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Staff scheduling and rostering: A review of applications, methods and models

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Abstract

This paper presents a review of staff scheduling and rostering, an area that has become increasingly important as business becomes more service oriented and cost conscious in a global environment.

Optimised staff schedules can provide enormous benefits, but require carefully implemented decision support systems if an organisation is to meet customer demands in a cost effective manner while satisfying requirements such as flexible workplace agreements, shift equity, staff preferences, and part-time work. In addition, each industry sector has its own set of issues and must be viewed in its own right. There are many computer software packages for staff scheduling, ranging from spreadsheet implementations of manual processes through to mathematical models using efficient optimal or heuristic algorithms. We do not review software packages in this paper. Rather, we review rostering problems in specific application areas, and the models and algorithms that have been reported in the literature for their solution. We also survey commonly used methods for solving rostering problems.

Keywords: Staff scheduling; Personnel scheduling; Rostering

1. Introduction

Personnel scheduling, or rostering, is the process of constructing work timetables for its staff so that an organisation can satisfy the demand for its goods or services. The first part of this process involves determining the number of staff, with particular skills, needed to meet the service demand. Individual staff members are allocated to shifts so as to meet the required staffing levels at different times, and duties are then assigned to individuals for each shift. All industrial regulations associated with the relevant workplace agreements must be observed during the process.

It is extremely difficult to find good solutions to these highly constrained and complex problems and even more difficult to determine *optimal* solutions that minimise costs, meet employee preferences, distribute shifts equitably among employees and satisfy all the workplace constraints.

In many organisations, the people involved in developing rosters need decision support tools to help provide the right employees at the right time and at the right cost while achieving a high level of employee job satisfaction. The components of such

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a decision support system will typically include spreadsheet and database tools and possibly rostering tools developed from appropriate mathematical models and algorithms. The rostering tools are the main focus of this review.

The development of the mathematical models and algorithms underlying a rostering tool will involve: (a) a demand modelling study that collects and uses historical data to forecast demand for services and converts these to the staffing levels needed to satisfy service standards, (b) consideration of the solution techniques required for a personnel scheduling tool that satisfies the constraints arising from workplace regulations while best meeting a range of objectives including coverage of staff demand, minimum cost and maximum employee satisfaction, and (c) specification of a reporting tool that displays solutions and provides performance reports.

In general, the unique characteristics of different industries and organisations mean that specific mathematical models and algorithms must be developed for personnel scheduling solutions in different areas of application.

There are a large number of commercial software packages available to assist with rostering. We do not provide a review of rostering software in this paper, but note that those software packages that provide significant optimisation capabilities are generally targeted at a specific application area and cannot be easily be transferred to another industry, while those designed to be broadly applicable generally focus more on providing users with manual editing functions and extensive reporting but have limited support for automated roster generation.

There have been a number of general survey papers in the area of personnel rostering, these include [32] and [179]. The latter survey concentrates on general labour scheduling models. An early survey of some application areas and methodologies is [5]. A survey of crew scheduling and rostering is given in [36]. Surveys of the literature in airline crew scheduling and rostering appear in [17,94,155]. A good survey of tools, models and methods for bus crew rostering is [190]. A survey of the nurse scheduling literature is provided in [37,168]. Call centre rostering is a more recent application and articles relating to this market are found in [101,129]. There have been a few edited volumes: [61,62,68,153,186,189], arising from conferences conducted in the area of personnel scheduling, particularly in the area of public transport.

In Section 2 of this paper we look at definitions and notation, and develop a classification of personnel scheduling problems which we use in the rest of the paper. We classify the personnel scheduling literature into various application areas in Section 3. Section 4 contains descriptions of solution methods and offers comments on the applicability of various methods for solving different problems in the literature. Finally, we consider a number of possible future trends and offer some conclusions in Section 5.

2. Problem classification and models

In this section we propose a taxonomy of rostering, or personnel scheduling. For the purposes of this paper we treat rostering and personnel scheduling as synonymous. The taxonomy is not intended to be complete, but to provide a general framework for classifying much of the work that has been carried out in the area of rostering.

The classification considers two aspects of the rostering problems addressed in the literature. On a general level the overall rostering process involves a number of different modules, and within these modules different models may be needed for specific applications.

Other classifications have been proposed in the literature. For example, the authors in [179] divide the general personnel scheduling problem into five subproblems, temporal staff requirements, total staff requirements, recreation and leave, work schedules, and shift schedules. Similarly, three stage approaches involving crew pairing generation, crew pairing optimisation, and crew rostering, are often used in air crew scheduling [17,51]. For general labour scheduling [22], days off, shift, and tour scheduling are commonly studied in the literature.

The classification presented here is intended to be slightly more general than these. We suggest a number of modules associated with the processes of constructing a roster. Some or all of these modules may require consideration in order to build a roster in a particular application area.

Before discussing our classification, we note that there are a number of areas that are related to, though not strictly part of, the rostering process. Among those that we allude to in this paper are workforce planning and the sociological and psychological impact of different work patterns.

There is a significant workforce planning literature dealing with strategic questions relating to the optimal size or mix of a workforce. While there may be some flexibility associated with the utilization of permanent and part-time staff, rostering is primarily concerned with the allocation of jobs among a given workforce. There is also a large body of research related to the social and psychological effects of different types of rosters, particularly those involving shift work or long periods of duty. These studies may effect the development of rosters by influencing the specification of appropriate workplace regulations, but we take such regulations to be existing constraints within a rostering context.

2.1. The rostering process

Our classification presents the rostering process as a number of modules starting with the determination of staffing requirements and ending with the specification of the work to be performed, over some time period, by each individual in the workforce. Although the modules suggest a step by step procedure, the development of a particular roster may require only some of the modules and, in many practical implementations, several of the modules may be combined into one procedure. Moreover, requirements of different modules depend on applications.

