AN EXACT APPROACH FOR A DYNAMIC WORKFORCE SCHEDULING PROBLEM

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Ersin Koç

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AN EXACT APPROACH FOR A DYNAMIC WORKFORCE SCHEDULING PROBLEM

Approved by:

Associate Professor Okan Örsan Özener,
Advisor,

Department of Industrial Engineering

Özyeğin University

Associate Professor Ali Ekici,

Department of Industrial Engineering

Özyeğin University

Associate Professor Serhan Duran,

Department of Industrial Engineering

Middle East Technical University

Date Approved: January 2018

To my family

ABSTRACT

Taking into account the global and national rules and regulations, assigning a given number of employees to planned shifts while paying attention to required working hours, rest times and off day/days is one of the most complex planning issue both in literature and real world, and this is the concept of workforce planning in particular. This issue is deserved to have an intense concern in real world because there are so many considerations that it is not an easy and simple planning issue; rather, one of the most complex problems, namely a subject of NP-Hard Problems.

In this thesis, as a prototype of a possible real world problem in workforce scheduling, we study a company trying to minimize the all the direct and indirect cost related to workforce scheduling. Satisfying the given limited workforce and labor-related constraints, our aim is to determine the minimum cost solution. This is why, reviewing the studies in the literature including with examples of some problems, we define our problem along with the main characteristics and assumptions. We propose a solution approach based on an exact solution of the integer programming formulation of the problem and observe that our solution approach generates high quality solutions in acceptable solution time. The optimality gap of the solutions obtained in one-hour computational time limit is only 19.38%.

Keywords: workforce scheduling; planning; integer programming; cost minimization

ÖZET

Küresel ve ulusal kurallar ve düzenlemeler altında, belirli sayıdaki çalışanı planlı vardiyalara belirli çalışma ve dinlenme saatleri ile tatil gün/günlerine dikkat ederek atamak, teorik ve gerçek dünyadaki en karmaşık planlama konularından biridir ve işgücü planlama özelinde bir konudur. Bu konu, dikkate alınması gereken çok fazla kritere haiz olması nedeniyle, kolay ve basit bir planlama konusu olmasının tam aksine en karmaşık planlama problemleri olan NP-Hard problemlerinden biridir.

Bu tezde, gerçek dünyada olabilecek örnek bir işgücü çizelgeleme sorununu ele alarak, işgücü çizelgelemesine ilişkin doğrudan ve dolaylı tüm maliyetlerini en aza indirmeye çalışan bir şirketi inceliyoruz. Belirli iş gücüne ve işle ile ilgili kısıtlamalara uygun olarak minimum maliyet çözümünü belirlemeyi amaçlıyoruz. Bu nedenle, bazı problemlerin örnekleri dâhil olmak üzere literatürdeki çalışmaları inceleyerek, temel karakteristik ve varsayımlarla birlikte problemimizi tanımlıyoruz. Probleme tam sayılı programlama ile kesin bir çözüm öneriyoruz ve bu yöntemin kabul edilebilir sürelerde yüksek kalitede çözümler ürettiğini gözlemliyoruz. Bir saat koşma süresince elde edilen çözümlerin optimum aralığının %19.38 olduğunu görüyoruz.

Anahtar kelimeler: işgücü çizelgeleme; planlama; tam sayılı programlama; maliyet minimizasyonu

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CHAPTER I

INTRODUCTION

In contemporary world, companies in many industries, especially the ones in production and service industries, have to have an ongoing process in order to take a place in the competition of the markets and keep up with the companies all around the globe because of the easy access to substitute companies within the border of the city, country and even the rest of the world thanks to the globalization. Hence, the work in the companies which are in such industries is required to be continuous during the day and night times. In other words, 24 hours a day and 7 days a week the work has to be carried out. However, the companies which may not need 24-hour working period in a day still need to have a continuous work period during the day except the night hours. This is why, any company of today's world needs to have a good workforce schedule that contributes to the efficient use of working time and effective production and service time as well as meets the company's needs to carry out necessary work without intercepting required company performance in order to fulfill expectations and planned works.

At this point, the importance of workforce scheduling is so crystal-clear that companies must strongly pay attention and attach a great importance to it. Therefore, it is required to show special interest for this topic and it must be well understood for the good of any company.

Why workforce scheduling is an important issue within an organization can be well-defined by the reason-result relations of some aspects. The first one is the time-consuming side because the manager has less time for managing the business and employees due to scheduling by hand, which is the case in most sectors due to the fact that the automatic scheduling applications do not meet the companies' needs and employees' expectations although the technology has reached an unimaginable level. The second one is that employees perform better and increase their productivity and service quality if the schedule is fair and meets their preferences. And the last one is reducing and minimizing the costs created by overstaffing or understaffing supplied with overtime payments thanks to a good and effective schedule.

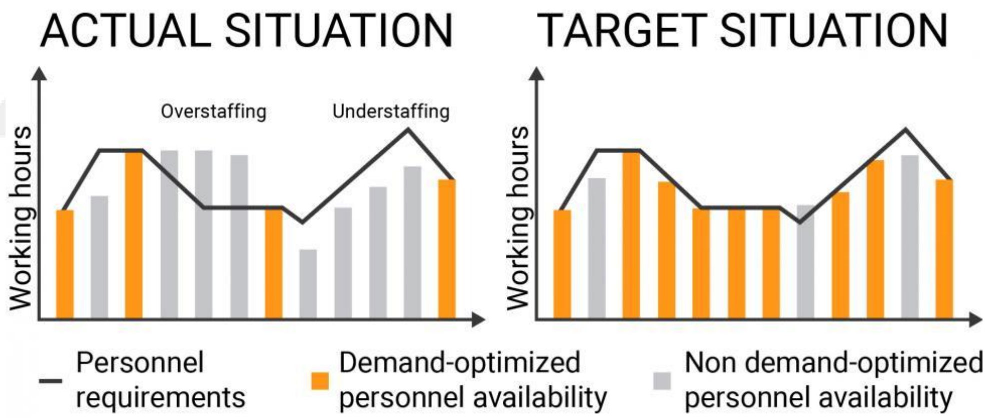

Figure 1: Workforce Scheduling - Overstaffing and Understaffing [1]

Workforce scheduling is to effectively assign a given number of employees to planned shifts and to determine the off times during the working hours in a day and off day/s of the employees in a week. This is a derivative of a planning issue but not a simple and straightforward one; on the contrary, it is one of the most complex and hardest one to be tackled with.

