Annals of Operations Research 127, 145–175, 2004

Survey, Categorization, and Comparison of Recent Tour Scheduling Literature

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Abstract. The employee tour scheduling problem involves the determination of both work hours of the day and workdays of the week for each employee. This problem has proven difficult to solve optimally due to its large size and pure integer nature. During the last decade, numerous approaches for modeling and solving this problem have been proposed. In this paper, employee tour scheduling literature published since 1990 is reviewed and classified. Solution techniques are classified into ten categories: (1) manual solution, (2) integer programming, (3) implicit modeling, (4) decomposition, (5) goal programming, (6) working set generation, (7) LP-based solution, (8) construction and improvement, (9) metaheuristics, and (10) other methods. The objective is to identify broad classifications, present typical mathematical models, compare the different methods, and identify future research directions.

Keywords: workforce scheduling, staffing, labor management, mathematical programming, optimization, heuristics

Introduction

Today's economy is characterized by fast growth in the service sector, which tends to be labor intensive (Bechtold, Brusco and Showalter, 1991). Therefore, it is now more important to effectively utilize human resources, which are generally the most expensive resources for the majority of organizations. Effective labor scheduling can reduce the cost of the human resources and also improve customer service and increase employee satisfaction. Numerous approaches have been published in the literature for dealing with different versions of workforce scheduling problems.

Baker (1976) classifies labor scheduling problems into three types: (1) shift, or time-of-day, scheduling, (2) days-off, or days-of-week, scheduling, and (3) tour scheduling, which combines the first two types. Baker (1976), Tien and Kamiyama (1982), Bedworth and Bailey (1987), and Nanda and Browne (1992) provide comprehensive surveys of literature on all these types up to 1990. In this survey, the primary focus is on tour scheduling publications during the 1990–2001 period. This survey excludes the special cases identified by Nanda and Browne (1992, pp. 249–254) as nonstandard work schedules, namely: nurse scheduling, transit operator scheduling, airline crew scheduling, telecommuting, and flexiyear (annualized hours).

Workforce tour scheduling is a practical problem for organizations that operate seven days a week, more than one shift a day, such as hotels, police stations, and airlines.

Naturally, employees must be given daily and weekly breaks. Therefore, employees must be assigned to specific days off during each week, and specific hours off during each day. In other words, we need to specify the particular tour (i.e., the hours of the day and days of the week) in which each employee must work. The objective is to determine the number of employees assigned to each work tour, in order to satisfy labor demands for each work hour of each day at minimum cost or with minimum workforce size.

The complexity and size of tour scheduling problems depend on a number of factors relevant to workforce structure and work rules. The workforce can be homogeneous (one type of full-time employee only) or mixed (several types of full-time and part-time employees). Each type of employees may be classified according to skill level, learning rate, wage, availability, and work hours. The complexity of the problem is profoundly affected by the duration of the minimum planning interval, which may range from 15 min to 8 h. Tour scheduling problems are classified as continuous if the daily work period is 24 h, and discontinuous if the work period is less than 24 h.

Work rules define allowable work schedules in terms of features such as: (1) allowable shift starting times, (2) the minimum and maximum length of each shift, (3) the frequency and duration of meal and rest breaks, (4) the minimum rest period between shift change, (5) the operating hours per day, (6) the number of workdays per week, (7) limits on the number of consecutive workdays, and (8) shift rotation. Other complicating factors include labor demand patterns, employee preferences, seniority rules, and fairness in assigning employees to schedules.

According to Bechtold, Brusco and Showalter (1991), objective function criteria suggested in tour scheduling literature include: (1) total labor hours scheduled, (2) total number of employees, (3) labor costs, (4) unscheduled labor costs, (5) customer service, (6) overstaffing, (7) understaffing, (8) number of schedules with consecutive days off, (9) number of different work schedules utilized, and (10) some combination of the above. Additional objectives also used in tour scheduling literature include the following: (11) net present value of profit, (12) employee satisfaction, (13) consistent employee workloads, and (14) fair assignment of employees to schedules.

Subsequent sections of this paper are organized as follows. First, a sample of typical mathematical programming formulations is presented. Then, the various solution methods are classified and techniques under each category are surveyed. Subsequently, the features of each technique are tabulated to facilitate comparison. In the final section, suggestions for future research are made.

1. Typical mathematical programming formulations

The various employee tour scheduling approaches in the literature have many different objectives and assumptions, and therefore a wide variety of mathematical models. Easton and Mansour (1999) attempt to unify many of these models into a single one for deterministic and stochastic labor scheduling. The purpose of this section is to present a sample of three commonly used formulations of the problem, namely: set covering, goal programming, and implicit modeling.

In the basic tour scheduling problem, a homogeneous workforce is employed, all tours have the same cost, and the objective is to minimize the number of employees. The integer programming (IP) model of the basic tour scheduling problem, which is based on the general set-covering model developed by Dantzig (1954), is given as follows:

$$\text{minimize } W = \sum_{j=1}^{J} x_j \tag{1}$$

subject to

$$\sum_{j=1}^{J} a_{ij} x_j \geqslant r_i, \qquad i = 1, 2, \ldots, I, \tag{2}$$

$$x_j \geqslant 0 \text{ and integer}, \quad j = 1, 2, \ldots, J, \tag{3}$$

where

W = workforce size, i.e., total number of employees assigned to all J tours,
x_j = number of employees assigned to weekly tour j,
a_{ij} = 1 if time i is a work period for tour j, 0 otherwise,
r_i = minimum number of employees required in time period i,
I = number of time periods to be scheduled over the week,
J = number of work tours to be considered.

Easton and Rossin (1996) develop a stochastic goal programming (GP) model for a mixed workforce consisting of E categories, with penalties for overstaffing and understaffing. Labor demands r_i are either calculated from probability distributions to satisfy given service levels or set to deliver the best economic service levels. In the GP model, the objective function (1) and demand constraints (2) are transformed as follows:

$$\text{minimize } Z = \sum_{e=1}^{E} \sum_{j \in J_e} C_j x_j + \sum_{i=1}^{I} \left(u_i d_i^- - o_i d_i^+ \right) \tag{4}$$

subject to

$$\sum_{e=1}^{E} \sum_{j \in J_e} a_{ij} x_j + d_i^- - d_i^+ = r_i, \quad i = 1, 2, \ldots, I, \tag{5}$$

where

Z = total labor cost over I time periods,
C_j = cost of assigning one employee to tour j, $j \in J_e$,
J_e = set of feasible tours for employee category e, $e = 1, \ldots, E$,
d_i^+, d_i^- = labor understaffing and overstaffing in period i, respectively,
u_i, o_j = penalty for understaffing and overstaffing in period i, respectively.

The implicit tour scheduling IP model developed by Jacobs and Brusco (1996), which requires substantially fewer variables than Dantzig's (1954) set-covering model, is represented as follows:

$$\text{minimize} \sum_{s=1}^{S}\sum_{j=1}^{J} x_{sj} \tag{6}$$

subject to

$$\sum_{s=1}^{S}\sum_{h=1}^{H} \alpha_{ish} y_{dsh} \geqslant r_{id}, \qquad i = 1, 2, \ldots, I, d = 1, 2, \ldots, D, \tag{7}$$

$$\sum_{h=1}^{H} y_{dsh} - \sum_{j=1}^{J} \beta_{dj} x_{sj} = 0, \quad d = 1, \ldots, D, s = 1, \ldots, S, \tag{8}$$

$$x_{sj}, y_{dsh} \geqslant 0 \text{ and integer}, \qquad \text{for all } d, j, h, s, \tag{9}$$

where

α_{ish} = 1 if period i is a work period in a shift in start-time band s beginning in hour h, 0 otherwise,
β_{dj} = 1 if day d is a work day for days-off pattern j, 0 otherwise,
x_{sj} = number of employees assigned to start-time band s and days-off pattern j,
y_{dsh} = number of employees assigned to a shift on day d in start-time band s beginning in period h,
r_{id} = minimum number of employees required in time period i on day d,
S = number of start-time bands,
J = number of days-off patterns,
H = number of shift start times per start-time band,
I = number of planning time periods per operating day,
D = number of work days per operating week (7 for continuous operations).

