Stolletz prepared a schedule for the employees in check in counters at airport [11]. Personnel requirement changes in 30 minutes intervals. Shift scheduling is done to meet the need of this variable demand. Bechtold *et al.* implements and compares previously published heuristics for a large scale problem [12].

## III. Problem Description and Solution Method

### A. Problem Description

The focus of this study is improving the personnel scheduling quality of a production company. Production factory operates 24 hours a day, seven days a week. Employee schedules must be prepared weekly by supplying personnel demand for each day and each shift. That is, the output schedule must satisfy the number of workers needed for each day and shift. Additionally, there are some essential official rules for employee schedules. Those rules may be listed as follows; if an employee has night shift on Sunday, he cannot be assigned to day shift on the following Monday, if an employee has weekend off, he/she cannot be off on adjacent Monday and an employee cannot work consecutive more than six days. These additional official constraints make the problem difficult to solve. Under these constraints, the first aim of this study is to determine high quality weekly employee schedules for the factory and second aim is to provide fair schedule distribution between employees for a given number of weeks. The company under focus has over 2000 employees. Planning weekly schedules for this number of employees manually has undeniable cost and work force.

The problem in this study is divided into two sub problems; those are tour scheduling problem and employee assignment problem. These problems can't be solved as an integrated single problem because the integrated single problem turns out to be a general assignment problem with many numbers of constraints that make the formulation solvable only for very small instances. On the other hand, when separated, the output tour scheduling problem is input of shift assignment model, and tour scheduling produces a weekly plan while employee assignment model organizes several weeks. Employee requirements taken from the company contain employee demand for each day of week and each shift of a day. Employee requirements are updated every four weeks period, hence personnel scheduling is required according to the updated requirements. A tour is a weekly schedule that contains shift type data for work days and the off days. Tour scheduling exposes tours and their usage numbers as output which meet the expectations of employee requirements. Tour scheduling does not match employees and tours with each other that is why an assignment algorithm is required to do this process.

Working at night shifts or at the weekends is less preferable; however employee requirement in those undesirable time slots must be satisfied. Consequently, a fair assignment algorithm is indispensable which should provide a balanced distribution by matching tours and employees thorough a given time period. Employee tour matches are prepared once in four weeks and each employee has a different schedule for each of these weeks. Our assignment model provides a fair tour distribution for all employees during the planning period.

According to the personnel scheduling terminology, our problem of assigning employees to shifts and days off in a given week is a continuous tour scheduling problem which spans 24 hour period of the day. The tour scheduling problem turns out to be the well-known set covering problem and it can be formulated as an integer linear program.

TABLE I: Shift Type, off Day Type Enumeration

| | CT1 | CT2 | CT3 |
|---|---|---|---|
| Day shift | 1 | 1.1 | 1 |
| Evening shift | 2 | 1.2 | 1.5 |
| Night shift | 3 | 1.3 | 2 |
| Weekend off | 1 | 1.1 | 1 |
| Friday - Saturday off | 2 | 1.2 | 1.5 |
| Sunday weekday off | 3 | 1.3 | 2 |
| Consecutive weekday off | 4 | 1.4 | 2.5 |
| Separate weekday off | 5 | 1.5 | 3 |

Production factory works in three 8 hour shifts in a day and seven days in a week. Shift types are day shift, evening shift and night shift. Day shift is between 07:00 and 15:00, evening shift is between 15:00 and 23:00, night shift is between 23:00 and 07:00.

Each employee is assigned to one of those shifts each week; additionally each employee has two off days during a week. A tour may be defined by a seven lettered string containing D, E, N or X which mean day shift, evening shift, night shift and off day, respectively and each letter corresponds to the days of the week starting from Monday up to Sunday. An example schema string is "XXDDDDD", this string means Monday and Tuesday are off and the week continues with five successive day shifts. Another example schema string is “NNXNNXN”, employee is assigned to night shift in this schema and Wednesday and Saturday are off days. One can easily calculate that there are exactly 63 different schemata with three shift types and two day off rules.