[1] taken from the company website of ATOSS Workforce Management

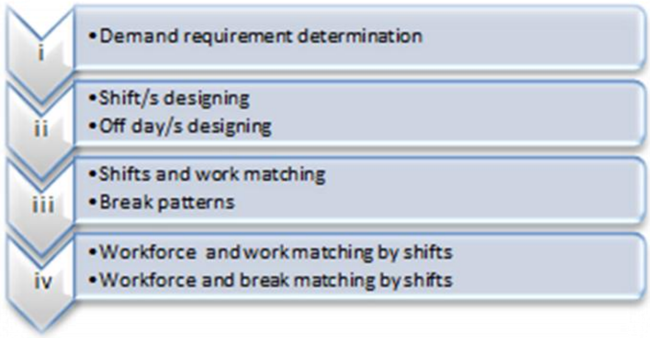

Figure 2: Main Decisions of an Operation Day in a Workforce Scheduling Problem

Two variants of this process are rotating and non-rotating workforce schedules. If employees have the same schedule in different working areas and optimal schedule for all employees on average is planned, that means this is a rotating workforce scheduling. If employees have different schedules fulfilling their preferences, however, that means this is a non-rotating workforce scheduling.

The main reason for this problem to be complex is the combinatorial nature of the scheduling problems. In the literature, many scheduling related problems are proved to be very complex problems, NP-Hard Problems, and workforce scheduling is no exception. In fact, considering that number of employees to be scheduled might be increased and the similarity of the workforce (different employees may perform the same task), it becomes one of the most complex problems tackled in the literature (i.e. airline crew scheduling).

The complexity of this scheduling is not limited combinatorial nature of the problem as there are too many various external constraints to satisfy such as taking health and safety rules and regulations into consideration. For example, the work periods during a day, rest times and required time to be off work between two consecutive working shifts of an employee are all limited under national laws and national and global rules and regulations.

One other complexity may be due to different type of employees that can be assigned to shifts. Full time employees are subject to different rules and regulations compared to part time employees. Not only the rules but also the stipends are different between full time and part time employees. Last but not least the availabilities of these two different types of employees are different from one another.

The cost incurred due to workforce scheduling is not limited to the salaries of the full-time employees or the payments of the part time employees. There are some additional benefits provided by the company. First of all, due to rules and regulations, companies have to pay extra for the overtime work performed by the employees. Second, companies might be forced to pay the travel expenses of the employees. Finally, the meal expenses of the employees, depending on the shift, it might incur or not, are to be paid by the company as well.

Since this is an important concept for effective usage of employees which leads to cost minimization, there have been too many studies done on this subject. In literature, there are many academics studied on many types of workforce scheduling problems.

Great importance is attached to flexibility and mobility by employees within the frame of this topic. These two variables play a big role on employees' performance and so, on the firm performance. None of employers want to lose their best employees; hence, there must be compromises to keep them at the company and (Eaton, 2003) and

(Martinez-Sanchez, Perez-Perez, Luis-Carnicer, & Vela-Jimenez, 2007) have worked on the subject to show this relation in this scope.

In this thesis, a prototype of a possible real world problem in workforce scheduling will be analyzed. The company is trying to minimize the all the direct and indirect cost related to workforce scheduling, which includes the regular payment of the employees, overtime payments, travel expenses, etc. The company may utilize part time employees when the full time workforce is not sufficient or when it is economical to do so. In Section 2, we review the studies in the literature including with examples of some problems in the field and discuss the rules and regulations governing workforce scheduling. In Section 3, we define our problem, discuss the main characteristics of our problem and list our assumptions. In Section 4, we propose a solution approach based on an exact solution of the integer programming formulation of the problem. Our objective is to determine the minimum cost solution that satisfies the given the limited work force and the labor-related constraints. In Section 5, we present our computational findings and finally concluding remarks are presented in Section 6.

CHAPTER II

PREVIOUS WORK

Workforce scheduling is required for a broad range of sectors and hence there is a vast literature on workforce scheduling problem arising from real-life application from different sectors. In this section, we try to classify these studies and briefly review their contributions to the literature. We also refer the reader to survey papers on workforce scheduling such as (Baker K. , 1976), (Miller, 1976), (Golembiewski & Proehl Jr, 1978), (Cheang, Li, Lim, & Rodrigues, 2003) and (Ernst, Jiang, Krishnamoorthy, & Sier, 2004).

The most common application of workforce scheduling studied in the literature is the crew scheduling in transportation systems. In transportation systems, each task has its own starting time and location as well as its own ending time and location and each task has to be started and completed based on a given timetable. For instance, a task may correspond to a flight leg in airlines or a trip between two or more bus stop points. Most attention for workforce scheduling problems related to this sector is on the airline industry because of its volume and potential. The workforce scheduling turns into crew scheduling for this industry and there are too many criteria to be taken into account to treat this problem such as: crew categories, fleet types, network structures, rules and regulations, flight timetables and finally cost structures. (Andersson, Housos, Kohl, & Wedelin, 1997)

In general airline crew scheduling problem is solved in three stages:

- Crew pairing generation: feasible pairings/duties from a given timetable are constructed.

- Crew pairing optimization: flight legs/trips are covered by selecting pairs from the first stage at a minimum cost
- Crew rostering: pairings from the second stage are assigned to individual crew by sequencing into rosters.

We refer the reader to the articles (Anbil, Gelman, Patty, & Tanga, 1991), (Baker, Bodin, Finnegan, & Ponder, 1979), (Bodin, Golden, Assad, & Ball, 1983), (Crainic & Rousseau, 1987), (Day & Ryan, 1997), (Desaulniers, et al., 1997), (Lasry, Mc Innis, Soumis, Desrosiers, & Solomon, 2000), (Gamache & Soumis, A Method for Optimally Solving the Rostering Problem, 1998), (Gamache, Soumis, Villeneuve, Desrosiers, & Gelinas, 1998), (Hoffman & Padberg, 1993), (Rushmeier, Hoffman, & Padberg, 1995), (Ryan, 1992) and (Wedelin, 1995) on airline crew scheduling.