2. Classification of tour scheduling approaches

There are many possibilities for classifying the various tour scheduling studies in the literature. For example, distinction could be made between methods that focus on the left-hand side of demand constraints (2) and those that focus on the right-hand side. Left-hand methods take the labor demands as given and try to optimize the models and procedures needed to satisfy these demands. Right-hand methods try to analyze labor demand values and characteristics, such as the nonlinear relationship between the value and the staffing level in each period, and the dependence and overlap of the staffing levels of successive periods. Thompson (1998a, 1998b, 1999a, 1999b) discusses these and several related issues in a four-paper series on workforce scheduling.

Another distinction could be made between papers that evaluate alternative scheduling policies and papers that develop new scheduling methods, or between application papers and theoretical papers. Scheduling methods themselves could be classified into special-purpose methods and general-purpose methods, or into optimal and heuristic approaches. Alternatively, papers could be classified according to the particular *problem* that is solved instead of the *solution method* that is applied. In this survey, papers are classified on the basis of the solution method because: (1) it is the classification scheme used by previous researchers, and (2) it provides a reasonable spread of papers into categories.

Bechtold, Brusco and Showalter (1991) identify two categories for heuristic tour scheduling approaches: linear programming (LP) based and construction. Easton and Rossin (1991b), Brusco and Jacobs (1993a), and Brusco and Johns (1996) respectively add the categories of decomposition (two-phase solution), working set generation, and implicit modeling. Considering all the various methods in the literature, in light of the previous categorizations, the following classification of tour scheduling approaches is proposed:

1. Manual solution (Mn),
2. Integer Programming (IP),
3. Implicit modeling (Im),
4. Decomposition (Dc),
5. Goal Programming (GP),
6. Working set generation (Ws),
7. LP-based solution (LP),
8. Construction/Improvement (CI),
9. Metaheuristics (Mh),
10. Other methods (Ot).

The above approaches are not necessarily stand-alone solution techniques; often, a number of approaches must be combined together in order to obtain a solution. The first two categories, and to some extent the third, can be considered as optimal solution approaches, while the remaining categories can be considered as heuristic solution approaches.

3. Manual solution

It is perhaps unexpected to learn that manual solutions exist for the notoriously hard employee tour scheduling problem. However, optimal and heuristic manual solutions have been devised for highly simplified versions of this problem. Simplifying assumptions include: only three starting times (three shifts) per day, no breaks, constant demand for all days of the week, and homogeneous workforce.

Hung and Emmons (1993), Burns and Narasimhan (1999), Hung (1993, 1994a, 1994b, 1997a, 1997b), Narasimhan (2000), and Alfares (2001) consider different combinations of the following characteristics for the same basic problem: number of employee categories, pattern of labor demands, limit on work-stretch length, constraints on weekend work frequency, and number of work days per week. Narasimhan (2000) provides a table for comparing all these manual approaches. Chew (1991) and Laporte (1999) also develop manual approaches but for another problem, which is multiple-week rotating workforce tour scheduling.

Hung and Emmons (1993) develop optimal algorithms for 3, 4 workweek scheduling of a mixed workforce. The 3, 4 workweek schedule has a 2-week cycle, in which each employee works 4 days in one week and 3 days in the other week. The multiple-shift, hierarchical-workforce model allows shift rotation and employee substitution. The objective is to minimize total labor cost assuming: (1) labor demands are constant throughout the week for each shift, (2) each employee must receive at least A out of B weekends off, (3) the work stretch cannot exceed 5 days, and (4) there are m types of employees. Two optimal algorithms are presented: one for $A/B \leqslant 1/2$ and the other for $A/B \geqslant 1/2$. Hung (1994b) presents a similar technique for the 3–4 workweek scheduling problem with work-stretch constraints.

Focusing on compressed workweek scheduling, Hung (1993, 1994a), respectively, models and optimally solves the 3-day and the 4-day workweek multiple-shift scheduling problem for a homogeneous workforce under the same assumptions. The objective is to minimize the workforce size given two levels of labor demands for shift j: D_j for weekdays and E_j for weekends, where $D_j \geqslant E_j$, $j = 1, 2, 3$. For both problems, the minimum workforce size is first determined, and then feasible employee shift and days-off assignments are constructed. Hung (1997a) extends his previous work by incorporating phase delay features under the 5-day workweek and under the 3, 4-day workweek. Phase delay in shift change means that the next shift always starts later than the current one. This clockwise (forward) direction in shift work results in better employee health and higher satisfaction. Hung (1997b) develops a manual scheduling algorithm for another specialized tour scheduling situation, known as the Baylor plan. According to this plan, three 8-hour shifts are assigned for each weekday, and two 12-hour shifts are assigned for each weekend day.

Burns and Narasimhan (1999) extend the work of Hung (1993, 1994a) by restricting the length of maximum work stretches. Their manual optimal algorithm divides the problem into two cases according to the relationship between W and E, eliminating one-day work stretches in one case and minimizing their occurrences in the other. Constraints are imposed on the ratio of weekends off, length of the work stretch, and the transition time (number of days off) required when changing shifts. Narasimhan (2000) presents another manual solution technique for multiple-shift three-day or four-day workweek scheduling of a hierarchical workforce. The same assumptions used by

Hung (1993, 1994a) hold, except that the workforce is not homogeneous but composed of several employee categories.

Chew (1991) schedules full-time apron crews at an airport terminal using a two-stage procedure that minimizes the total number of teams required. First, the problem is formulated as an integer program (IP) whose special structure is utilized to manually determine the minimum manpower requirements for each shift. Then, crews are assigned in the form of a cyclic roster to each work tour in order to meet these requirements. Chew assumes a scheduling cycle of Q weeks in which Q crews rotate on weekly assignments, giving each crew at least one day off per week.

Laporte (1999) describes the basic arithmetic principles governing the development of rotating employee schedules. He argues that these principles combined with operating rules are too rigid for many practical situations, necessitating bending some of the rules in order to obtain a workable schedule, making the design of these schedules more of an art than science. He then suggests a number of manual approaches for achieving this aim, including the use of shift breaks, extended and overlapping shifts, and relief teams.

Alfares (2001) develops an integer programming models to determine the optimum staffing levels and associated employee schedules at an industrial security gate. The staffing requirements of the gate at different times of each day of the week are determined as a function of the number of open lanes, the amount of traffic, and allowances for employee breaks. Although IP can be used to obtain the optimum solution of the model, the structure of the problem allows it to be manually solved by inspection.

4. Integer programming

Since the tour scheduling problem is formulated as an IP model, it seems only natural to use IP approaches for its solution. However, in most practical cases the size of the problem makes IP inefficient for obtaining the optimum solution. Approaches used to overcome this difficulty include using advanced starting continuous solutions, LP cuts, using heuristic rules, sequentially adding constraints, and utilizing special problem structure. Different implementations of IP approaches are used by Vakharia, Selim and Husted (1992), Brusco and Johns (1995a, 1996), Alfares (1999), Brusco (1998), Brusco and Jacobs (2001), Beaumont (1997), and Lin, Lai and Hung (2000).

Vakharia, Selim and Husted (1992) develop an IP model and a heuristic to maximize part-time employee work-time preferences and minimize their wages. Utilizing the model's transportation problem structure, an initial solution is obtained by IP. A heuristic method then modifies the solution by removing the gaps in each employee's schedule and allowing labor demands to be exceeded in each period. The approach is illustrated with actual data from a restaurant and a computer laboratory.

Brusco and Johns (1995a) evaluate the performance of different types of heuristics under different types of actual and synthetic labor demand patterns. Four synthetic demand parameters (mean, amplitude, shape, and smoothness) are used. Since the model contains only 56 integer variables, optimum solutions are easily obtained by IP. In a subsequent study, Brusco and Johns (1996) take advantage of the problem structure by sequentially restricting subsets of tours to be integer valued. First, they restrict tours with shifts starting in the first hour of the day, then tours with shifts ending in the last hour of the day, and finally tours in the middle of the day. The heuristic outperforms the LP-based heuristics of both Keith (1979) and Morris and Showalter (1983).