Module 1: Demand modelling

The first module in developing a roster is to determine how many staff are needed at different times over some planning period, or rostering horizon. Staff are needed to perform duties that arise from *incidents* that occur during the planning period. In this context, incidents could be taken to mean enquiries to a call centre, a specified sequence of tasks, the components of an aircraft flight timetable, or simply a per shift specification of staff levels.

Demand modelling is the process of translating some predicted pattern of incidents into associated duties and then using the duty requirements to ascertain a demand for staff. There are three broad incident categories on which staff demand can be based

Task based demand. In this case demand is obtained from lists of individual tasks to be performed. Tasks are usually defined in terms of a starting time and duration, or a time window within which the task must be completed, and the skills required to perform the task. In some cases tasks may be associated with locations. Tasks are often derived from timetables of services to be carried out by an organisation. An initial demand modelling step is to combine individual tasks into task sequences that could usefully be carried out by one person. Rostering from task based demand is commonly used in transport applications where the demand modelling module is associated with crew pairing generation and crew pairing optimisation.

Flexible demand. In these cases the likelihood of future incidents is less well known and must be modelled using forecasting techniques. Requests for service may have random arrival rates and possibly random service times. The link between the requests for service and staffing levels often takes the form of a service standard applied to a queuing analysis of the incident arrival distributions. The outcome is usually a specification of the numbers of staff required at different times of the day for each day in the rostering horizon. For example, staff levels could be specified for each hourly interval over a four week planning period. This rostering to flexible demand is often needed for call centres, police services and airport ground staff.

Once the flexible demand pattern has been generated it may be apportioned to shifts that cover the demand. For example, six morning shifts may be needed to cover the demand between 6 am and 2 pm on a given day. Once the shifts are determined they can be scheduled into lines of work. Alternatively, the demand may be fed directly into the later rostering phases as a constraint on the number of staff working at each time. In this case suitable penalties may be associated with under and/or over cover of the demand. In some cases it may be cost effective to allow under cover and deal with it using overtime.

Shift based demand. Here the demand is obtained directly from a specification of the number of staff that are required to be on duty during different shifts. Shift based demand arises naturally in applications such as nurse scheduling and ambulance services where staff levels are determined from a need to meet service measures such as nurse/patient ratios or response times. Shift based demand may also be applied as a simplification of task based or flexible demand rostering.

Module 2: Days off scheduling

This module involves a determination of how rest days are to be interspersed between work days for different lines of work. This problem arises more frequently when rostering to flexible or shift based demand than when rostering to task based demand.

Module 3: Shift scheduling

Shift scheduling deals with the problem of selecting, from a potentially large pool of candidates, what shifts are to be worked, together with an assignment of the number of employees to each shift, in order to meet demand. When rostering to flexible demand we also need to consider the timing of work and meal breaks within the limits allowed by workplace regulations and company requirements. When rostering to task based demand shift scheduling is usually called crew scheduling, or crew pairing optimisation, the main task being to select a good set of feasible duties, shifts or pairings to cover all tasks. This module is, obviously, redundant when rostering to shift based demand.

Module 4: Line of work construction

This module involves the creation of lines of work, which are sometimes referred to as work schedules or roster lines, spanning the rostering horizon, for each staff member. The process of constructing a line of work depends on the basic building blocks, typically shifts, duties or stints, that are used.

If the basic building blocks are shifts, then any shift can be assigned to an individual's work days. There may be some additional constraints limiting the valid shift patterns, for example it might not be possible to immediately follow a sequence of night shifts with a day shift. Duties arise from tasks which may take up only part of a shift or may span several shifts. Each duty can be included exactly once in the roster. Stints are predefined sequences of shifts and rest days. They may be the result of an aggregation of tasks during the demand modelling module, or simply predefined patterns that reflect workplace rules and regulations.

This module involves a consideration of both the rules relating to lines of work and the pattern of demand. The former ensures the feasibility of individual lines of work while the latter ensures that, taken together, they satisfy the work requirements at all times in the rostering horizon.

Line of work construction is usually called tour scheduling when dealing with flexible demand, and crew rostering when dealing with crew pairings.

Module 5: Task assignment

It may be necessary to assign one or more tasks to be carried out during each shift. These tasks may require particular staff skills or levels of seniority and must therefore be associated with particular lines of work.

Module 6: Staff assignment

This module involves the assignment of individual staff to the lines of work. Staff assignment is often done during construction of the work lines.

The procedures outlined in Modules 1–6 above provide a general framework within which different rostering models and algorithms may be placed. In the remainder of this section we elaborate on how this classification can be used to differentiate many of the rostering solutions presented in the literature.

2.2. Common decompositions of the rostering problem

It is usually not computationally practical to deal simultaneously with all the modules required to generate a roster, though such an approach is desirable from the perspective of creating the best overall rosters. Decomposing the problem into several separate modules makes it more tractable and often makes sense in terms of an organisation's business practices. For example, provided the shifts remain fixed, task assignment could be carried out at any time before a shift starts without causing significant disruption to the staff. So it may be sensible to generate the shifts ahead of time but delay any task assignments until one or two days before the actual 'day of operation', when the set of jobs that need to be performed is better known.

In most cases demand modelling can be treated as a naturally separate module. For example, when rostering to task based demand it is usually possible to pick sensible ways of aggregating tasks without significantly reducing the flexibility of the line of work creation. Furthermore, unless the number of tasks is quite small, this aggregation is essential in order to make the problem tractable.