An extension of the airline crew scheduling problem is called operational crew pairing optimization, and it deals with the topic to manage day-to-day operations by making compulsory changes on pre-planned monthly assignments in order to tackle with sick leave and incident interruptions. In airline industry, some pilots and flight attendants are reserved and not assigned to active fly for emergency needs in day-to-day operations, which is called reserve pilots and flight attendants. (Graves, Mc Bridge, Gershkoff, Anderson, & Mahidfara, 1993)

Finally, in public transport system, the approach is similar to the one used airline crew scheduling and a given bus timetable is used for bus schedules and rosters. The main differences are the time scale which is smaller and there is no long rests as duties are done by the crew complements. Also, starting and ending locations do not have to be the same location. (Daduna & Voss, 2001) and (Falkner & Ryan, 1987)

Another common application area of workforce scheduling is home health care operations. This problem includes visiting and nursing patients at their home as described in (Bertels & Fahle, 2006). The criteria:

- patients preferences for the visiting time
- working hour limits of nurses per day
- starting and ending time of nurses
- transportation issue if more than one visit is done
- nurses having different skills for different type of patients
- nursing duration
- requirement for more than one nurse at the same time
- shift types
- legal requirements, and
- keeping the same nurse for the same patient as much as possible.

The authors have employed hybrid approaches, integer programming and heuristics for the scheduling and routing problems, for this home care workforce problem. (Begur, Miller, Weaver, & J.R, 1997)

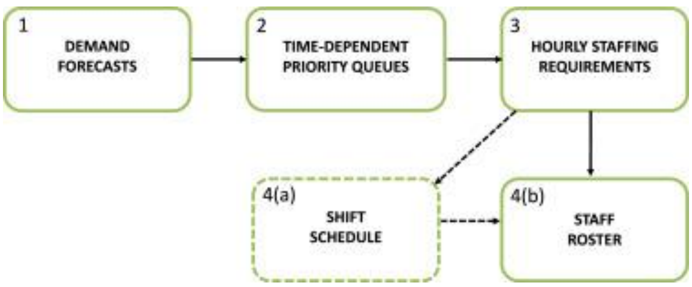

Figure 3: Workforce Scheduling - As an Example, Integration of Techniques in Workforce Capacity Planning in Health Care [2]

As alternative approach, (Bertels & Fahle, 2006) proposes a two-phase method. In the first phase of this method, constraint programming is employed to obtain a

[2] taken from the article of Time-Dependent Stochastic Methods for Managing and Scheduling Emergency Medical Services written by J.L. Vile, J.W. Gillard, P.R. Harper, V.A. Knight

feasible solution, and in the second phase, a series of meta-heuristics like simulated annealing or tabu search is used to improve the solution found in the first stage.

In addition to them, (Barnhart, Johnson, Nemhauser, Savelsbergh, & Vance, 1998) used branch and price method as an exact method following a set partitioning formulation for the master problem. They used real variables for activity scheduling and binary variables to show if an activity is performed by a specific employee or not. And, they solved the pricing problem to bring out the shortest path.

There are also studies in the literature tacking a similar problem to home health care problem explained above but the schedule is assumed to be repeated regularly and for a long time. This problem is based on the community care service to elderly and disabled people by local authorities in order to schedule care workers in a region while reducing travel time (Akjiratikarl, Yenradee, & Drake, Pso-based Algorithm for Home Care Worker Scheduling in the UK, 2007) and (Evaborn, R'onnqvist, Einarsd'ottir, Eklund, Lid'en, & Almroth, 2009). This workforce problem is solved by linear programming, heuristics and hybrid approaches (De Angelis, 1998). For assignment model used for new visits and scheduling models used for generating weekly visits of this problem, mixed integer linear programming is used (Borsani, Matta, Sommaruga, & Beschi, 2006).

For heuristic methods, local search based on simple heuristics, meta-heuristics like tabu search (Blais, Lapierre, & Laporte, 2003), evolutionary approaches such as particle swarm optimization (Akjiratikarl, Yenradee, & Drake, An Improved Particle Swarm Optimization Algorithm for Care Worker Scheduling, 2006) and (Akjiratikarl, Yenradee, & Drake, Pso-based Algorithm for Home Care Worker Scheduling in the UK, 2007), and agent-based modeling (Itabashi, Chiba, Takahashi, & Kato, 2006) are used. The strategy for similar for all heuristic methods: first generating an initial solution and then local improvement procedures such as common neighborhood.

As the last approach to solve this version of the workforce scheduling problem, a set partitioning model and a repeated matching algorithm is combined to suitably match the employee pairs with the routes. (Evaborn, Flisberg, & R'onnqvist, Laps Care an Operational System for Staff Planning of Home Care, 2006) and (Evaborn, R'onnqvist, Einarsd'ottir, Eklund, Lid'en, & Almroth, 2009)

Manpower allocation problem is another derivative of the workforce scheduling problem which aims to assign servicemen of different activities to different customer locations while minimizing number of servicemen used, total distance travelled and waiting time at service points as well as maximizing number of tasks assigned. (Lim, Rodrigues, & Song, 2004) proposes meta heuristics with tabu search, simulated annealing and squeaky wheel optimization to solve this problem. (Li, Lim, & Rodrigues, 2005) employs simulated annealing and finally (Dohn, Kolind, & Clausen, 2009) uses an exact method, branch and price, to solve a set covering formulation based on integer programming.

Finally, workforce scheduling for call center operations is another related research area that attracted attention from the researchers. For this derivative of workforce scheduling problem, entire planning horizon is taken into account so that scheduling and rostering becomes more complicated. Workforce requirements in call center change from day-to-day and from week to week. Even the start times and the lengths of the shifts may be changed to cover the need for workforce through low-cost rosters. Demand varies for different time intervals; hence, rosters make the call center over staffed or under staffed to respond to the calls in an expected time.

Most commonly, a three-stage method is proposed for the workforce scheduling problem in a call center. The stages, forecasting, workforce requirement and integrated scheduling, are handled in sequence. To determine the number of required staff in each time interval for workforce scheduling in a call center, queuing models and simulation models are proposed. The most preferred queuing model for call center applications is the Erlang-C queuing model. Although these models give analytical results, simplifications are generally made for real world cases. In addition to that, researchers use simulation to take practical factors into account while providing solutions. There are also studies in the literature where queuing models and simulations are employed together. (Henderson, Mason, Ziedins, & Thomson, 1999), (Grossman, Samuelson, Oh, & Rohleder, 1999), (Andrews & Parsons, 1993), (Chen, 2000), and (Brigandi, Dragon, Sheehan, & Spencer III, 1994)

In this problem, effective workforce planning and rostering is important as each calls might be related to a different type of request and each of these call types might require different call-handling skills. Therefore, even though some of constraints are standard workforce scheduling constraints, such as maximum shift duration, earliest shift starting time and latest finishing time, the skills of staff must be taken into account while generating rosters in call center workforce scheduling problem. (Buffa, Cosgrove, & Luce, 1976)

Motivated by the literature on the workforce scheduling problems discussed above, our research focuses on a potential real-life problem of a fictitious company. We propose an exact solution based method to determine a tailored, cost efficient solution given the workforce regulations imposed by the authorities and requirements specified by the company. Our objective is to identify a feasible, cost efficient solution for this complex planning problem in acceptable computational time.