Brusco (1998) develops an optimum solution method using the dual all-integer cutting plane with an LP objective cut and sophisticated source row selection rules. Advanced starting solutions based on the LP-relaxation method by Hanna and Austin (1985) are utilized. A computational study using four sets of tour scheduling test problems shows that this method significantly outperforms branch and bound. Brusco and Jacobs (2001) use the same solution method in an experimental study to evaluate the effect of starting-time decisions in continuous tour scheduling. Using two workweek alternatives, three starting time limitations, and 45 demand patterns, the minimum workforce size is found to be associated with only a very small proportion of possible starting times.

Beaumont (1997) describes a multiple-week continuous tour scheduling model for a mixed workforce. A simplified mixed IP formulation using especially ordered sets is presented to make the optimum solution possible. The procedure is applied to a real case study, in which demand varies with the hour of day and the day of week, saving 17% of the labor cost. Alfares (1999) uses an IP model to find the minimum cost schedule of aircraft maintenance crews that satisfies varying labor demands for each shift and each day of the week.

Lin et al. (2000) use IP in a three-stage methodology for scheduling a call center's employees. First, regression and simulation are used to convert the number of incoming calls into hourly staffing requirements. Next, mixed IP is used to determine daily staff and meal break assignments. Finally, an extended version of Burns and Carter (1985) algorithm is used to assign shifts and construct the monthly roster.

5. Implicit modeling

In order to reduce the number of decision variables, Bechtold and Jacobs (1990, 1991) and Thompson (1995a) use implicit modeling of breaks in shift scheduling. Instead of defining a variable for each shift with a specific break, shift *types* are considered as variables. A shift type is identified by a start time, a shift length, and a break window within which the break must begin. This leads to a large reduction in the size of the model, since a single variable is used to represent all shifts of the same type regardless of break starting time. However, a number of conditions must be added to ensure that each shift receives a break within its designated window. The implicit modeling of breaks is applied to tour scheduling by Bailey (1985), Thompson (1992), Jacobs and Bechtold (1993a, 1993b), Jarrah, Bard and deSilva (1994), Jacobs and Brusco (1996), Isken and Hancock (1998), and Brusco and Jacobs (2000).

Thompson (1992) presents two implicit IP models and solves them by an LP-based heuristic. Jacobs and Bechtold (1993a) schedule a homogeneous workforce with increased flexibility in terms of shift length, tour length, meal break, shift start, nonconsecutive days off, and part-time labor. Higher flexibility leads to greater productivity, by a closer matching of labor requirements to employees assigned. However, high flexibility results in an extremely large number of variables (an average of 64 millions for 128 test problems). Implicit modeling is used to substantially reduce the number of variables in order for the model to be solved. Since the implicit model does not provide the timing of breaks and shifts, procedures are developed to make the appropriate assignments.

Jacobs and Bechtold (1993b) use implicit modeling in order to examine the effect of scheduling flexibility and labor demand variation on labor utilization. Six labor scheduling flexibility alternatives, three labor demand characteristics, and four daily/weekly labor demand distributions are considered. The objective is to minimize total labor hours assigned such that shifts are either 5 or 9 h, days are less than 24 h, and tours are either 2 or 5 days. Break-placement flexibility, shift-length flexibility, and labor demand amplitude are found to be among the most significant factors impacting labor utilization.

Jarrah, Bard and deSilva (1994) use aggregate (implicit) variables to decompose discontinuous tour scheduling problems into seven daily shift scheduling subproblems. A partial enumeration scheme and a heuristic for ensuring feasibility, which converge rapidly to near-optimum solutions, are used to find upper and lower bounds on the number of tours. To illustrate real world practicality, the model is applied at a general mail facility. The model allows for full and part-time employees, different shift lengths and break placements, four- and five-day workweeks, and minimum full-time to part-time ratios. Isken and Hancock (1998) use an implicit tour scheduling model for scheduling full- and part-time hospital employees. Their model has been in use in a large hospital since the early 1990s.

The implicit tour scheduling model developed by Jacobs and Brusco (1996) restricts shift start times each day to a given range (start-time band). This model is much more compact than the general set-covering model, allowing realistically sized problems to be solved (often optimally) by IP. The model is applied to schedule toll collectors on the Illinois Tollway, producing an average reduction of 5% in the workforce size. Integrating and extending the models of Bechtold and Jacobs (1990) and Jacobs and Brusco (1996), Brusco and Jacobs (2000) incorporate both start-time and meal-break flexibility in an implicit model, which they apply to continuous tour scheduling of employees at a call center.

6. Decomposition

Decomposition (or two-phase) approaches break the large tour scheduling problem into a number of smaller and easier subproblems. The tour scheduling problem integrates shift scheduling with days-off scheduling. Therefore, a popular approach to decompose the tour scheduling problem is to break it down into shift scheduling and days-off scheduling subproblems. Usually, the first phase involves decomposing the tour scheduling problem into seven shift scheduling problems (one for each day of the week). In the second phase, first phase solutions become input to a weekly days-off scheduling problem.

As counter examples, Khoong (1993) and Alvarez-Valdes, Crespo and Tamarit (1999) decomposition approaches reverse the order of the two phases.

Different decomposition approaches are used by Melachrinoudis and Olafsson (1992, 1995), Khoong (1993), Lauer et al. (1994), and Mason, Ryan and Panton (1998). Decomposition is also used in combination with such diverse techniques as network flow, implicit modeling, goal programming, construction and improvement, working set, and tabu search. This hybrid approach is illustrated by Love and Hoey (1990), Panton (1991), Jarrah, Bard and deSilva (1994), Bechtold and Brusco (1994a), Brusco et al. (1995), and Alvarez-Valdes, Crespo and Tamarit (1999).

Melachrinoudis and Olafsson (1992) apply a PC-based IP model within an electronic spreadsheet environment for scheduling supermarket cashiers. The objective is to minimize the workforce size, subject to variable labor demand and limited availability of employees for each day of the week. The tour scheduling problem is broken down into seven daily shift scheduling problems, which are solved separately for each day of the week. The shift scheduling solutions are then combined to construct feasible days-off schedules. Melachrinoudis and Olafsson (1995) enhance this approach by including a forecasting module to estimate labor demands for the following week.

Khoong (1993) presents a heuristic that starts with days-off scheduling to generate monotonic schedules, characterized by non-decreasing shift start times and non-decreasing rest periods between shifts. The heuristic decomposes the workshift assignment problem into three stages: (1) determination of shift labor requirements, (2) assignment of off-days, and (3) assignment of workshifts. The algorithm provides an extension to the capabilities of ROMAN, a generic toolkit for manpower rostering developed by Khoong and Lau (1992).

Lauer et al. (1994) uses a two-phase decomposition procedure to schedule part-time (student) employees with limited availabilities at a number of college computer labs. In phase one, optimal daily shift schedules are generated by LP for each day of the week. In phase two, students are interactively assigned to their daily and weekly schedules for the semester.

Mason, Ryan and Panton (1998) combine heuristic, optimization, and simulation methods in a decomposition scheme for scheduling an airport customs staff. First, heuristic rules are used within a simulation model to determine minimum staffing requirements. These requirements are then inputted to an IP model that assigns full- and part-time personnel to shifts for each day of the week. Finally, the seven daily shift schedules are integrated to construct a cyclic days-off roster. Complete cyclic rosters are generated based on the technique developed by Panton (1991), whose optimality conditions are discussed in (Van Den Berg and Panton, 1994).

Decomposition is also combined with other techniques in order to facilitate solutions of tour scheduling problems. Love and Hoey (1990) decompose and solve a large tour scheduling IP model as two network flow subproblems, then use post-optimality analysis to improve the resulting employee schedule. The model schedules full- and part-time employees, with differing skills and work-time availabilities and preferences, for work in a group of four fast-food restaurants. Panton (1991) first decomposes the cyclic multiple-shift rostering problem into several days-off scheduling modules, one for each shift, then assign shifts to each workday using IP and network flow models.