When rostering to flexible demand, second order effects may arise from the choice of rosters. For example, it is usually not possible to exactly match the staff on duty to a demand that varies on an hourly basis when using shifts that are between 6 and 8 hours long. As a result, there may be times when relatively fewer staff are on duty and this could lead to longer customer queues, thus creating artificially higher demand in later time periods. That is, the choice of rosters affects the pattern of demand. These effects are usually small and dealing with them by combining the demand and rostering modules may lead to significant modelling complications. In some cases, where there is an unusually strong interaction, such effects may be suitably reduced, as in [111], by a small number of iterations between the rostering modules and the (consequent) demand distribution.

In many applications the final module, staff assignment, is performed manually. Staff may select from the lines of work based on seniority or through some consultative process. If this is not the case, then it generally makes sense to consider individual staff already during the line of work construction rather than treating staff assignment as a completely distinct module.

In summary, there are three main factors that influence the differences between rostering problems and models:

1. The degree to which days off scheduling, line of work construction and task assignment are integrated. An appropriate decomposition strategy can reduce the modelling complexity.
2. The modules required to construct a roster. Some problems do not have tasks, others require non-trivial demand modelling, and some, such as crew scheduling and rostering, do not require task assignment.
3. The type of demand and the fundamental unit from which lines of work are constructed. For example, the modelling techniques used for airline crew rostering are very different from those used for call centre rostering. The demand for the former is based on fixed tasks and on flexible tasks for the latter.

2.3. Duty generation

Duty generation often occurs when dealing with task based demand and involves the aggregation of individual tasks into larger pieces of work. In later rostering modules these pieces of work are treated as indivisible units that are to be performed by the same person. Crew pairing or crew scheduling is a well-known example of duty generation.

Duty generation is often used to deal with location dependencies by combining multiple tasks into roundtrips or pairings that allow staff to return to their home base after performing multiple tasks. The main aims in this module are to minimise paxing (the movement of crew between locations with no assigned duties during the transfer), time away from home, quality of life, cost of overnight stays, and so on.

Duty generation is often carried out in two steps. The first step involves the generation of a large number of feasible duties, shifts, pairings or roundtrips, and the second step involves selecting a good subset of these duties so as to cover all of the demand.

Treating duty generation as a separate module can provide a convenient way of removing some of the complexity associated with detailed work rules from an optimisation model. These rules may be quite difficult to include in a full optimisation model but often have only a limited effect on the overall solution quality. For example, it makes sense to deal with rules governing work breaks while setting up pairings rather than including them as a set of possibly complex side constraints in an optimisation model.

2.4. Line of work construction

Constructing lines of work involves the determination of a sequence of duties spanning some longer-term period of time, commonly fortnightly or monthly, to be allocated to individual staff members. The problem usually contains a number of conflicting objectives and constraints.

There are a number of different line of work models:

Cyclic/acyclic rosters. In a *cyclic* roster all employees of the same class perform exactly the same line of work, but with different starting times for the first shift or duty. This roster type is most applicable for situations with repeating demand patterns. For example, many train timetables repeat weekly and therefore it is not uncommon to have cyclic rosters for train drivers. In *acyclic* rosters, the lines of work for individual employees are completely independent. This situation applies in cases where demand fluctuates with time and where shifts have different lengths and starting times. Acyclic rosters are often employed in call centres. Sometimes a complete cyclic roster, for all staff, is not feasible, but it may be possible to have cyclic rosters within subgroups of the workforce or over subperiods of the rostering horizon.

Stint based. In some organisations only certain shift sequences, called *stints*, are allowed. For example, DDD may be used to refer to a stint with three consecutive day shifts, DND to a stint starting with a day shift followed by a night shift and finishing with another day shift, and OOOO to a stint of four consecutive off days. A line of work is constructed as a sequence of stints. In constructing lines of work, rules indicating allowed stint transitions must be followed. A stint transition matrix can be used to specify which stints can follow a particular stint, and also to indicate preferred transitions. It is possible to construct either cyclic or acyclic rosters using stints. A typical application of stint based rostering is nurse scheduling.

Line of work constraints. In most applications, feasible rosters are significantly constrained by rules governing which work patterns are allowed for an individual. Such rules might impose restrictions on the number of sequential night shifts to be worked, or specify some minimum time off between successive shifts, or refer to more complex preference constraints such as a requirement that no more than two 12 hours shifts be worked per fortnight.

Often there is a distinction between hard and soft constraints. The former *must* be satisfied while the latter may be violated, though it is generally undesirable to do so. Modelling soft constraints usually involves the inclusion of penalty terms in the objective function.

These constraints, which must be applied independently to each line of work, usually vary significantly between different organisations and these differences give rise to the great variety of rostering problems and models.

An important aspect of rostering is to allow for staff preferences. A number of approaches to this problem are used in airline crew rostering. One approach is to use bidding systems in which lines of work are generated and then bid for by crew members. Bids are normally taken in order of decreasing seniority, the most senior staff having the widest range of work lines from which to select so as to best satisfy their preferences. Successive crew members bid for the remaining lines of work. Another approach is to try and accommodate preferences while constructing the lines of work. In preferential bidding systems [96] crew members bid for particular duties and these duties are then incorporated into their lines of work wherever possible. On a more general level, equitable systems attempt to distribute the workload fairly and evenly within each crew class. Constructing cyclic rosters is a typical strategy in equitable systems.

2.5. Assignment

Assignment can occur as a subproblem at various modules of the rostering process. The most frequently used assignments are:

Task assignment. Task assignments are often required when working shifts have been determined but tasks have not been allocated to individuals. Tasks are grouped and assigned to shifts, or employees, based on their starting times and durations. The assignment methods depend on whether tasks times are fixed or movable, breaks exist in shifts, overtime is allowed or specific skills or qualifications are required to perform certain tasks. Task assignment can also be carried out when constructing lines of work.