Rules and Regulations

In workforce scheduling, there exist a long set of rules that is imposed by International Labor Organization (ILO) internationally and governments nationally. In this section, we cover the related rules mostly on working times and rest periods. This part will help us shape the variables and criteria of the model through national requirements for labor rights.

Daily Working Hour Limit: ILO promotes an international standard of maximum 8 daily working hours. However, this might be increased up to 11 hours if required. In US, according to the FLSA (Fair Labor Standards Act), normal working hours limit is 8 hours per day and can be increased to 11 hours with overtime. In Turkey, however, normal working hours limit is 8 hours per day and cannot exceed 11 hours including overtime period.

Weekly Working Hour Limit: ILO encourages companies to apply the normal working hours as 40 hours per week without any reduction in wages. However, this limit can be 48 hours with overtime by higher rates for these extended working hours.

In US, according to the FLSA, normal working hours limit is in line with ILO standards and 40 hours per 7-day workweek without any reduction in wages. And, at least minimum wage is paid to employees till the working hours of 40 in a week and at least one and a half times their regular rates of pay must be paid for the overtime hours.

However, according to the 4857 Labor Law, normal weekly working time is maximum 45 hours in Turkey, and it should be divided equally by the days of working week in the company. The working hours exceeding 45 hours weekly working time is called "overtime" and this period cannot be more than 3 hours daily, and total of 270 hours in a year. Corresponding to this overtime period, wages for each overtime hour must be paid as one and a half times of the normal hourly working rate.

Day Break: Regarding meal periods in US, it lasts at least 30 minutes. These are completely rest periods and not similar to coffee and snack breaks which are counted as hours worked, so these are not work time. In Turkey, the rest breaks are not counted as part of daily working time and defined in the Article 68 of the 4857 Labor Law based on the requirements of the work. These breaks must be in the middle of daily working hours and these periods are as below:

- fifteen minutes, when the work lasts four hours or less
- half an hour, when the work lasts longer than four hours and up to seven and a half hours (seven and a half included)
- one hour, when the work lasts more than seven and a half hours.

After-Day Break: After-Day Break is an interval between two shifts, made up of a period of continuous non-working hours (e.g. 10, 11, 12 …) within a 24-hour period.

Weekly Rest: A minimum break of 24 consecutive hours (1 day) from work within a seven-day period.

Part-Time Employees: In Turkey, if the length of the part-time employee's working time is not distinctly written on his/her contract, then the weekly working time is considered to have been fixed as 20 hours, and in any case, normal weekly working time of a part-time employee must be fixed considerably shorter than a full-time employee’s normal weekly working time which is 45 hours. If the daily working time is not decided in the contract, the employer must engage the employee in work for a minimum of 4 consecutive hours each day.

CHAPTER III

WORKFORCE SCHEDULING PROBLEM

In this section, we provide a formal definition of the problem and list the assumptions.

Problem Definition

We consider a workforce scheduling problem of an office with full time employees, part time employees and supervisors. The supervisors are higher rank employees and the office requires one at duty for any time slot the office is operational. We consider a weekly problem as the overtime for the employees is accounted on a weekly basis. In that aspect, we assume that the week starts at 6:00AM Monday morning, till when we assume that the office is closed, and determine a weekly schedule starting at that time. Most importantly, the problem we consider is a flexible shift problem where each employee has their own individual schedule/shift rather than one or multiple fixed schedule(s) imposed to employees. This aspect of the problem makes the problem considerably more complicated compared to a fixed shift scheduling problem as the combinatorial complexity is significantly higher in the former case. We list characteristics of our problem as well our assumptions below:

Assumptions

- We solve a weekly problem where the planning horizon is divided into intervals with equal lengths, half an hour. The reason for having half-hour intervals is the fact that short breaks of the employees during a working shift is only half an hour.

- At each time slot, there is a certain demand value to be satisfied by the full time and part time employees, but not supervisors. Supervisors are like manager that oversee the operation but do not actually involve in it.
- There is a certain and constant demand satisfying rate for each full and part time employee in a given time slot of half an hour. If the demand (or at least a portion) cannot be satisfied, then it is considered as lost demand. The goal considering the demand is to satisfy a given portion of the entire demand in a week, say 90% as in fill rate.
- The office can only be operated at allowed times, however, the decision of operating the office at a given time slot should be determined for the allowed time slots.
- The full time employees and supervisors receive fixed salaries so their payment are not considered in the objective function whereas the part time employees are paid by the hour, hence their total salary cost is to be minimized along with other cost items.
- Full time employees and supervisors have a daily working hour limit, weekly working hour limit during regular time, and weekly working hour limit including possible overtime. The total overtime cost is one of the cost items that need to be minimized. The part time employees also have daily working hour and weekly working hour limits during regular time but they do not work overtime.
- Between two consecutive shifts, each employee needs to take a long daily break, which should be at least 8 hours. In addition to this, no employee should be assigned to two different shifts in the same calendar day even if the long break

has been given.

- Full time employees and supervisors may be paid taxi cab fare if they get off work during inconvenient times. The cab fare they receive is based not only the time but also the distance between the office and their home. Some do not get cab fare as they live close by. Part time employees do not get cab fare compensation from the company. This is another cost item to be minimized.
- Each employee can specify available times for work for the upcoming week. Some of these specifications might be based on the assignments in the previous week. For instance, a full time employee performing a late night shift on Sunday may not work early on Monday this week. The rest might be based on personal preference. In any case, this available hour restriction should be in line with the other work related rules. For instance, a full time employee may not specify lower number of hours for the upcoming week than the minimum required number of hours due to regulations.
- Each type of employee has minimum shift duration; hence once they start their shift, they should be working for at least a given number of time slots.

Full time employees need one or two short breaks during their shifts. For instance, after working 4 hours, they need half an hour break. If they continue working for a total of 8 or more hours, they need another half an hour break. In other words, they cannot work more than 4 hours without a short break and more than 8 hours without two short breaks. Part time employees do not need short breaks by law. Supervisors do need breaks; however, as they are not actually involved in the operations, we assume that they can give short breaks without specifically assigned one.