For determining the quality of a schema, we made use of its shift type and off day types, and we assigned numerical values for measuring the quality. For example, enumeration for shift type can be 1, 2 and 3 for D, E and N, respectively. Similarly, we have identified 5 off day types; these are weekend off, Friday-Saturday off, Sunday-Weekday off, consecutive weekday off and separate weekday off with numerating from 1 to 5, respectively. We assigned a predetermined cost to each schema, obtained by the multiplication of its off day type and shift type. So, the objective of the problem turns out to be minimizing the cost rather than maximizing the quality. As an example “DDDDDNN” is the most preferable, because 5 consecutive week days, day shift and weekend off is the best case among all schemas and therefore has the lowest cost (has the highest quality), while a separate weekday off schema has the highest cost (lowest quality). We have used three different sets of enumeration values which are illustrated in Table I. CT1, CT2, CT3 are cost type 1, 2, 3 respectively. Most preferred shift type (day shift) has the lowest value among shift types and most preferred off day type (weekend off) has the lowest value among all off day types for each cost type. As preference of shift type and off day type decreases the cost value increases. Those cost definitions provide reasonable cost value diversity considering for undeniable personnel preference.

TABLE II: SCHEMA COST COMPUTATION

| Schema | c1(s) | c2(s) | c3(s) |
|---|---|---|---|
| 21 | 1 (1*1) | 1.21 (1.1*1.1) | 1 (1*1) |
| 42 | 2 (1*2) | 1.32 (1.1*1.2) | 1.5 (1*1.5) |
| 63 | 3 (1*3) | 1.43 (1.1*1.3) | 2 (1*2) |
| 8 | 5 (5*1) | 1.65 (1.5*1.1) | 3 (3*1) |
| 29 | 10(5*2) | 1.8 (1.5*1.2) | 4.5 (3*1.5) |
| 50 | 15(5*3) | 1.95 (1.5*1.3) | 6 (3*2) |

An illustrative example is given in Table II. Schema 21, 42 and 63 are considered as the best schemata because the off days are on the weekend. We can order these according to the shifts; schema 21 has cost of 1 because its shift type is day shift, schema 42 has a cost of 2 because its shifts type is evening and schema 63 has a cost of 3 because its shifts type is night. Schemas 8, 29 and 50 are three samples of the schemata which are considered as the worst ones because the off days are separated in the week days. The order among these is also done according to their shift types.

### B. Problem Formulation

Below, we firstly provide the notation and then the formulation of the tour scheduling problem.

*S* = set of schemas. (Remember a schema is a seven letter string denoting the shift types and off days. There are totally 63 types of schemata used in the model and each is denoted by a number from 1 to 63.)

*T* = set of time slots of week. (There are totally 21 time slots in a week, one day contains 3 shifts (planning time slot), 7 day comprises 21 time slots similarly. Each time slot is denoted by a number from 1 to 21)

*c(s)* = cost of each schema,

*x(s)* = number of times schema *s* is used,

*r(t)* = the requirement at time slot *t*,

$$a(s,t) = \begin{cases} 1, & if\ schema\ s\ covers\ time\ slot\ t \\ 0, & otherwise \end{cases}$$

$$minimize \sum_s c(s) * x(s)$$

$$s.t. \sum_s a(s,t) * x(s) \geq r(t)\ \ for\ \forall\ t \qquad (1)$$

$$x(s) \geq 0\ for\ \forall\ s \qquad (2)$$

$$s \in S, t \in T$$

The objective is minimizing the total schema cost. Thus, the schemata having high desirability (having lower costs) will be used more in the optimum solution. First constraint ensures that requirement in each time slot (that is, the required number of employees) is satisfied, second constraint ensures that number of times schema *s* used is more than or equal to 0. The solution is given by the values of the *x* variable, showing how many times each schema is used.

Once how many times each schema will be used is specified by tour scheduling model output, the next step is assigning workers to schemata. Fairness based employee assignment can be formulated as a Generalized Assignment Problem (GAP). Assignment is done for four weeks in a fair manner (our model is dynamic where week is a parameter). The model compute all weeks average costs for all employees (*M*), also all weeks average costs are computed individually for each employee (*N*(*e*)). The distance between these values indicates the fair distribution (*D*(*e*)). If *M* and all *N*(*e*) values are equal to each other than distance *(D*(*e*)) will be zero, which means that employees are assigned to totally equal costed schemas during given number of weeks. Employee assignment problem notation and formulation is given below.

*x*(*s*) = number of times schema *s* is used, (This value is the output of tour scheduling problem.)

*T* = set of time slots of week, (Also used in tour scheduling model.)