Shift assignment. Shift assignments arise when constructing lines of work. As discussed previously, in tour scheduling and crew rostering the aim is to construct lines of work from shifts/duties/pairings. In airline crew rostering, sequential assignment methods have been frequently employed to generate rosters. Examples include assigning the highest priority duties/pairings to highest priority employees and assigning duties/pairings to employees on a day by day basis.

Roster assignment. Roster assignment involves the allocation of lines of work to individual staff members. This assignment can be done either after generating all lines of work, as with the bidding systems discussed above, or during construction of the lines of work. If the assignment takes place as the line of work is constructed, then it is common to include individual staff preferences, availability and qualifications as part of the process.

3. Application areas

The origin of staff scheduling and rostering can be traced back to Edie's work on traffic delays at toll booths [79]. Since then, staff scheduling and rostering methods have been applied to transportation systems such as airlines and railways, health care systems, emergency services such as police, ambulance and fire brigade, call centres, and many other service organisations such as hotels, restaurants and retail stores. Extensive model and algorithm development has been carried out in the literature on crew scheduling and rostering in transportation systems, nurse scheduling in health care systems, and tour scheduling for various service systems. A focussed review on applications of both personnel and vehicle scheduling can be found in [5] where scheduling objectives, constraints, and methodologies are surveyed for each application area.

In this section we provide a brief description of the key problems related to staff scheduling in different application areas. We also point to key papers in the research literature that attempt to provide solutions.

3.1. Transportation systems

Staff scheduling and rostering is known as crew scheduling and rostering in the transportation market—airlines, railways, mass transit and buses. The common features for all these applications are

1. Both temporal and spatial features are involved, that is, each task is characterised by its starting time and location and its finishing time and location.
2. All tasks to be performed by employees are determined from a given timetable (either flight, train, subway or bus). Tasks are the smallest elements (or building blocks) and are obtained from decompositions of flight, train or bus journeys. A task may be a flight leg in airlines, a trip between two or more consecutive segments in a train journey, or a trip between two or more consecutive stops in a bus line.

Because of its economic scale and impact, airline crew scheduling and rostering is probably the biggest application of staff scheduling and rostering. More articles have been devoted to methodologies and applications in this area than to any other rostering application area. An earlier survey can be found in [17]. Many applications and methodologies have been collected in proceedings of the symposia of the Airline Group of the International Federation of Operations Research Societies (AGIFORS).

Crew scheduling and crew rostering vary between different airlines, notably between airlines in North America and Europe. The major differences, in terms of crew categories, fleet types, network structures, rules and regulations, regularity of the flight timetables, and cost structures, are highlighted in [15].

The most popular approach for solving airline crew scheduling and rostering is the well-known decomposition technique. In this decomposition technique, the overall problem is solved in three major stages: (a) crew pairing generation; (b) crew pairing optimisation; (c) crew rostering. Crew pairing generation is a process of constructing all or a large number of feasible pairings/duties from the given timetable. Some of the pairings generated in the first stage will be selected so that all flight legs/trips are covered at a minimum cost. In the last stage, the pairings selected in the second stage are sequenced into rosters that will be assigned to individual crew. Many articles deal with airline crew pairing generation, crew pairing optimisation and crew rostering including [14,25,36,60,66,67,71,94,96,109,155,156,184]. Some existing airline crew scheduling and rostering systems are reviewed in [15,17,94].

Most articles in the literature are concerned with planning crew pairing and rostering. Operational crew pairing optimisation is studied in [170]. The operational problem consists of modifying, as necessary, personalized planned monthly assignments of airline crew members during day-to-day operations to deal with sick leave and/or incident interruptions. One operational problem is to construct rosters for reserve pilots and flight attendants who are on call to operate flights that assigned crews cannot fly or flights to which no crew has been assigned [73].

A deadhead problem is considered in [29]. Generation of pairings is done by attempting to eliminate extended rest periods and to reduce the cost and reposition crew for better utilization. Some degree of under coverage and/or over coverage may be beneficial globally. Extra under coverage and over coverage can be eliminated by adding penalties in the objective [100].

Downgrading is a concept used in [65] in order to fill in positions required for lower ranked crew by higher ranked crew.

A model is proposed in [115] to improve the repetition or regularity of itineraries over a weekly horizon since solutions with more regularities are much easier to implement and manage. More importantly, crew members prefer to repeat itineraries. In order to satisfy passengers' requirements, many irregular flights that do not repeat daily may be scheduled [171].

Some integrated models, that deal with both crew scheduling and vehicle scheduling in one pass, can be found in [36,92,104].

Crew scheduling and rostering has also received considerable attention in public transport systems. Progress can traced in a series of dedicated volumes entitled Computer-Aided Scheduling of Public Transport [61,62,68,153,186,189]. A comprehensive survey on vehicle and crew scheduling can be found in [36]. Quite a few decision support systems have been developed and used in public transport systems. A number of software systems for bus scheduling and rostering are described in [28,52,54,62,69,81,89,154,191].

As with airline crew scheduling and rostering, bus schedules and rosters are usually constructed from given bus timetables. Unlike airlines, the time scale may be much smaller since the concept of roundtrips is normally replaced by the concept of duties, and most duties can be performed by a crew complement without long rests. Though the spatial feature is still very important when generating duties in bus crew scheduling and rostering, the concept of home depots does not generally apply. In other words, the starting and finishing locations of a duty need not necessarily be the same.

Railways applications of crew scheduling and rostering have appeared only recently in the public transport sector literature. Most work reported in the literature is about real applications to railway crew rostering applications in different countries [13,49,85,93,116,132,134–137,149]. Integration of crew scheduling and rostering can be found in [51,84].

Crew scheduling and rostering has also been used in other transport systems such as in a light rail train in Hong Kong [57] and shipping lines [98] and trucks [159].