CHAPTER IV

MATHEMATICAL MODEL FORMULATION and SOLUTION APPROACH

In this section, we present an integer programming formulation as the solution approach. Before presenting the mathematical model, we first present our parameters and decision variables. The parameters of the problem are listed below:

F : Set of full time employees

P : Set of part time employees

S : Set of supervisors

D : Days in a week

$\tilde{D}$: Days in a week excluding the last day

T : Time slots in a day

$\tilde{T}$: Time slots in a day excluding the last time slot

$DemF$: Demand satisfied by a full time employee in a time slot

$DemP$: Demand satisfied by a part time employee in a time slot

DEM_{dt} : Demand value on day d at the t^{th} time slot $\quad d \in D, t \in T$

OD_{dt} : 1, if office can operate on day d at the t^{th} time slot;
0, otherwise $\quad d \in D, t \in T$

AX_{fdt} : 1, if full time employee f is available for duty on day d at the t^{th} time slot;
0, otherwise $\quad f \in F, d \in D, t \in T$

APX_{pdt} : 1, if part time employee p is available for duty on day d at the t^{th} time slot;
0, otherwise $\quad p \in P, d \in D, t \in T$

ASX_{sdt} : 1, if supervisor s is available for duty on day d at the t^{th} time slot;
0, otherwise $\quad s \in S, d \in D, t \in T$

FDaily: Daily working hour limit on regular time for full time employees

FReg : Weekly working hour limit on regular time for full time employees

FOve : Incremental weekly working hour limit on overtime time for full time employees

PDaily: Daily working hour limit on regular time for part time employees

PReg : Weekly working hour limit on regular time for part time employees

SDaily: Daily working hour limit on regular time for supervisors

SReg : Weekly working hour limit on regular time for supervisors

SOve : Incremental weekly working hour limit on overtime time for supervisors

FOveCost: Overtime cost rate for full time employees

SOveCost: Overtime cost rate for supervisors

$FTaxiCost_f$: Cab fare cost of full time employee *f* $f \in F$

$STaxiCost_s$: Cab fare cost of supervisor *f* $s \in S$

FMinBreak: Minimum number of time slots between two consecutive shifts for a full time employee

PMinBreak: Minimum number of time slots between two consecutive shifts for a part time employee

SMinBreak: Minimum number of time slots between two consecutive shifts for a supervisor

FMinWork: Minimum number of time slots of work between two consecutive breaks for a full time employee

PMinWork: Minimum number of time slots of work between two consecutive breaks for a part time employee

SMinWork: Minimum number of time slots of work between two consecutive breaks for a supervisor

FMaxWorkShortBreak: Maximum number of time slots of work a full time employee can work before giving the first short break

FMaxWorkDoubleBreak: Maximum number of time slots of work a full time employee can work before giving both the first and the second short break

SalaryRate: Hourly rate for the part time employees

The decision variables used in the mathematical are presented below:

X_{fdt} : 1, if full time employee f is on duty on day d at the t^{th} time slot;
0, otherwise $f \in F, d \in D, t \in T$

B_{fdt} : 1, if full time employee f is on a short duty break on day d at the t^{th} time slot;
0, otherwise $f \in F, d \in D, t \in T$

DO_{fd} : 1, if full time employee f has a day-off on day d;
0, otherwise $f \in F, d \in D$

TX_{fd} : 1, if full time employee f takes a taxi-cab from work on day d;
0, otherwise $f \in F, d \in D$

OV_f : Overtime hours for full time employee f $f \in F$

ID_f : Idletime hours for full time employee f $f \in F$

PX_{pdt} : 1, if part time employee p is on duty on day d at the t^{th} time slot;
0, otherwise $p \in P, d \in D, t \in T$

PDO_{pd} : 1, if part time employee p has a day-off on day d;
0, otherwise $p \in P, d \in D$

SX_{sdt} : 1, if supervisor s is on duty on day d at the t^{th} time slot;
0, otherwise $s \in S, d \in D, t \in T$

SDO_{sd} : 1, if supervisor s has a day-off on day d;
0, otherwise $s \in S, d \in D$

TSX_{sd} : 1, if supervisor s takes a taxi-cab from work on day d;
0, otherwise $s \in S, d \in D$

SOV_s : Overtime hours for supervisor s $s \in S$

SID_s : Idletime hours for supervisor s $s \in S$

O_{dt} : 1, if office is open on day d at the t^{th} time slot;
0, otherwise $d \in D, t \in T$

U_{dt} : Unsatisfied demand on day d at the t^{th} time slot; $d \in D, t \in T$

Using these decision variables, the mathematical model proposed for the problem under consideration is as follows:

$$\text{Min} \quad FOveCost \sum_{f \in F} OV_f + SOveCost \sum_{s \in S} SOV_s + \sum_{f \in F} \sum_{d \in D} FTaxiCost_f (TX_{fd}) + \sum_{s \in S} \sum_{d \in D} STaxiCost_s (TSX_{sd}) + SalaryRate \sum_{p \in P} \sum_{d \in D} \sum_{t \in T} PX_{pdt} \tag{1}$$

s.t.

$$\sum_{f \in F} DemF(X_{fdt} - B_{fdt}) + \sum_{p \in P} DemP(PX_{pdt}) + U_{dt} \geq DEM_{dt} \ \forall d \in D, t \in T \tag{2}$$

$$\sum_{d \in D} \sum_{t \in T} U_{dt} \leq 0.1(\sum_{d \in D} \sum_{t \in T} DEM_{dt}) \tag{3}$$

$$O_{dt} \leq OD_{dt} \quad \forall d \in D, t \in T \tag{4}$$

$$\sum_{f \in F} X_{fdt} + \sum_{p \in P} PX_{pdt} + \sum_{s \in S} SX_{sdt} \leq M(O_{dt}) \ \forall d \in D, t \in T \tag{5}$$

$$\sum_{s \in S} SX_{sdt} \geq O_{dt} \ \forall d \in D, t \in T \tag{6}$$

$$X_{fdt} \leq AX_{fdt} \qquad \forall f \in F, d \in D, t \in T \tag{7}$$

$$\sum_{d \in D} \sum_{t \in T} X_{fdt} \leq FReg + FOve \qquad \forall f \in F \tag{8}$$

$$\sum_{d \in D} \sum_{t \in T} X_{fdt} + ID_f \geq FReg \qquad \forall f \in F \tag{9}$$

$$\sum_{d\in D}\sum_{t\in T} X_{fdt} - OV_f \leq FReg \qquad \forall f \in F \tag{10}$$

$$\sum_{t\in T} X_{fdt} \leq FDaily(1- DO_{fd}) \qquad \forall f \in F, d \in D \tag{11}$$

$$\sum_{i\in T, i>t+1} X_{fdi} \leq M - MX_{fdt} + MX_{fd(t+1)} \qquad \forall f \in F, d \in D\backslash\widetilde{D}, t \in \tilde{T} \tag{12}$$