Jarrah, Bard and deSilva (1994) use aggregate variables and related cuts to decompose their previously described implicit model into seven daily shift scheduling subproblems. Bechtold and Brusco (1994a) apply GP within a decomposition heuristic for tour scheduling of a mixed workforce. First, shift scheduling is done independently for each day of each of the week using a preemptive GP model. Next, the algorithm of Bechtold (1988) is applied on shift scheduling results to find the optimal days-off solutions. Finally, a procedure developed by Bechtold and Showalter (1987) is used to integrate shift and days-off schedules into feasible tours and employee assignments.

Combining decomposition with working set and construction/improvement, Brusco et al. (1995) present two modules designed to improve tour scheduling performance of the United Airlines' Pegasys Manpower Planning system. The first module is Shift Generation Heuristic (SGH) that solves the shift scheduling problem associated with a "composite day" generated by the taking the maximum demand across each day of the week. Using a working set heuristic, SGH assigns employees to a set of shifts to minimize scheduling costs. The shift scheduling solution is used to construct a feasible tour scheduling initial solution. The second module is Local Search Heuristic (LSH) that uses simulated annealing (SA) to improve the initial solution.

Alvarez-Valdes, Crespo and Tamarit (1999) use tabu search with decomposition in order to schedule a mixed workforce at an airport refueling facility. This is a whole-year scheduling problem, where labor demands may vary throughout the day, from day to day, and from week to week. As in the case of (Khoong, 1993), Alvarez-Valdes, Crespo and Tamarit (1999) start with the days-off scheduling subproblem, decomposing the problem into three steps. First, tabu search is used to determine the best shifts and days-off combination needed to cover labor demand. In the second step, weekly days-off schemes are assigned to available employees. Finally, shift starting and finishing times are assigned to each employee for each work day.

7. Goal programming

Goal programming (GP) is a mathematical modeling technique that allows a set of multiple objectives to be prioritized and optimized. GP models can be either deterministic or stochastic. GP has been applied to tour scheduling by Loucks and Jacobs (1991), Bechtold and Brusco (1994a), Brusco and Johns (1995b), Easton and Rossin (1996), and Thompson (1997a).

Loucks and Jacobs (1991) consider a noncontinuous dual-objective tour scheduling problem for a mixed workforce of a fast food restaurant. The primary objective is to meet labor demands with minimum overstaffing, while the secondary objective is to minimize deviations from targeted work hours for each employee. Since several variations of work tours are allowed, the 0–1 goal programming model proves too large for optimal solution. Therefore, Loucks and Jacobs (1991) propose a practical heuristic procedure consisting of two phases, a construction phase followed by an improvement phase.

Goal programming is used in the first stage of the previously discussed decomposition method of Bechtold and Brusco (1994a). The primary objective of the GP model, used in shift scheduling for each day, is to minimize labor cost. The secondary objective is to maximize the utilization of the earliest and latest shift start times. An LP-rounding procedure developed by Showalter and Mabert (1988) is used to obtain integer shift scheduling solutions. Penalty weights for the GP model are chosen in order to: (1) use as few shift start times as possible, (2) use the same shift start times for each day of the week, and (3) give priority to full-time employees.

Brusco and Johns (1995b) present a two-stage preemptive GP (PGP) approach associated with an LP-based heuristic to provide an even distribution of surplus labor. The PGP process consists of the sequential solution of two LP models. The first model is a mixed workforce set-covering formulation, in which is the objective is to minimize labor cost. The second model uses the cost bound obtained from the first model to find an alternative solution that minimizes the maximum ratio of surplus labor to demand across all periods.

Easton and Rossin (1996) develop a stochastic GP model that integrates and simultaneously optimizes labor demands and employee scheduling assignments. The model assumes a probability distribution of labor demand for each work period, and easily accommodates both linear and nonlinear penalties for overstaffing and understaffing. A tabu search algorithm is used to efficiently solve the proposed model. Based on computational experiments, the stochastic GP significantly outperformed traditional deterministic GP models in terms of workforce size and cost. Thompson (1997a) schedules telephone operators using a binary GP model, which is solved by a PC-based specialized shift assignment heuristic. The preemptive goals include satisfying shift requirements, and satisfying employee preferences in the order of seniority.

8. Working set generation

Tour scheduling problems are characterized by a rapid growth in model size in response to increasing labor scheduling flexibility. Implicit modeling, decomposition, and working set generation are all approaches that aim to reduce problem size. Working set generation attempts to reduce problem size by selecting a subset of decision variables from the master set of variables associated with the complete problem. The process of working set generation consists of two steps: (1) working set generation, and (2) implementation. In the implementation phase, optimal or heuristic methods are applied to find the solution of the reduced (working set) problem. The working set generation approach is illustrated by Easton and Rossin (1991a, 1997), Bechtold and Brusco (1994b, 1995), and Brusco and Jacobs (1998b).

Easton and Rossin (1991a) develop a heuristic column generation method that reformulates the tour scheduling problem using a small subset of available tours. Quite often, it is necessary to choose a small subset to make the solution practical. However, solution quality depends on the specific tours included in the model. Dynamic programming is utilized to solve the column generation subproblems for each full- and part-time employee category. Using about 4% of the 1,239 available tours for a mixed workforce, the method produced costs statistically identical to those obtained with all feasible tours, in a much shorter time.

Bechtold and Brusco (1994b) describe working set labor scheduling methods as having two stages: generation, and implementation, classifying generation procedures into three types: structural, demand-based, and refinement. They introduce structural and demand-based heuristics for discontinuous tour scheduling. Bechtold and Brusco (1995) develop two two-phase working set procedures for discontinuous tour scheduling. The first procedure, which applies to full-time employees, uses Bechtold and Showalter's (1987) method in the first stage and IP in the second stage. The second procedure, which applies to a mixed workforce, uses Bechtold and Brusco's (1994a) method in the first stage and LP-based heuristics in the second stage. The first procedure produced optimal solutions for all test problems, while the second produced lower mean cost in considerably less CPU time than other available methods.

Easton and Rossin (1997) compare the economic and operational advantages of overtime assignment to full-time employees versus using part-time employees. A dynamic program similar to the one used by Easton and Rossin (1991a) is used to generate a feasible set of tours that would be active in the optimum continuous LP solution. The resulting reduced IP is solved by the SA heuristic proposed by Brusco and Jacobs (1993a).

Brusco and Jacobs (1998b) use a simple procedure to eliminate redundant columns (variables, or tours) in set covering models of continuous tour scheduling problems. The procedure simply eliminates all the tours containing work shifts that either start or end in periods of zero labor demand. Application of the procedure to labor requirements at 27 United Airlines airport stations resulted in an average reduction of 56% in the number of tours. This not only makes the solution easier, but also removes undesirable tours from the employee schedule.

9. LP-based methods

In general, linear programming (LP) based approaches to tour scheduling problems apply various rounding heuristics to fractional LP solutions in order to obtain efficient integer solutions. Brusco and Johns (1995b) describe LP-based heuristics as a four-step process. In step one, the LP solution is obtained, stopping if values of all decision variables are integer. Otherwise, all integer values are rounded or truncated in step two. In step three, employees are added iteratively until a feasible solution is obtained. In step four, search procedures are used to improve the initial solution. LP-based heuristics are developed or applied by Mabert and Showalter (1990), Li, Robinson and Mabert (1991), Thompson (1992, 1993), Ashley (1995), Brusco and Johns (1995b), and Cezik, Gunluk and Luss (2001).

Mabert and Showalter (1990) schedule part-time employees at two commercial banks. The heuristic procedure developed by Showalter and Mabert (1988) is used to obtain near-optimal solutions by applying a round-down/build-up approach to solutions obtained by LP relaxation. As expected, increased flexibility provided by part-time employees reduces labor idle time. Li, Robinson and Mabert (1991) consider a more general tour scheduling problem, with three types of full-time and part-time employees. Four LP-based heuristic methods are evaluated using 40 test problems, using data from a commercial bank. Li, Robinson and Mabert (1991) conclude that sophisticated heuristic methods outperform simple round-up procedures.