3.2. Call centres

Unlike crew scheduling and rostering, personnel rostering in call centres does not involve a geographical (or spatial) feature. In one sense this makes scheduling and rostering a little easier. However, unlike crew scheduling applications in transport applications, the exact nature and the number of tasks that need to be performed is not known *a priori*. All that is known is that a *workforce requirements* pattern exists for the entire planning horizon. This feature complicates scheduling and rostering in call centres. It is important to note that the workforce requirements in call centre applications are necessarily variable from day to day and from week to week. Shift start times and shift lengths need to vary in order to obtain good, low-cost rosters that cover the workforce requirements adequately. More often than not, the rosters may need to *over cover* demand in certain time intervals and *under staff* in other time intervals. A review of important call centre problems that can be solved using operations research techniques is provided in [129]. A more recent review is provided in [101].

A method for evaluating workforce requirements is provided in [42]. Queuing models [42] and simulation models [38,106] may be used to obtain the correct numbers of staff members in each time interval. The work in [38] enabled AT&T to reduce costs and also won the 1993 Edelman Prize. Another study for the Hong Kong telephone bill enquiries call centre is given in [148]. An approach to determine how calls are answered (and in what manner) is studied in [55]. The Erlang-C queuing model is preferred in most call centre applications. Queuing models are elegant and may give analytical results but in general many real world simplifications need to be made. Simulation can take many practical factors into account but these may be very computationally expensive solutions. Sometimes, queuing models and simulation are combined to obtain ideal staff requirements.

Once workforce requirements are known, we still need to derive good shifts and rosters. Modern call centre staff scheduling solutions need to take into account the fact that not all calls will be of the same type and that different staff will have different call-handling skills. When generating rosters the above skill issues must be considered in addition to the usual constraints such as maximum shift duration, earliest shift starting time, latest finishing time and so on. Depending on these conditions, the number of feasible shifts can range from a few to a few billion. The rostering problem is to allocate lines of work to individuals who have the requisite attributes. A staffing requirements and scheduling study in telephone companies was undertaken in [58]. Mathematical programming and heuristic approaches to shift scheduling in call centres have been derived in [16,42,161,177]. The work in [42] studied the three stages of forecasting, staff requirements, and integrated scheduling to derive call centre solutions. Shift scheduling approaches have been studied in [107,108]. Some recent approaches at integrating demand estimation, workforce requirements planning, staff scheduling and rostering have been developed in [106,177].

3.3. Health care systems

The major rostering focus in health systems has been in nurse scheduling, usually in acute care hospital wards. There are both clinical and cost imperatives associated with providing appropriate levels of staff in the different medical wards in a hospital. The rosters must provide suitably qualified nurses to cover the demand arising from the numbers of patients in the wards while observing work regulations, distinguishing between permanent and casual staff, ensuring that night and weekend shifts are distributed fairly, allowing for leave and days off, and accommodating a range of employee preferences. The resulting rostering problems are, in most cases, over-constrained.

Approaches in the 1970s and 1980s addressed a number of problem formulations and solution techniques. A goal in many studies was to provide support tools to reduce the need for manual construction of nurse rosters. Some studies

[126,142,157,187,188] addressed the problem of determining staff levels and skills based on the numbers of patients and their medical needs. Others adopted mathematical programming [182,183], branch and bound techniques [180], or goal programming [18,145,146], approaches in which the objective contains weighted coverage and shift satisfaction terms and the constraints enforce hard rules such as the ratios of nurse grades that must be observed on shifts. Others [138,169], used iterative algorithms to generate cyclic rosters in which fairness is achieved by having each nurse work the same sequence of shifts with individual shift sequences offset so as to provide the required coverage and skill mix within wards.

In the 1990s a number of papers [37,165,168], provided classifications of nurse rostering systems and reviews of methods for solving different classes of problems. Further advances [113,131,178] were made in applying linear and/or mixed integer programming and network optimisation techniques for developing nurse rosters. Constraint programming (CP) methods [56,185] were also used to model the complicated rules associated with nurse rosters. The methods were applied to problems involving cyclic and non-cyclic rosters. Typically, the problems contained roster rules applicable to a particular hospital. As such, these approaches may require substantial reformulation for use in a different hospital.

A number of approaches have included a mix of heuristic and simulation techniques in an attempt to deal with more complex nurse rostering and clinical service problems. A simulation model augmented by AI methods is used in [141] to incorporate nurse training into rosters. A decision support system based on a shift pattern generating heuristic is used in [151] to provide an interactive system for developing weekly work schedules. A simulated annealing (SA) algorithm for solving a large set covering integer programming formulation is used in [112] to develop rosters for a mix of permanent and casual staff with demand specified in half hourly intervals over a 10 day period. Day to day nurse scheduling based on decisions arising from stochastic models of patient acuity, assessed via simulation modelling, is considered in [166]. An attempt to develop a knowledge based system for generating weekly nurse rosters and then adjusting the rosters so as to react to daily changes in demand and staff availability is discussed in [124].

More recently, a mix of tabu search (TS) and integer program subproblems is used in [77,76] to generate weekly ward rosters while satisfying a complex set of shift rules, cost restriction, nurse grade, and employee preference constraints. A hybrid TS algorithm is used in [44] to obtain solutions within a reasonable timeframe for a commercial nurse rostering system. The approach in [44] has been refined in [43] using a set of memetic (evolution by imitation) algorithms. The algorithms incorporate various tabu and hybrid TS procedures within a genetic algorithm (GA). These algorithms are designed to overcome one of the basic problems associated with using heuristics for complex nurse rostering problems, namely that, as indicated by the authors, "the quality of a solution is not necessarily a sum or combination of the partial solutions".