$$\sum_{i=2}^{FMinBreak} X_{f(d+1)i} \leq M - MX_{fdt} + MX_{f(d+1)1} \qquad \forall f \in F, d \in \widetilde{D}, t \in T\backslash\tilde{T} \tag{13}$$

$$\sum_{i\in T, i>t+1} X_{fdi} + \sum_{i\in T, i\leq FMinBreak-|T|+t} X_{f(d+1)i} \leq M - MX_{fdt} + MX_{fd(t+1)} \qquad \forall f \in F, d \in \widetilde{D}, t \in \tilde{T} \tag{14}$$

$$\sum_{d\in D} DO_{fd} = 1 \qquad \forall f \in F \tag{15}$$

$$X_{fdt} - X_{fd(t+1)} \leq TX_{fd} \qquad \forall f \in F, d \in D, t \in \tilde{T} \tag{16}$$

$$FMinWork(X_{fd(t+1)} - X_{fdt}) \leq \sum_{i=t+2}^{\min\{FMinWork+t, |T|\}} X_{fdi} \qquad \forall f \in F, d \in D\backslash\widetilde{D}, t \in \tilde{T} \tag{17}$$

$$FMinWork(X_{f(d+1)1} - X_{fdt}) \leq \sum_{i=2}^{FMinWork} X_{f(d+1)i} \qquad \forall f \in F, d \in \widetilde{D}, t \in T\backslash\tilde{T} \tag{18}$$

$$FMinWork(X_{fd(t+1)} - X_{fdt}) \leq \sum_{i=t+2}^{\min\{FMinWork+t,|T|\}} X_{fdi} + \sum_{i=1}^{\max\{FMinWork-|T|+t,0\}} X_{f(d+1)i} \quad \forall f \in F, d \in \widetilde{D}, t \in \tilde{T} \tag{19}$$

$$3B_{fdt} \leq X_{fd(t-1)} + X_{fdt} + X_{fd(t+1)} \quad \forall f \in F, d \in D, t \in \tilde{T} \tag{20}$$

$$2B_{fdt} \leq X_{fd(t-1)} + X_{fdt} \quad \forall f \in F, d \in D, t \in T \setminus \tilde{T} \tag{21}$$

$$2B_{fdt} \leq X_{fdt} + X_{fd(t+1)} \quad \forall f \in F, d \in D, t = 1 \tag{22}$$

$$\sum_{i=t}^{\min\{FMaxWorkShortBreak+t,|T|\}} (X_{fdi} - B_{fdi}) \leq FMaxWorkShortBreak \quad \forall f \in F, d \in D \setminus \widetilde{D}, t \in T \tag{23}$$

$$\sum_{i=t}^{\min\{FMaxWorkShortBreak+t,|T|\}} (X_{fdi} - B_{fdi}) + \sum_{i=1}^{\max\{FMaxWorkShortBreak+t-|T|,0\}} (X_{f(d+1)i} - B_{f(d+1)i}) \leq FMaxWorkShortBreak \quad \forall f \in F, d \in \widetilde{D}, t \in T \tag{24}$$

$$\sum_{i=t}^{\min\{FMaxWorkDoubleBreak+t,|T|\}} (X_{fdi} - B_{fdi}) \leq FMaxWorkDoubleBreak \quad \forall f \in F, d \in D \setminus \widetilde{D}, t \in T \tag{25}$$

$$\sum_{i=t}^{\min\{FMaxWorkDoubleBreak+t,|T|\}} (X_{fdi} - B_{fdi}) + \sum_{i=1}^{\max\{FMaxWorkDoubleBreak+t-|T|,0\}} (X_{f(d+1)i} - B_{f(d+1)i}) \leq FMaxWorkDoubleBreak - 1 \quad \forall f \in F, d \in \widetilde{D}, t \in T \tag{26}$$

$$PX_{pdt} \leq APX_{pdt} \quad \forall\, p \in P, d \in D, t \in T \tag{27}$$

$$\sum_{d\in D}\sum_{t\in T} PX_{pdt} \leq PReg \quad \forall p \in P \tag{28}$$

$$\sum_{t\in T} PX_{pdt} \leq PDaily(1 - PDO_{pd}) \quad \forall p \in P, d \in D \tag{29}$$

$$\sum_{i\in T, i>t+1} PX_{pdi} \leq M - MPX_{pdt} + MPX_{pd(t+1)} \quad \forall p \in P, d \in D\backslash\widetilde{D}, t \in \tilde{T} \tag{30}$$

$$\sum_{i=2}^{PMinBreak} PX_{p(d+1)i} \leq M - MPX_{pdt} + MPX_{p(d+1)1} \quad \forall p \in P, d \in \widetilde{D}, t \in T\backslash\tilde{T} \tag{31}$$

$$\sum_{i\in T, i>t+1} PX_{pdi} + \sum_{i\in T, i\leq PMinBreak-|T|+t} PX_{f(d+1)i} \leq M - MPX_{pdt} + MPX_{pd(t+1)} \quad \forall p \in P, d \in \widetilde{D}, t \in \tilde{T} \tag{32}$$

$$\sum_{d\in D} PDO_{pd} = 1 \quad \forall p \in P \tag{33}$$

$$PMinWork(PX_{pd(t+1)} - PX_{pdt}) \leq \sum_{i=t+2}^{\min\{PMinWork+t,|T|\}} PX_{pdi} \quad \forall p \in P, d \in D\backslash\widetilde{D}, t \in \tilde{T} \tag{34}$$

$$PMinWork(PX_{p(d+1)1} - PX_{pdt}) \leq \sum_{i=2}^{PMinWork} PX_{p(d+1)i} \quad \forall p \in P, d \in \widetilde{D}, t \in T\backslash\tilde{T} \tag{35}$$

$$PMinWork(PX_{pd(t+1)} - PX_{pdt}) \leq \sum_{i=t+2}^{\min\{PMinWork+t,|T|\}} PX_{pdi} + \sum_{i=1}^{\max\{PMinWork-|T|+t,0\}} PX_{p(d+1)i} \quad \forall p \in P, d \in \widetilde{D}, t \in \tilde{T} \tag{36}$$

$$SX_{sdt} \leq ASX_{sdt} \quad \forall\, s \in S, d \in D, t \in T \tag{37}$$

$$\sum_{d\in D}\sum_{t\in T} SX_{sdt} \leq SReg + SOve \quad \forall s \in S \tag{38}$$

$$\sum_{d\in D}\sum_{t\in T} SX_{sdt} + SID_s \geq SReg \quad \forall s \in S \tag{39}$$