Thompson (1992) divides employee tasks (and consequently labor demands) into uncontrollable work (UW), based on customer arrivals or demands, and controllable work (CW) which can be scheduled by management. Two implicit IP models are presented to optimally schedule CW simultaneously with employee work tours. A two-phase procedure is used to obtain integer solutions of both models. First, the relaxed LP version is solved to determine the total number of scheduled tours T_{LP}. A constraint is then added setting the number of tours at least equal to T_{LP}, and the model is solved again by IP.

Thompson (1993) conducts simulation experiments to evaluate two forms of treating employee requirements: as lower bounds prohibiting shortages, and as target levels allowing both under- and over-staffing. Two cost approaches are also evaluated: constant problem-independent costs, and variable problem-specific costs. LP models that approximate nonlinear under- and over-staffing costs are solved by an LP rounding heuristic similar to that developed by Keith (1979) for shift scheduling. Target staffing procedures using problem-specific costs produced the lowest cost schedules.

Ashley (1995) uses a spreadsheet package with What's Best! (LINDO Systems) LP add-in to assign limited-availability staff at a university library to noncyclical weekly tours. The scheduling requirements are modeled as a binary integer linear program. Without integer restrictions, LP solution is facilitated by What's Best! cell protection features, which reduce the number of variables and constraints. If fractional results occur, a full integer solution can be obtained by restricting a small subset of the variables to integer values, taking advantage of the network structure of the model. As mentioned earlier, Brusco and Johns (1995b) use an LP-based heuristic with their two-stage preemptive goal programming approach.

Cezik, Gunluk and Luss (2001) develop a mixed IP formulation for cyclic tour scheduling by combining seven daily shift schedules into a network flow model. The objective is to minimize the total cost of labor and unsatisfied demand for a call center's employees. The difference of start times on consecutive days may not exceed a given bound, and one of the off days per week has to be on a weekend. A fix-and-branch LP rounding heuristic is used; first the LP relaxation is solved, then in successive iterations the zero-valued variables are fixed while variables with large fractional parts are rounded up.

10. Construction/improvement

Construction/improvement (CI) methods work on an iterative basis, starting with no employees assigned to any labor tour schedule. Employees are allocated at each iteration to given tours until all labor requirements are satisfied. In the improvement phase, the objective function is improved by modifying the existing solution according to a set of heuristic rules. The process is repeated until no further improvement is possible. CI methods are applied to tour scheduling by Easton and Rossin (1991b), Loucks and Jacobs (1991), Gopalakrishnan, Gopalakrishnan and Miller (1993), Thompson (1995a), Goodale and Tunc (1996, 1998), and Brusco and Jacobs (1993a, 1993b, 1995, 1998a).

Easton and Rossin (1991b) describe an improvement heuristic that improves tour scheduling solutions provided by other procedures. Tour scheduling problems frequently have alternative optima, allowing the heuristic to choose schedules based on secondary criteria such as employee satisfaction and customer response time. At each iteration, the heuristic perturbs an incumbent solution to generate an equal-cost alternative. If the new schedule is superior in terms of secondary criteria, it becomes the new incumbent. After obtaining the tour scheduling solution, a generalized assignment problem (GAP) model is used to maximize employee satisfaction with assigned tours.

Loucks and Jacobs (1991) develop a seven-step CI heuristic procedure for scheduling the workforce in a fast food restaurant. The construction phase involves three steps: (1) select critical task-hour, (2) change prior assignment, and (3) select employee for assignment. The improvement phase requires four steps: (1) correct maximum-workdays violations, (2) eliminate overstaffing assignments, (3) meet targeted tour hours, and (4) improve task assignment constancy.

Gopalakrishnan, Gopalakrishnan and Miller (1993) introduce models and heuristics for scheduling a newspaper's part-time employees based on their availability and preferences. A two-phase heuristic is developed to solve the binary IP model of the problem. In the construction phase, shifts are assigned to employees in the order of seniority and preference. This phase ends when all part-time employees have been assigned. If all labor demands are not met at the end of the first (construction) phase, the second (improvement) phase is used to obtain feasibility.

Brusco and Jacobs (1993a, 1993b) develop a two-phase tour scheduling heuristic that combines CI with SA. First, the *Generate procedure* iteratively constructs a feasible employee schedule. Next, the *Search procedure* uses SA to improve the initial solution. The same approach is used by Brusco and Jacobs (1995) to compare two alternative formulations of continuous tour scheduling problems. In the continuous formulation, employee schedules may begin in any hour of the week. The discontinuous formulation simplifies the problem by prohibiting shift schedules that would overlap from one 24-hour period to the next. Computational results confirm the superiority of the continuous over discontinuous formulation and the superiority of the heuristic over IP.

Brusco and Jacobs (1998a) extend Brusco et al.'s (1995) restricted starting-time tour scheduling model, which includes constraints on separating starting times, and develop a near-optimal two-stage heuristic strategy. In the first stage, simple working set generation heuristics are used to select a subset of shift starting times. In the second stage (tour schedule construction) Brusco and Jacobs' (1993a) combined CI–SA heuristic is applied to the working set. The procedure is applied to four sets of labor demands for 27 United Airline ground stations.

Thompson (1995a) presents a formulation of the weekly tour scheduling problem designed to take advantage of customer service information in relation to the number of employees needed for each work period. In simulation of 1,152 service environments, solved by Brusco and Jacobs' (1993a) CI–SA heuristic, the new formulation produced higher profit than classical models. This model determines the optimal assignment of employees in order to maximize the net present value (NPV) of profit.

Goodale and Tunc (1996, 1998) develop a tour scheduling model for a mixed workforce, in which productivity changes according to a learning curve for transient employees. This model is a variation of the Thompsons's (1995a) NPV formulation, incorporating varying employee service rates and elements of queuing theory. The objective is to maximize NPV profit subject to varying service rates. The model requires enough employees to be assigned in order to make service rates exceed arrival rates for all periods. The model is solved by Brusco and Jacobs' (1993a) CI–SA heuristic.

11. Metaheuristics

Metaheuristic approaches are generally regarded as the most effective heuristic approaches for solving a large variety of combinatorial optimization problems. There are three main types of metaheuristics: genetic algorithms (GA), simulated annealing (SA), and tabu search (TS). The advantage of metaheuristics over conventional search methods is their ability to avoid getting trapped in local optima by allowing inferior or infeasible solutions during the search. Pirlot (1992) provides an excellent tutorial on metaheuristics. Although all the three types (GA, SA, and TS) have been applied to different versions of the employee tour scheduling problem, SA seems to be the most popular.

11.1. Genetic algorithms (GA)

Genetic algorithms start with a number of solutions (initial generation) and progress through the operations of mutation and crossover through a number of generations, yielding the best solution achieved in the process as the final solution. The origins and theory of GA are initiated by Holland (1975). GAs are applied in tour scheduling by Easton and Mansour (1993, 1999), Tanomaru (1995), and Cai and Li (2000).

Easton and Mansour (1993) introduce a distributed genetic algorithm (DGA) for mixed workforce tour scheduling. Before the DGA is applied, Easton and Rossin's (1991b) working set heuristic is used to reduce the problem size. Using 36 published test problems, the DGA proves to be superior to six top-rated heuristics. Easton and Mansour (1999) use a similar DGA to solve three labor scheduling models: generalized set covering, deterministic goal programs, and stochastic goal programs. Comparing their DGA approach to six alternative solution methods including SA and TS, they conclude that DGA is more efficient in terms of solution quality versus computation time.

Tanomaru (1995) uses a customized genetic algorithm that combines stochastic and heuristic operators to schedule a mixed workforce subject to many realistic constraints.

The constraints either apply to all employees (e.g., available number of employees), to a group of employees (e.g., maximum and average duration of a work shift), or to a single employee (e.g., individual time preferences). The GA defines costs associated with violating these constraints, and then applies heuristics to decrease the violation costs.

Cai and Li (2000) propose a genetic algorithm for a multi-criteria, multi-skill workforce scheduling problem. The primary objective is to minimize total cost. The secondary objective is to maximize staff surplus of equal-cost schedules in order to reduce sensitivity to demand underestimation. The third objective is to minimize the variation of surplus demand in order to balance staff workload. The GA has three new features: (1) parent selection is based on successively considering the three criteria, (2) a multi-point crossover is based on the hamming distance between schedules, and (3) a heuristic is used to resolve infeasibility created by crossover.