A number of other aspects of health system rostering systems have been studied by different researchers. Models for developing rosters for nurses serving home care and regional clinics, in which travel between different locations is an important factor, have been developed in [34,91]. A queuing model is used in [6] to determine the staffing levels needed to handle call arrivals for inpatient, outpatient and other hospital generated appointments. Simulation modelling is used in [9] to consider operational management policies for providing maintenance staff in a large hospital. The use of a simple relational database system to manage work schedules for radiologists is discussed in [130].

3.4. Protection and emergency services

An important aspect of staffing police, ambulance, fire and security services is the need to meet expected service standards. These standards may be specified in terms of response times to attend incidents, the ability to dispatch specified numbers of properly trained officers to different types of incidents, and so on. In addition, given the nature of the duties, most emergency services have very tightly controlled regulations specifying acceptable patterns of shift work.

The frequency of incidents requiring emergency services officers will typically vary at different times of a day, week or even season. For example, there may be a higher demand for ambulances and police officers in certain areas on Friday and Saturday nights, or in resort areas during holiday periods. Given a need to meet service standards, changes in incidence frequency will result in changes to the numbers of staff needed to provide the required levels of coverage.

The study in [173] considers the problem of assigning police officer shifts so that under cover is minimised. Shifts can have different start times but the allowed shift patterns are tightly specified (4 days/10 hours, 5 days/8 hours, with 3 consecutive days off). New rosters are obtained by applying a local search heuristic with tabu restrictions, starting with the current roster as an initial solution. Intermediate solutions may need manual adjustment and further optimisation to provide good feasible final solutions. Another study of police rostering is given in [46], which considers the problem of determining cyclical patterns of day, afternoon and night shifts with pairs of rostered days off. The objective is to minimise the deviation from desired staffing levels given some specified variability in demand.

Rostering ambulance officers to satisfy a demand for officers of different classification to be on duty for specified shifts is considered in [83]. Rosters over a period of one year are constructed from allowed patterns of day, night and 'off' shifts together with annual leave periods. These shift patterns are defined as *stints* and examples are DDNN and OOO where D represents a 10 hours day shift, N a 14 hours night shift and O an off shift. A transition matrix is used to specify which stints can follow any given stint and to give the relative preferences for different stint successions. The solution method uses a shortest path algorithm to generate rosters which are ranked according to how well they cover demand, how evenly the workload is spread and so on.

The focus of [167] is the problem of developing rosters for security guards. The problem is formulated as a multi-objective integer program. The different objectives involve minimising under cover of demand and satisfying workers' preferences. There is a mix of full time and part-time guards. Constraints specify the allowed shift and leave patterns for the guards. As the resulting problem is large, the paper discusses a mix of a branch and bound technique and a heuristic for solving the problem.

3.5. Civic services and utilities

Governments at all levels (local, state and national) operate a large number of labour intensive services. Optimised staff rostering for these public services provides a significant opportunity to improve the services provided by the government while at the same time containing costs. However these application areas also present unique challenges as government employment conditions tend to have more generous employment conditions and these can severely restrict the flexibility of the rosters. The following give an indication of the breadth of applications in this area.

A case study is given in [139] deals with the sorts of claims processing that might occur in government agencies dealing with claims for pensions and other social security entitlements, or in private companies dealing with insurance claims. A demand modelling system is described that allowed management to better deal with large fluctuations in the workload.

Weekly schedules for a postal processing centre are produced in [122]. A different application is in the assignment of personnel in the military services. Here the main problems related to assessing how well a person fits a particular position [90] and dealing with the very large number of staff (up to 500,000), skills and positions involved [118].

Two applications in the context of a university are staffing of the reference and circulation desk at a library [19], and the scheduling of proctors [20] to oversee university examinations. Both of these problems are complicated by availability restrictions, the first due to the study commitments by student assistants and the second due to the qualification and preferences of the proctors.

Toll collection is another area of personnel scheduling that has been studied in the literature.

This problem was first introduced in 1954 [79] inspired by the New York Port Authority. The same problem was revisited 40 years later [63] with an emphasis on stochastic demand modelling based service standards.

With privatisation trends in the utilities sector (water, gas and electricity), efficient deployment of resources in this sector is critical to improvements to bottom-line performance. Rostering shift workers and operators in public service utilities and allied services is becoming an important area of application. There are, however, not too many papers in the literature dealing with workforce scheduling studies of electric power supply/generation workers, personnel at gas installations, oil and gas facilities and off-shore facilities. Some aspects of staff scheduling in the utilities area, particularly dealing with occupational health and safety and fatigue, are discussed in [147]. A column generation approach for generating employee rosters for about 50 employees working in a 24/7 electric power generation operation is described in [80].

3.6. Venue management

There are many different types of operations that involve completing tasks with a variety of skill requirements all at the same location. Examples of this include the ground operations at an airport, cargo terminals, casinos and sporting venues.

The largest number of published applications in this category are on airport related staff scheduling, including customs staff at Auckland International Airport [128], aircraft refuelling staff [11] and general ground staff including baggage handlers [75]. All of these problems are characterised by the fact that the demand for services is relatively well known as it is driven by the regular airline timetables. A somewhat different type of rostering problem arises in the scheduling of aircraft maintenance personnel where the main difficulty is to allocate a variety of small tasks to shifts in the presence of skill constraints [72,78].

Two sporting applications include the scheduling of umpires in the American Baseball League [86] and for cricket games in England [193]. However, these problems are more closely related to timetabling than other personnel scheduling problems described here.

3.7. Financial services

Rostering is important for banks in the staffing of tellers as well as some back office staff. This has similar characteristics to other customer service activities. The main difficulty is the variability of demand over the day [125,133]. It is possible to cope with this variability through the judicious use of part-time staff and overtime.

Another quite different problem arises in the scheduling of audit staff. Here the main complexity arises through the non-homogeneous nature of demand with a variety of audit jobs that have a mix of skill requirements and different locations. Various people have studied both the work loads and the detailed scheduling requirements for audit staff [74,158].