$$\sum_{d\in D}\sum_{t\in T} SX_{sdt} - SOV_s \leq SReg \quad \forall s \in S \tag{40}$$

$$\sum_{t\in T} SX_{sdt} \leq SDaily(1 - SDO_{sd}) \quad \forall s \in S, d \in D \tag{41}$$

$$\sum_{i\in T, i>t+1} SX_{sdi} \leq M - MSX_{sdt} + MSX_{sd(t+1)} \quad \forall s \in S, d \in D\backslash\widetilde{D}, t \in \tilde{T} \tag{42}$$

$$\sum_{i=2}^{SMinBreak} SX_{s(d+1)i} \leq M - MSX_{sdt} + MSX_{s(d+1)1} \quad \forall s \in S, d \in \widetilde{D}, t \in T\backslash\tilde{T} \tag{43}$$

$$\sum_{i \in T, i > t+1} SX_{sdi} + \sum_{i \in T, i \leq SMinBreak - |T| + t} SX_{s(d+1)i} \leq M - MSX_{sdt} + MSX_{sd(t+1)} \quad \forall s \in Ss, d \in \widetilde{D}, t \in \tilde{T} \tag{44}$$

$$\sum_{d \in D} SDO_{sd} = 1 \quad \forall s \in S \tag{45}$$

$$SX_{sdt} - SX_{sd(t+1)} \leq TSX_{sd} \quad \forall s \in S, d \in D, t \in \tilde{T} \tag{46}$$

$$SMinWork(SX_{sd(t+1)} - SX_{sdt}) \leq \sum_{i=t+2}^{\min\{SMinWork+t, |T|\}} SX_{sdi} \quad \forall s \in S, d \in D \backslash \widetilde{D}, t \in \tilde{T} \tag{47}$$

$$SMinWork(SX_{s(d+1)1} - SX_{sdt}) \leq \sum_{i=2}^{SMinWork} SX_{s(d+1)i} \quad \forall s \in S, d \in \widetilde{D}, t \in T \backslash \tilde{T} \tag{48}$$

$$SMinWork(SX_{sd(t+1)} - SX_{sdt}) \leq \sum_{i=t+2}^{\min\{SMinWork+t, |T|\}} SX_{sdi} + \sum_{i=1}^{\max\{SMinWork-|T|+t, 0\}} SX_{s(d+1)i} \quad \forall s \in S, d \in \widetilde{D}, t \in \tilde{T} \tag{49}$$

$$X_{fdt}, B_{fdt} \in \{0,1\} \quad \forall f \in F, d \in D, t \in T \tag{50}$$

$$TX_{fd}, DO_{fd} \in \{0,1\} \quad \forall f \in F, d \in D \tag{51}$$

$$OV_f, ID_f \geq 0 \quad \forall f \in F \tag{52}$$

$$PX_{pdt} \in \{0,1\} \quad \forall p \in P, d \in D, t \in T \tag{53}$$

$$PDO_{pd} \in \{0,1\} \quad \forall p \in P, d \in D \tag{54}$$

$$SX_{sdt} \in \{0,1\} \qquad \forall s \in S, d \in D, t \in T \tag{55}$$

$$TSX_{sd}, SDO_{sd} \in \{0,1\} \qquad \forall s \in S, d \in D \tag{56}$$

$$SOV_s, SID_s \geq 0 \qquad \forall s \in S \tag{57}$$

$$O_{dt}, U_{dt} \in \{0,1\} \qquad \forall d \in D, t \in T \tag{58}$$

In this model, the objective (1) is to minimize the sum of all relevant costs for the operations. Constraints (2) and (3) make sure that at least 90% of the total demand in a week is satisfied. Constraint (4) imposes that the office is closed out of the operating hours. Constraint (5) makes sure that nobody is working when the office is closed. Constraint (6) guarantees that if office is open, then there is at least one supervisor working to oversee the operations. Constraint (7) states that the full time employees can only work on their available times. Constraints (8), (9), and (10) guarantee that the weekly working hour limit is satisfied by the full time employees. Similarly, Constraint (11) guarantees that the daily working hour limit is satisfied by the full time employees and in their off-day they cannot work. Constraints (12), (13) and (14) force that the full time employees have at least the minimum amount break between two consecutive shifts. Note that an employee cannot be assigned to two different shifts in the same calendar day, which is also restricted by these constraints. Constraint (15) makes sure that full time employees get one day-off in a week. Constraint (16) guarantees that the full time employees will take a cab after work, if they get off work afterhours. Note that for employees living close by the office, even though this binary variable might be set to one, the cab fare parameter is set to zero, hence there will be no cost incurred for the company. Constraints (17), (18) and (19) force that the full time employees should work at least the minimum amount required between two consecutive breaks. Constraints (20), (21) and (22) make sure that the short break is allowed only when the full time employee is working and it cannot be at the first or the last time slot of the shift of the employee. Constraints (23), (24), (25) and (26) make sure that the full time employee should not continue working without a break more than a certain amount of time and similarly should not continue working without a second break if the total work time exceeds a certain amount. Constraint (27) states that the part time employees can only work on their available times. Constraint (28) guarantees that the weekly working hour limit is satisfied by the part time employees. Similarly, Constraint (29) guarantees that the daily working hour limit is satisfied by the part time employees and in their off-day they cannot work. Constraints (30), (31), and (32) force that the part time employees have at least the minimum amount break between two consecutive shifts. Note that an employee cannot be assigned to two different shifts in the same calendar day, which is also restricted by these constraints. Constraint (33) makes sure that part time employees get one day-off in a week. Constraints (34), (35) and (36) force that the part time employees should work at least the minimum amount required between two consecutive breaks. Constraint (37) states that the supervisors can only work on their available times. Constraints (38), (39), and (40) guarantee that the weekly working hour limit is satisfied by the supervisors. Similarly, Constraint (41) guarantees that the daily working hour limit is satisfied by the supervisors and in their off-day they cannot work. Constraints (42), (43), and (44) force that the supervisors have at least the minimum amount break between two consecutive shifts. Note that an employee cannot be assigned to two different shifts in the same calendar day, which is also restricted by these constraints. Constraint (45) makes sure that supervisors get one day-off in a week. Constraint (46) guarantees that the supervisors will take a cab after work, if they get off work afterhours. Constraints (47), (48) and (49) force that the full time employees should work at least the minimum amount required between two consecutive breaks. Finally, the rest of the constraints are binary and non-negativity restrictions.