11.2. Simulated annealing (SA)

Simulated annealing (SA) imitates the process of solidifying metals. At the beginning, almost all random neighborhood moves (new solutions) are accepted, allowing the entire solution space to be explored. As the "temperature" gradually cools, the method becomes increasingly more selective. The idea of using SA to solve optimization problems was first proposed by Kirpatrick, Gellat and Vecchi (1983), who applied SA to the traveling salesman problem. SA is used in tour scheduling by Brusco and Jacobs (1993a, 1993b, 1993c, 1995, 1998a), Brusco et al. (1995), Thompson (1995a, 1997b), Goodale and Tunc (1996, 1998), and Easton and Rossin (1997).

Brusco and Jacobs (1993a, 1993b) use a two-stage CI–SA heuristic to solve cyclic full-time, continuous tour scheduling problems, with the objective of minimizing the workforce size. In the first stage (Generate module), a feasible solution is iteratively obtained by CI. In the second stage (Search/select module), SA is used to improve the solution by performing a partial search of the neighborhood. The heuristic converges rapidly to near-optimal solutions, comparing favorably to other methods in terms of both solution quality and computation time. It is interesting to note that all the remaining papers reviewed in this section use procedures based on the original SA heuristic of Brusco and Jacobs (1993a).

Brusco and Jacobs (1993c) examine the effect of varying shift length and meal break placement on scheduling efficiency, using Brusco and Jacobs's (1993a) SA heuristic to solve six test problems. In comparing two alternative formulations of continuous tour scheduling, Brusco and Jacobs (1995) use Brusco and Jacobs' (1993a) SA heuristic. Brusco and Jacobs (1998a) also apply Brusco and Jacobs' (1993a) SA heuristic in the second stage of their heuristic strategy for restricted starting-time tour scheduling problems. Brusco et al. (1995) use SA to improve the tour scheduling performance of the United Airlines' Pegasys Manpower Planning system.

Thompson (1995a) uses an SA procedure based on Brusco and Jacobs' (1993a) heuristic to solve a tour scheduling model in order to maximize the net present value (NPV) of profit. Thompson (1995a) uses a similar approach to solve two Controlled

Labor Scheduling Models (CLSM) that analyze the tradeoff between labor costs and customer service. The first model minimizes workforce cost subject to a specified service level, assuming unlimited labor availability and budget. The second model maximizes the overall service level subject to limitations on the number or cost of employees.

Goodale and Tunc (1996, 1998) also use Brusco and Jacobs' (1993a) SA heuristic to solve a modified version of Thompsons's (1995a) NPV model. In comparing overtime assignment to full-time employees versus using part-time employees, Easton and Rossin (1997) first generate a feasible set of tours, and then they use Brusco and Jacobs' (1993a) SA heuristic to solve he resulting reduced integer program.

11.3. Tabu search (TS)

In TS, move operations that reverse any of the most recent moves leading to the current (incumbent) solution are forbidden (tabu) unless they result in a new minima. The incumbent is always replaced by its best nontabu neighbor even if it is inferior to the incumbent. These rules limit the likelihood that search will cycle to a previous incumbent or get stuck in a local minimum. The idea of TS is originally proposed by Glover (1986). The application of TS to employee scheduling problems is first considered by Glover and McMillan (1986) and Taylor and Huxley (1989). Tabu search is specifically used in employee tour scheduling by Jarrah, Bard and deSilva (1994), Easton and Rossin (1996), Alvarez-Valdes, Crespo and Tamarit (1999), and Gartner, Musliu and Slany (2001).

Jarrah, Bard and deSilva (1994) use TS in the post-processing of the solution obtained from their implicit formulation, in order to assign breaks to shifts and shifts to tours. To convert daily shifts into weekly tours, first an initial set of tours is constructed, and then their quality (i.e., start time variability) is improved by TS. Instead of terminating the search when a tour fails to improve, it is put on hold (tabu listed) for a certain number of iterations.

Easton and Rossin (1996) use TS to solve deterministic goal programming (DGP) and stochastic goal programming (SGP) models that integrate and simultaneously optimize labor demands and employee tour assignments. For each DGP and SGP test problem, two independent tabu searches are performed based on two initial starting solutions. TS provides good efficient solutions, showing that SGP generally provides lower cost and smaller workforce schedules than DGP.

Alvarez-Valdes, Crespo and Tamarit (1999) use TS in the first step of a three-step decomposition heuristic for workforce scheduling. A TS algorithm, based on Glover and Kochenberger's (1996) procedure for multidimensional knapsack problems, is used to determine the set of employee tours required to cover labor demand. The algorithm oscillates between a constructive phase in which the variables are increased, and a destructive phase in which the variables are decreased. Gartner, Musliu and Slany (2001) develop a two-stage process for workforce scheduling: choosing an optimal subset of possible shifts (shift design), and then assigning shifts and days-off to employees (tour scheduling). A TS procedure utilizing problem domain knowledge and improved initial solutions is used for shift design. A half-automatic (interactive) heuristic procedure is used to develop rotating tour scheduling assignments.

12. Other methods

A variety of distinct procedures have been developed to handle unique employee tour scheduling situations. Many of these procedures do not fall under any of the general categories defined above. These include works by Balakrishnan and Wong (1990), Shaffer (1991), Andrews and Parsons (1993), Van Den Berg and Panton (1994), Goodale and Thompson (1996), Vaughan (1996, 2000), Lin (1999), and Chan and Weil (2001).

Balakrishnan and Wong (1990) propose a network flow model for rotating workforce scheduling. The model can handle multiple-shift cases with time-varying demands. The first day in the planning horizon is considered as source node and the last day as sink node. A two-phase approach is developed to solve the problem. First, a Lagrangian dual-based algorithm is used to determine a good lower bound, then, the K-shortest path technique is used to identify the optimal path. As noted earlier, network flow models are used by Love and Hoey (1990), Van Den Berg and Panton (1994), and Cezik, Gunluk and Luss (2001).

Shaffer (1991) presents a rule-based expert system capable of scheduling up to 100 employees in as many as seven departments. The system applies three kinds of rules: (1) DON'T rules, (2) DO rules, and (3) TRY rules. The inputs considered include departmental labor requirements, employee availability, and user-defined scheduling rules. A test case is used to demonstrate the system's applicability, involving 30 nursing personnel in three departments, within a hospital operating 24 h a day. Although the system is reasonably efficient, it can be made faster by relaxing some of the rules.

Andrews and Parsons (1993) present an optimization model for telephone-agent scheduling. Using queuing theory principles, the model does not maintain a fixed level of service (i.e., staffing), but rather maximizes net expected profits. An expected-total-cost-minimization algorithm is used to determine staffing demands, which are inputted into an automated scheduler to generate on-duty tours for individual operators. Goodale and Thompson (1996) develop three heuristics for assigning individual employees to labor tour schedules. Experiments are conducted to compare the different heuristics, which include a manual (managerial) heuristic, a productivity/cost ratio heuristic, and a net present value heuristic.

Vaughan (1996, 2000) develops models to find the optimum combination of regular and on-call employees to schedule when shifts do not overlap. The models introduce labor demand uncertainty and the use of on-call labor into tour scheduling problems. Vaughan (2000) incorporates on-call labor into a single-period newsboy model, and into a multiple-period shift and tour scheduling model. Both models are based on an unconstrained optimization approach in which labor coverage is enforced by a shortage penalty term. Vaughan (2000) presents a shift scheduling application of the second model in a rural hospital.

Lin (1999) develops a heuristic algorithm to generate a monthly roster for hospital porters to meet the daily demands and satisfy several conditions that include labor constraints, management requirements, and staff preferences. The computerized algorithm assigns porters to shifts on a day-by-day basis starting from the first day of the month; but it may require slight manual adjustments. Chan and Weil (2001) use constraint logic programming to develop cyclic timetables of up to 150 employees to cover labor demands for 24 h a day and seven days a week over a whole year. A model is presented to unify daily and weekly cycles, in which work cycles are not constant but vary to accommodate employee annual leaves and labor regulations.