*S* = set of schemas, (Also used in tour scheduling model.)

*E* = number of employee,

*W* = number of weeks,

$$a(s,t) = \begin{cases} 1, & if\ schema\ s\ covers\ time\ slot\ t \\ 0, & otherwise \end{cases}$$

$$A(e,w,s) = \begin{cases} 1, & if\ employee\ e\ is\ assigned\ to\ schema\ s\ in\ week\ w \\ 0, & otherwise \end{cases}$$

*M* is the average cost value for all employees, calculated by total of schema assignment number and schema cost multiplication, divided by the employee number.

$$M = \frac{\sum_s x[s] * c(s)}{E}$$

*N(e)* is the all weeks average cost value for each employee. This value is calculated separately for each employee. If employee e is assigned to schema s during week *w*, *A*[*e*,*w*,*s*] variable is equal to 1 and schema cost *W(s)* is added to the total. The sum off all weeks' schema cost is calculated and divided by total number of planning week number *W*. So that average cost value is calculated for each employee.

$$N(e) = \frac{\sum_w \sum_s A[e,w,s] * c(s)}{W}$$

*D(e)* is the absolute difference of each employee individual weekly average *N(e)* and the general average *M*.

$$minimize \sum_e D(e)$$

$$\sum_s A[e,w,s] = 1 \;\; for \, \forall \;\; e,w \qquad (3)$$

$$\sum_e A[e,w,s] = x(s) \quad for \, \forall \;\; w,s \qquad (4)$$

$$D(e) \geq |M - N(e)| \qquad (5)$$

The objective is minimizing the difference of each employee so that maximum fairness is sought. First constraint means that each employee is assigned to only one schema in each week. Second constraint means that the number of employees assigned to the schema s is equal to *x*(*s*) for each week. Constraints 3 ensures the positivity of *D*(*e*).

Furthermore, there are some additional official rules for shift assignments. Constraint 5 carries out the rule; if employee has night shift on Sunday, cannot be assigned to day shift on Monday. Another official rule is; if an employee has weekend off, he/she cannot be off on Monday, implemented by constraint 6. Constraint 7 enforces the rule; an employee cannot work consecutive more than 6 days. *w*+1 and *s*1 are used in constraint 5 to 7. *w*+1 demonstrates the following week and *s*1 corresponds to the schema assignment of the following week.

$$\mathrm{Assignment(e,w,s)} * \mathrm{a(s,'21')} + \mathrm{Assignment(e,w+1,s1)} * \mathrm{a(s1,'1')}) \leq 1; \qquad (6)$$

$$\sum_{k=16}^{21} \mathrm{Assignment(e,w,s)} * \mathrm{a(s,'k')} + \sum_{k=1}^{3} \mathrm{Assignment(e,w+1,s1)} * \mathrm{a(s1,'k')} \geq 1 \qquad (7)$$

$$\sum_{k=3q+1}^{21} \mathrm{Assignment(e,w,s)} * \mathrm{a(s,'k')} + \sum_{k=1}^{3q} \mathrm{Assignment(e,w+1,s1)} * \mathrm{a(s1,'k')} \leq 6 \quad for \;\; \mathrm{q=1\ldots6} \qquad (8)$$

$$\mathrm{s,s1} \in \mathrm{S}, \mathrm{t} \in \mathrm{T}, \mathrm{e} \in \mathrm{E}, \mathrm{w} \in \mathrm{W}$$

## IV. Environmental Setup and Results

As previously mentioned, the company we work with has over 2000 employees. Each of these employees is working in different departments within the company. Weekly personnel requirements vary according to the departments; therefore weekly schedule plan is done separately for each department. In this study, experimental tests are done for a department that has 147 employees.

Models described exhaustively in section 3 are implemented in GAMS software using CPLEX solver. The application runs at Intel Core i7, 3.10 Ghz processor personal computer. Our solutions are compared with the real assignments prepared by the company. For a fair comparison, the total cost of the company assignments are calculated based on our costs values given in the previous section.