We solve the model presented above to determine the minimum cost solution to assign individual work schedules for all of the employees while covering at least a certain fraction of the demand. This exact solution approach we propose would be very effective in solving problem however it may not be scalable for larger instances of the problem. In such cases effective decomposition techniques might be employed to solve the problem. One other potential method to use in larger instances is to solve the problem using a rougher time scale (i.e. one time slot is equal to one hour or two, four hours etc.) and then try to fine tune this solution to handle short breaks and other time sensitive considerations.

CHAPTER V

COMPUTATIONAL STUDY and FINDINGS

In this section, we test the effectiveness of the proposed exact solution method on randomly generated instances. We have generated 10 instances, each with 15 full time employees, 5 part time employees and 3 supervisors. We assume that we have 7 days in a week and the workplace has demand 18 hours a day since we assume that the workplace is closed between 12:00AM and 6:00AM. Demand is randomly generated between 0 and 10 for each 30-min interval and these values are adjusted for the specific time of the day (peak demand is in the afternoon and the evening). Each full-time and part time employee can handle 1.5 times the base demand value in a 30-min interval. Therefore, we require at most 7 working employees in a given time slot (clearly excluding the ones on a short break). The available times of the employees are randomly generated on a weekly time slot basis, but on average we tried to make each full time employee and each supervisor to be available at least 40 hours at most 60 hours in a week. Note that this is not the assigned work shifts for the employees, just the available times. For part time employees, these values are reduced in half.

Daily working hour limit for the full time employees and the supervisors is 12 hours (including the breaks) and the weekly working hour limit is 48 hours (again including the breaks). On top of 48 hours, each full time employee and each supervisor can work a total of 21 hours, where he/she is paid overtime. Note that this 21-hour work does not include short breaks. The minimum work hours in a shift are 6 hours for the full time employees and the supervisors. Daily working hour limit for the part time employees 6 hours and they do not get a break during this 6-hours. The weekly working hour limit is 30 hours and they are not paid overtime. The minimum work hours in a shift are 2 hours for the part time employees.

The full time employees and the supervisors have fixed salaries and therefore that cost figure is not considered while solving this problem. Hourly salary for the part time employees is $16 and the hourly overtime pay is $19 for both full time employees and the supervisors. The cab fare costs of the employees depend on where they live. Some assumed to live very close hence do not get cab fare compensation and approximately one-third of the employees are assumed to live in the near vicinity. The rest of the employees do get a cab fare compensation if the get off work afterhours (that will be between 8PM and 12AM). The cab fare cost is randomly generated between $30 and $40.

The minimum break between two consecutive shifts for all types of employees is 8 hours. In addition to this, the employees cannot be assigned two different shifts on the same calendar day. Full time employees need a half-hour break after working consecutively for 4 hours and need a second half-hour break if they work more than 8 hours. Note that the supervisors do not need these short breaks as they do not actively work in their assigned shifts all the time and hence they are assumed to take short breaks when the time is convenient.

The proposed algorithm is implemented using C++ and CPLEX Concert Technology. All the computational experiments are carried out on a 64-bit Windows Server with two 2.4 Ghz Intel Xeon CPU’s and 24 GB RAM. The time limit for the run is set to one hour and after the 75% of the time limit, CPLEX is set to polish the best known result. As the problem definition is quite specific, we could not find a benchmark proposed in the literature for our problem. Therefore, our criterion for assessing the performance of the proposed approach is the optimality gap calculated by CPLEX.

In Table 1, we present the computational results over the ten randomly generated instances. Each row corresponds to a specific instance of the problem and the last row is the average values over the ten instances. The first column presents the final objective function value, the second column presents the total cab fare compensation cost, the third column presents the total overtime cost, the fourth column presents the total salary cost of the part time employees and the last column presents the optimality gap values. Note that the computational times are not presented as we pre-specify the computational time limit to one hour.

Table 1: Computational Results over Ten Randomly Generated Instances

Instance	Obj. Fun.	Cab Fare Cost	Overtime Cost	Part Time Salary Cost	Opt. Gap
1	466.25	367.61	0.00	98.64	33.88
2	1003.47	288.33	0.00	715.14	22.31
3	979.54	437.02	0.00	542.52	11.22
4	629.58	267.90	0.00	361.68	28.66
5	290.59	290.59	0.00	0.00	24.24
6	386.55	255.03	0.00	131.52	29.99
7	235.90	235.90	0.00	0.00	20.78
8	159.46	159.46	0.00	0.00	0.00
9	128.97	128.97	0.00	0.00	0.00
10	848.66	411.31	9.92	0.00	22.71
Ave	512.90	284.21	0.99	184.95	19.38

As can be observed from the computational results, the company basically has to pay the cab fare compensation in order to cover the demand during afterhours. On average that is the dominating cost item for the company. Due to the relative values of the cost coefficients, the company prefers using part time employees rather than paying overtime for the full time employees, which is observed in the computational results. Nevertheless, in one of the instances the company pays overtime as it is cheaper to pay overtime for a very short amount of time. The optimality gap values are quite varied. The smallest optimality gap value is equal to 0% whereas the largest gap value is 33.88%. The average optimality gap value is 19.38%. Even though 0% optimality gap instances require no part time employees as expected, there does not exist a direct correlation between the part time employee salary cost and the optimality gap. For example, Instance 3 has the second largest part time salary cost however, it has the third smallest optimality gap value as well (counting the 0% optimality gap value instances twice).

CHAPTER VI

CONCLUSION

In this thesis, we study a workforce scheduling problem with distinct characteristics, such as supervisor requirements, cab fare compensation and complicated working hour rules and regulations. Most importantly, fixed-time shift schedules, such as 8AM-4PM, 4PM-12AM, 12AM-8AM do not work in this particular problem due to the dynamic nature of the problem where the demand changes in each time slot of 30-minutes length and this fluctuation may be quite significant. The challenge in this problem is to satisfy the complex workforce scheduling rules in such a dynamic environment. To this end, we propose an exact solution based approach and model the problem as a mixed integer linear program and solve it using commercial solvers. Based on the computational study, we conclude that our proposed approach is quite effective in solving this dynamic workforce scheduling problem.

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VITA

Ersin Koç was born in Malatya, Turkey, on August 1, 1988. Specializing in Finance, he received his undergraduate degree in Business Administration in 2013 from Özyeğin University. He joined the graduate program at Özyeğin University as a M.Sc. student of Industrial Engineering under the supervision of Associate Professor Okan Örsan Özener in 2014. His current research interests are workforce scheduling, planning and cost minimization. Since obtaining undergraduate degree, he has been working for Turkish Airlines as a Marketing and Sales Specialist.