13. Comparing tour scheduling techniques

Workforce tour scheduling is a highly practical and complex problem that has been well studied in the literature. During the 1990–2001 period, a wide variety of models, varying in both the complexity of functional forms and solution procedures, have been developed for improving the efficiency and effectiveness of employee tour schedules. This paper proposes classifying solution techniques are into ten categories: (1) manual solution, (2) integer programming, (3) implicit modeling, (4) decomposition, (5) goal programming, (6) working set generation, (7) LP-based solution, (8) construction and improvement, (9) metaheuristics, and (10) other methods.

In addition to categorizing solution approaches, it is important to compare different categories and individual techniques. Bechtold, Brusco and Showalter (1991) compare the performance of nine LP-based and construction tour scheduling heuristics. Based on computational experiments, Bechtold, Brusco and Showalter (1991) determine that LP-based methods generally outperform other methods, but they recommend integrating the best three methods in order to achieve a better performance. Today, the distinction between the two types of methods is less emphasized due to the recognition that construction heuristics can be applied to LP-based solutions.

Other limited and scattered comparative data exist for a few methods used in employee tour scheduling. Most researchers perform comparisons to establish the superiority of their proposed solution methods over a limited number of previously published methods. For example, Easton and Rossin (1991a) compare their working set method to four other heuristic methods, while Easton and Mansour (1999) compare their DGA approach to six alternative solution methods. Bechtold, Brusco and Showalter (1991) seem to offer the only truly comparative study of tour scheduling procedures during the 1990s. The need for up-to-date comprehensive computational comparisons among the different methods provides a challenging opportunity for future research. Access to the original codes of different authors is needed to facilitate such comparisons, since it would be impractical for one or a few researchers to develop the code for so many highly complex heuristics.

Other comparison efforts include tables presented by Thompson (1992, 1993, 1995b), Brusco and Jacobs (1993b), and Narasimhan (2000) that list the experimental conditions of previous studies. In each of these tables, the number of methods compared ranges from 7 to 24, while the number of features used for comparison ranges from 3 to 8. In comparison, table 1 shown below displays the characteristics of 70 papers in terms of 12 features, far beyond the number of papers and features specified by all previously published tables.

Table 1 summarizes the description of each technique and compares the features of different techniques as a step toward a comprehensive comparative study of tour scheduling methods. The 12 features used for comparison in table 1 are:

(1) objective function,

(2) solution method,

(3) work hours per day,

(4) shift length in hours,

(5) work days per week,

(6) whether workforce is homogeneous or mixed,

(7) whether work days are consecutive,

(8) whether shift start times are fixed or variable,

(9) whether break times are fixed or variable,

(10) minimum planning period in hours,

(11) maximum number of tours/variables, and

(12) case application.

In order to identify the trends in table 1, the frequency of applying each method has been determined for each year of the survey period (1990–2001). These frequencies, shown in table 2, are for the methods rather than papers. Thus, a paper involving several methods will be counted several times, once for each method. From table 2, we can conclude that meta-heuristics (GA, SA, and TS, but especially SA) are the most popular tour scheduling methods during the survey period. Other popular methods include construction and improvement (CI), decomposition (Dc), manual solution (Mn), and integer programming (IP). However, CI and Dc seem to be losing popularity, while Mn and IP seem to be sustaining their popularity.

14. Future research directions

The rapidly increasing power of the personal computer is making it practical to solve larger and larger problems, either optimally or heuristically. In the future, this should lead to tackling more complex problems. More variables will be included due to allowing higher scheduling flexibility. A trend already exists toward more flexible schedules, irregular work hours, and shorter workweeks. More constraints will be incorporated to impose a greater variety of realistic conditions. Metaheuristics such as genetic algorithms,

Table 1
Features of the tour scheduling methods surveyed.*

Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
(Alfares, 1999)	C	IP	16	8	5	H	Y	F	X	8		Airport
(Alfares, 2000)	C	Mn, IP	24	8	⩽7**	H	Y	F	X	1		Security gate
(Alvarez-Valdes, Crespo and Tamarit, 1999)	C	Dc, TS	24	7–9	**	M	N	V	X	1	3.5M	Airport
(Andrews and Parsons, 1993)	O	O	24							0.5		Library
(Ashley, 1995)	O	LP	7–14				N	V	X	0.5	815	Library
(Balakrishnan and Wong, 1990)	C	O	24	8	**	H	Y	Y	X	8		
(Beaumont, 1997)	C	IP	24	4, 8	**	M						Classified
(Bechtold, Brusco and Showalter, 1991)	S	O	16	9	5	H	N	F	F	1	168	
(Bechtold and Brusco, 1994a)	C	Dc, GP, Ws	16	4, 9	2–5	M	Y	F	F	1	1239	
(Bechtold and Brusco, 1994b)	S	Ws	16	9	5	H	N	F	F	1	168	
(Bechtold and Brusco, 1995)	C	Ws	16	4, 9	2–5	M	N	F	F	1	1239	
(Brusco, 1998)	C	IP	12, 16	4, 9	5	M	Y	F	V	1	203	
(Brusco and Jacobs, 1993a)	S	CI, SA	24	8	5	H	Y	F	F	1	168	
(Brusco and Jacobs, 1993b)	S	CI, SA	16	8	5	H	N	V	V	1	2.15B	
(Brusco and Jacobs, 1993c)	S	CI, SA	24	5, 9		H	Y	F	V	1		Phone Co.
(Brusco and Jacobs, 1995)	C	CI, SA	24	8	5	H	Y	F	F	1	336	
(Brusco and Jacobs, 1998a)	C	Ws, CI, SA	24	4, 8.5		M		V		0.25	1344	Airport
(Brusco and Jacobs, 1998b)	C	Ws	24	4, 8.5	4, 5	M	Y	F		0.25	1344	Airport
(Brusco and Jacobs, 2000)	S	Im	24	9	5	H	Y	V	V	0.25	1.1B	Call center
(Brusco and Jacobs, 2001)	S	IP	24	8, 10	4, 5	H	Y	F	X	1	25,344	Call center
(Brusco and Johns, 1995a)	S	IP	16	9	5	H	Y	F	F	1	56	
(Brusco and Johns, 1995b)	C	GP, LP	12, 16	4, 9	5	M	Y	F	F	1	1239	
(Brusco and Johns, 1996)	S	IP	16	9	5	H	Y	F	F	1	56	
(Brusco et al., 1995)	C	Dc, CI, Ws, SA	24		4, 5	M	Y	F		0.25	1344	Airport
(Burns and Narasimhan, 1999)	S	Mn	8–24	8	3, 4	H	N	F	X	8		
(Cai and Li, 2000)	O	GA	24	8, 9	5, 6	M	Y	F	F	1	504	Cargo Co.
(Cezik, Gunluk and Luss, 2001)	C	LP	19	9	5	H	N	V	V	0.25	9,410	Call center
(Chan and Weil, 2001)	O	O	24		**	H	N	F	X			
(Chew, 1991)	S	Mn	24	7.5–9	6**	H	Y	N	X	0.5		Airport
(Easton and Mansour, 1993, 1999)	C	GA	12, 16	4–9	2–5	M	Y	F	F	1	1239	
(Easton and Rossin, 1991a)	C	Ws	12, 16	4–9	2–5	M	Y	F	F	1	1239	

Table 1
(Continued).

Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
(Easton and Rossin, 1991b)	C	CI, LP	12, 16	4–9	2–5	M	Y	F	F	1	1239	
(Easton and Rossin, 1996)	C	GP, TS	16	4–9	2–5	M	Y	F	F	1	1239	
(Easton and Rossin, 1997)	C	Ws, SA	12–20	9	5	H	Y	F	F	1	184K	
(Gartner, Musliu and Slany, 2001)	O	TS	24	7–9	$\leqslant 7$**	H	Y	F	X	0.25		Call center
(Goodale and Tunc, 1996, 1998)	O	CI, SA	18	4, 8	5	M	Y	F		1		
(Gopalakrishnan, Gopalakrishnan and Miller, 1993)	S	CI	21	$\leqslant 8$	$\leqslant 5$	M			X	1	1680	Newspaper
(Hung, 1993, 1994a)	S	Mn	8–24	8	3, 4	H	N	F	X	8		
(Hung, 1994b)	S	Mn	$\leqslant 24$		3, 4**	H	N	F	X			
(Hung and Emmons, 1993)	S	Mn	8–24	8	3, 4	M	N	F	X	8		
(Hung, 1997a)	S	Mn	8–24	8	3–5	H	N	F	X	8		
(Hung, 1997b)	C	Mn	24	8, 12	2, 5	M	Y	F	X	4		
(Jacobs and Bechtold, 1993a)	C	Im	< 24	$\leqslant 8$	$\leqslant 5$	H	N	V	V	1	3.8B	
(Jacobs and Bechtold, 1993b)	C	Im	< 24	5, 9	2, 5	H	N	V	V	1	3.8B	
(Jacobs and Brusco, 1996)	S	Im	$\leqslant 24$	8	$\leqslant 5$	H	Y	V	X	0.5	125M	Tollway
(Jarrah, Bard and deSilva, 1994)	C	Im, Dc, TS	< 24	4–8.5	4, 5	M	N	V	V	0.5	1483	Mail center
(Khoong, 1993)	C	Dc			5, 6	H	Y	V	X			
(Laporte, 1999)	S	Mn	24	8	$\leqslant 7$**	H	Y	F	X	8		
(Lauer et al., 1994)	O	Dc	$\leqslant 19$	1–4	7	H	N	V	X	1		Comp. lab
(Li, Robinson and Mabert, 1991)	C	LP	20	4–8	5	M	Y	F	X	2	132	Bank
(Lin, 1999)	O	O	24	8	$\leqslant 6$**	H	Y	F	X	1		Hospital
(Lin, Lai and Hung, 2000)	C	IP	24	9, 9.5		M	N	V	V	0.5		Call center
(Loucks and Jacobs, 1991)	O	CI, GP	18	3–8	1–5	M	N	V		1	74B	Restaurant
(Love and Hoey, 1990)	O	Dc	18–24	3–8		M	N		X	0.5	100K	Restaurant
(Mabert and Showalter, 1990)	C, O	LP	12	3–8	2–5	M	Y	F	F	1	650	Bank
(Mason, Ryan and Panton, 1998)	C	Dc	20	3–8	6**	M	Y	V	X	0.25		Airport
(Melachrinoudis and Olafsson, 1992, 1995)	C	Dc	17	3–8		H					75/day	Supermarket
(Narasimhan, 2000)	S	Mn	24		3, 4	M	N	F	X			
(Panton, 1991)	S	Dc, IP	24	8, 9.5	4, 5	H	N	F	X	0.5		Casino, Road patrol
(Shaffer, 1991)	C	O	24	8	2–5	M		V	X	8		Hospital
(Tanomaru, 1995)	C	GA	24		$\leqslant 7$	M						

Table 1
(Continued).

Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
(Thompson, 1992)	C	Im, LP	20	9		H			F	1	12/day	
(Thompson, 1993)	C	LP	20	9	5	H	N	F	F	1	252	
(Thompson, 1995a)	O	CI, SA	18	9	5	H	Y	F	F	1	70	
(Thompson, 1997a)	O	GP	24		2–5	M	N			0.5		Phone Co.
(Vakharia, Selim and Husted, 1992)	O	IP	16, 9	$\leqslant 8$		M	N	V	X	1		Restaurant, Comp. lab.
(Vaughan, 2000)	C	O	24	9		M			F	1		Hospital

*Blank cells indicate that information is not provided in the given paper.
** Multiple-week cycles.
[1] Objective: C = min cost, S = min workforce size, O = other,
[2] Method: CI = construction/improvement,
Dc = decomposition, GA = genetic algorithms,
GP = goal programming, Im = Implicit modeling,
IP = integer programming, LP = LP-based,
Mn = manual, SA = simulated annealing,
TS = tabu search, Ws = working set, O = other.
[3] Operating (work) hours per day.
[4] Shift length in hours.
[5] Work days per week.
[6] Workforce composition: H = homogeneous, M = mixed.
[7] Consecutive work days: Y = yes, N = no.
[8] Shift start times: F = fixed, V = variable.
[9] Break time: F = fixed, V = variable, X = not given.
[10] Minimum planning period in hours.
[11] Max. number of tours/variables: $K = 10^3$, $M = 10^6$, $B = 10^9$.
[12] Case application.

Table 2
Number of times each method was used per year during the survey period.

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Sum
Mn		1		2	2			2		2	2		11
IP		1	1			1	1	1	1	1	2	1	10
Im			1	2	1		1				1		6
Dc	1	1	1	1	3	2			1	1			11
GP		1			1	1	1	1					5
Ws		1			2	2		1	2				8
LP	1	2	1	1		2						1	8
CI		2		4		3	1		2				12
GA				1		1				1	1		4
SA				3		3	1	1	2				10
TS					1		1			1		1	4
O	1	2		1						1	1	1	7
Sum	3	11	4	15	10	15	6	6	8	7	7	4	96

tabu search, and especially simulated annealing are becoming increasingly popular in tour scheduling. This trend is expected to continue, along with the growing tendency to integrate different approaches in order to improve performance.

There are numerous possibilities for future research on the employee tour scheduling problem. In addition to much needed computational comparisons of the different tour scheduling approaches, possible research directions may include various combinations of the following extensions:

1. Stochastic considerations in terms of labor demand, productivity, and availability. Some of these considerations have been addressed to some degree by Easton and Rossin (1996), Thompson (1995a, 1997b), Goodale and Tunc (1998), and Easton and Mansour (1999).
2. Dependent labor demand (demand is a function of the service or staffing level). In this case both demand and staffing level are decision variables.
3. Nonlinear objective functions and constraints.
4. Inclusion of employee transportation cost, either to and from a single remote work location, or among several work locations. This aspect was considered by Alfares (2000) for the days-off scheduling problem.
5. Different and more complex combinations of multiple objectives, multiple locations, and multiple skills.
6. Multiple-period (dynamic) scheduling to satisfy time-varying labor demands, whose objective may include the costs of hiring and firing.
7. Including weekend-off constraints, now considered only in simple manually-solved models, in higher-complexity tour scheduling models that involve hourly planning intervals, meal breaks, and so on.

8. Generalizing the models and solution methods of employee shift scheduling to tour scheduling. Aykin (2001) provides a recent survey and comparison of shift scheduling literature.
9. Determining the optimum tradeoff between two costs: the cost of satisfying the given labor demand as is, and the cost of smoothing this demand to obtain more efficient tour schedules.
10. Applying different versions of alternative work schedules in the tour scheduling framework. So far, only compressed (3- and 4-day) workweek scheduling has been considered. McCampbell (1996) describes several alternative work schedules suggested by the U.S. Office of Personnel Management.
11. Extending the manual algorithms such as those developed by Hung to handle limited employee availability and variable daily labor demands.
12. Extending Brusco and Jacobs' (2000) implicit IP model, which incorporates both start-time and meal-break flexibility, to include other aspects of scheduling flexibility.
13. Developing more efficient solution techniques that are capable of handling complex real-life employee tour scheduling problems. These techniques may include advanced heuristic or even optimal solution methods that take advantage of new optimization tools and increasing PC computing power.
14. Solving the employee tour scheduling problem within a larger organizational context. This is illustrated by the following examples of labor (not necessarily tour) scheduling within larger problem contexts:
    - Maintenance scheduling, as in Knapp and Mahajan (1998) and Alfares (1999).
    - Production scheduling, as in Yura (1994) and Berman, Larson and Pinker (1997).
    - Facility layout, as in Bartholdi III and Gue (2000).
    - Project scheduling, as in Alfares and Bailey (1997) and Al-Tabatabai and Alex (1997).

Acknowledgment

The author wishes to thank King Fahd University of Petroleum and Minerals for supporting this research project.

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