3.8. Hospitality and tourism

Staff scheduling forms a significant proportion of overall costs in hotels, tourist resorts and fast food restaurants. Staff costs (including training) are often a hotel's largest single expense. Payroll and related expenses are sometimes over 30% of the costs of operating a hotel. A reduction in this by even 1% represents considerable cost savings and differences to the organisations' bottom line. Hotels normally employ staff with many different skills such as catering, housekeeping, reception, accounting, billing, bookings and maintenance. Staff need to be rostered round the clock in some areas. Some staff may be multi-skilled and others will have training needs written into the workplace agreements. Demand for services is not generally known with certainty before hand and management often relies on a combination of intuition, software systems and local knowledge (particularly of marketing campaigns, events and attractions). Staff scheduling is a key element of management planning in such circumstances. Specific studies in the hospitality area have been carried out in [120] and [150].

3.9. Retail

A mathematical programming approach is proposed in [103] for constructing a weekly schedule for staff members in the retail business. The important criteria for generating quality schedules include the total cost and the service quality. This application can be dealt with in a similar fashion to call centre operator scheduling because shopping customers can be modelled as callers and sales clerks as call takers.

A review is presented in [110] addressing sales force deployment decisions relating to size, time effort allocation and territory alignment. These subproblems can be modelled separately. Recent focuses are on the integration of these separate models within one stage.

3.10. Manufacturing

In a dynamic production environment [1], decisions must be made in order to establish production levels for many different items in order to meet demand over a given period while keeping the inventories at acceptable levels. A critical problem associated with the balance between demand and supply is to decide the related manpower requirements for each production period.

Manpower and material scheduling is considered in [87] for achieving strategic and tactical objectives in an electronics firm. The objectives are, among others, to minimise the costs associated with labour, material, inventory, and penalties for late shipments.

A PC-based decision support system for planning and scheduling part-time workers at a local newspaper company is developed in [99]. The duties of part-time workers include loading and unloading materials, packing newspapers and advertisements into bundles, and distributing bundles. The system addresses two issues: Generating requirements for part-time workers for each shift and scheduling them based on certain criteria.

In construction companies, labour costs account for a large proportion of total project costs. An integration of project task scheduling and staff scheduling is studied in [10,23]. The project task starting times have time windows. The starting times of the tasks determine the daily staff requirements. The objective is to determine the number of staff needed on each day, based on proper scheduling of tasks, such that the overall cost is minimised.

The work reported in [21] is to schedule engineers to carry out various jobs located at different places. Each task can be characterised by a starting and finishing time window, duration and location. Tasks may also be constrained to be performed in particular orders. The main objectives are to maximize the amount of work done and to minimise the amount of time that workers spend travelling between locations.

4. Solution methods

In this section, we review rostering methods and techniques. We also comment on the applicability of these techniques for solving the specific problems. It should be noted that the literature is heavily skewed towards mathematical programming and metaheuristic approaches for rostering as opposed to CP and other techniques arising out of artificial intelligence research.

4.1. Demand modelling

The complicated processes involved in developing rosters are often broken down into modules as described in Section 2. The first step in this process according to our classification is the modelling of the requirements for labour. The type of demand model used varies significantly across different application and has a large effect of the remaining rostering steps. Hence, even though much of the rostering literature assumes that the demand for staff is either given or can be obtained without difficulty, we believe that it is important not to ignore this step.

There are usually two main components in demand modelling: we need a method for translating incident data to a demand for staff, and a method for forecasting incidents unless the incidents are derived from a known timetable.

In some cases the demand may be generated from incidents in a reasonably straightforward, though possibly complicated, manner. For example, in airline or rail crew scheduling instances, the demand for crew is very straightforward because crew rosters are determined by known timetables. However, for example in policing, a serious crime may require the attendance of some specified numbers of senior officers, forensic investigators and junior officers. The incident may also generate a demand for other staff to carry out interviews and collect evidence over the following days. In this case the incident could be translated to a demand for staff via a lookup table containing the immediate and follow up staff requirements for the incident type, together with some measure of the duration of the different jobs. Using such a scheme, the numbers of appropriately qualified staff needed in different time periods can be built up from a predicted time/place distribution of different incident types.

Similarly, in a hospital the numbers of nurses of different qualifications needed in, for example, intensive care or obstetrics wards may be related to the numbers of patients in the wards by a set of regulations specifying patient/nurse ratios for different medical specialities.

In other cases the link between incident frequency and staff demand may occur via a service standard specified in measures such as customer waiting times. In a call centre for example, the service standard may be that 95% of calls are answered within 3 minutes. Other possible service standards include: average waiting time, average number of customers waiting for a service and utilization of staff. Similar types of measure may also apply to customers waiting for service in banks, social service departments, supermarket checkout counters, hospital emergency departments, and so on.

An important aspect of these cases is that both the incident frequency, or customer arrival rate, and the service times associated with individual customers are usually random, though it may be possible to model them using Poisson, Erlang or other more general distributions. Queuing theory [42] and simulation modelling [39,106] are the two approaches most commonly used to translate customer arrivals during different time intervals into the staffing levels (demand) needed to maintain the required service standards.

The application of queuing theory to study staff levels and service standards is a research area in its own right and we will not explore it further here. However, some queuing studies related to determining server (staff) levels to meet service standards are given in [114,175,177] and [111]. A simple approach, assuming a stationary arrival process and based on the Erlang-C model, often provides the basis for "erlang calculators" which are used to determine staffing levels in call centres.