As it is explained before, a "tour" is a 7 days schedule; here we have assigned a cost value for each possible tour according to its preference. Our test case has totally 63 tours for three shift types and two off days during the week. Tour cost specification is explained in previous section. Shift requirements may change periodically. Tour scheduling model is solved in GAMS for given inputs. Weekly schedule output taken from tour scheduling model offers more preferable schedule for each input. The tours chosen to satisfy employee requirement, formed with low costed schemas as much as possible as a natural result of tour scheduling model. Tests are done for each cost type input and real application results are evaluated and prepared for each cost type. The average cost of real schedule for cost type 1 is decreased by %16. We have achieved %4 reduction in cost type 2, and %10 decrement in cost type 3. Outcomes demonstrate that our tour scheduling model composes more preferable tours while satisfying the same personnel requirement.

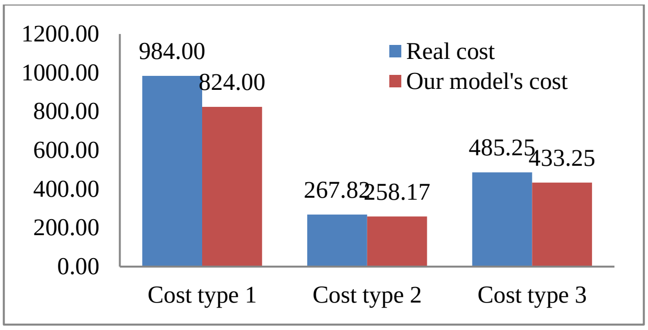


Fig. 1. Total cost demonstration of tours.

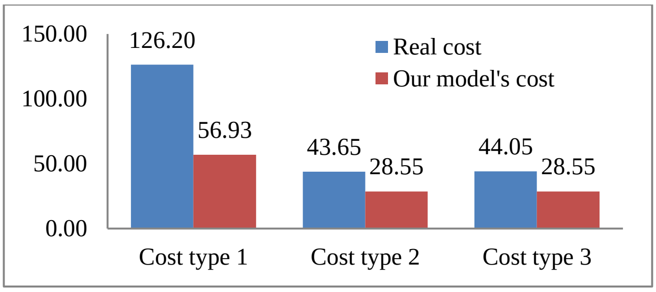


Fig. 2. Fairness comparison.

Employee assignment formulation is tested in the next step. Assignment formulation assigns employees to schemas during 4 weeks and tries to provide fair schema distribution during given number of weeks. The data retrieved from the company has 4 weeks shift schedules for 147 employees for each input. The success indicator of this model is the total schema quality difference between all employees This indication is explained detail in previous section. Fairness comparison results are illustrated in Figure 2 where the tests are done for a 4 week period. When we made tests for small number of employees, the difference was equal to zero, or in other words each employee was assigned to exactly equal and balanced shifts. However we have tested our formulation with 147 employees for this study and difference our model achieved %54 better total cost while it compared with the real cost for cost type 1. Similarly We have achieved %34 percent decrement for cost type 2 and %35 percent reduction for cost type 3. The results prove that the algorithm proposed may work with large number of employees and provides much fair and beneficial result.

## V. Conclusion and Further Research

We have offered a solution for employee scheduling problem of a company which has many employees. The problem is divided into two parts, tour scheduling model is implemented. A novel balanced assignment model is proposed to assign employees to tour for given number of weeks. Formulations are written and tested in GAMS environment with CPLEX solver. Solver results are compared with the results taken from the company and verified the utility of the proposed solution.

There are several interesting directions for the future research. Heuristic and meta-heuristic techniques may be applied to solve tour scheduling algorithm. A comparative study may be done for tour scheduling problem solution techniques and employee assignment techniques. The company that has large number of employees generally provides service busses for transportation of employees, employee location information may be as a constraint while making shift assignment.

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**Gözde Alp** was born in İzmir, Turkey in 1989. She received the B.S. degree in computer engineering from Suleyman Demirel University, Isparta, Turkey, in 2011, and the M.S. degree in computer engineering from Dokuz Eylul University, Izmir, Turkey in 2013. She is a Ph.D. student and a research assistant in Marmara University Computer Engineering Department, Istanbul, Turkey.

Her research interests include database systems, optimization, and evolutionary algorithms.

**Ali Fuat Alkaya** was born in Hatay, Turkey, in 1976. He received the B.S. degree in mathematics from Koc University, Istanbul, Turkey, and the M.S. degree in computer engineering and Ph.D. degree in engineering management from Marmara University. He is a Faculty Member with the Computer Engineering Department, Marmara University. His current esearch interests include meta-heuristics, combinatorial optimization and machine learning