Having decided on a suitable method for converting incident data into staff demand curves, we are still faced with the problem of forecasting the likely distribution of incidents over the forthcoming planning horizon. For example, the planning horizon for a roster may be one month and we may want to forecast the number of incidents that are likely to occur in each daily, hourly, or other, time interval over the next month. An important limitation applies when determining the number of time intervals to use in the planning horizon because traditional forecasting methods do not provide accurate forecasts if the number of forecasting periods is large.

A number of approaches, including simple averaging, exponential smoothing, and regression, may be used for incident forecasting. An approach using seasonal and non-seasonal moving averages is given in [42], while [119] considers a regression model for forecasting the number of calls in hourly intervals to a customer hotline centre. The application of heuristics to determine staffing levels by assuming steady state arrivals in each time interval and smoothing the demand curves by period linking is considered in [105,106].

4.2. Artificial intelligence approaches

Apart from CP (see Section 4.3) several other artificial intelligence techniques have been applied to rostering. These include fuzzy set theory, search and expert systems.

Fuzzy set theory has been used to solve air crew rostering problems in [174]. The fuzzy set membership is used to guide a greedy search algorithm in [174].

Several decision support systems have been developed to assist rostering staff in their task. For example [135] uses a neighbourhood search strategy to improve solutions with a user-selectable degree of automation that provides a range of options from fully manual rostering to complete automation. A similar philosophy underlies [12] where an expert system is used to assist rosterers in initial roster construction as well as in dealing with disruptions.

The decision support approach to rostering is particularly beneficial when there are a large number of human factors that cannot be codified in software and need to be left to the discretion of the person in charge of rostering. In some cases these partial automation approaches also provide a useful first step from a completely manual system in organisations where the lack of trust into a "black box" rostering engine is a significant issue. Note that many of the metaheuristic approaches described in Section 4.4 can also be modified to be used in some form of partially automated decision support.

4.3. Constraint programming

CP provides a powerful tool for finding feasible solutions to rostering problems. This technique is particularly useful when the problem is highly constrained and/or when any feasible solution will suffice even if it is not optimal. However this technique is less likely to produce good solutions for problems where the main challenge is to find an optimal or near optimal solution out of a vast number of feasible solutions.

While some authors, for example [162], use their own constraint propagation and search algorithm with hard coded constraints, most use the power and flexibility of a constraint logic programming language to express the rostering constraints. The advantage of this approach is that complex constraints can be expressed relatively easily.

Pure CP approaches have been applied to nurse rostering in [56,185]. CP performs well in this application area as most nurse rosters tend to be quite rigid and highly constrained.

However as optimisation with CP is generally quite inefficient, several people have tried to combine CP with traditional OR techniques. For example [102] use CP as a preprocessing technique to reduce the problem size before optimising with an LP based branch and bound method. Another alternative is to use CP to perform column generation for a set covering IP [50]. This hybrid technique allows complex work rules to be represented easily in generating columns while using the IP to ensure that a low cost solution is found. CP can also be combined with heuristic search by randomizing the labelling phase of the CP algorithm [144]. Overall this area of hybrid techniques is promising, though more research is required to determine the best way to combine the flexibility of constraint logic programming with some of the optimisation techniques discussed in this section.

4.4. Metaheuristics

Metaheuristics form an important class of methods that solve hard, and usually, combinatorial/discrete optimisation problems. Typically, these methods are used to solve problems that cannot be solved by traditional heuristics such as steepest descent or greedy local search. The problems are either difficult in their own right, or practical real-world instances make them intractable for solution through exact solution approaches. Metaheuristics are typically hybrids of heuristic algorithms. The algorithms combine different base methods under one framework. The different base methods are drawn from areas as diverse as classical heuristics, artificial intelligence, biological evolution, neural engineering and statistical mechanics. Examples of modern metaheuristics are SA, TS, GAs, problem space search, greedy random adaptive search procedure (GRASP), neural networks, machine learning, reinforcement learning and ant colony optimisation. Refer to [143,152] for recent reviews of metaheuristics.

Heuristics and metaheuristics have often been used for solving staff scheduling problems. The popularity of these types of methods for solving rostering problems is due to a number of factors including:

- They tend to be relatively robust. While they cannot be guaranteed to produce an optimal

solution, they can usually produce a reasonably good feasible solution for a wide range of input data in a limited amount of running time. By comparison many integer programming approaches run the risk of not returning any feasible solutions for a long time.
- Most metaheuristics are relatively simple to implement and allow problem specific information to be incorporated and exploited.
- Heuristics make it easy to deal with complex objectives, whether these are real staffing costs or penalties for violating constraints that are desirable but not mandatory.

Hence heuristics are generally the method of choice for rostering software designed to deal with messy real world objectives and constraints that do not solve easily with a mathematical programming formulation. However they generally don't work very well if the rostering problem is highly constrained unless the constraints can be built directly into the heuristic (say into the neighbourhood move operator for local search heuristics). For more highly constrained problems CP approaches tend to work better.

An early review of heuristics is provided is [179]. Swap and interchange based neighbourhood search heuristics are commonly used for solving airline crew rostering problems. See [17] and [94] for reviews of this area. A method for deriving weekly work schedules based on a shift pattern generating heuristic is used in [151].

Generalized local search and adaptive/randomised variations of this method have been used for employee scheduling in [160,181]. Local search methods have been used for bus driver scheduling in [121].

TS has found more recent acceptance as a metaheuristic method for obtaining solutions to staff scheduling problems. Examples of TS applications include nurse rostering [44,76,77], air crew scheduling [53], audit scheduling [74] and bus driver scheduling [163,164].

A hybrid TS algorithm is used in [44] to obtain solutions for a nurse rostering problems. This approach is further refined in [43] using a set of memetic (evolution by imitation) algorithms. This employs a hybrid TS procedure within the framework of a GA.

In general, SA is a popular metaheuristic method for solving a variety of rostering problems. Examples include [39–41,45,176]. Cyclic staff scheduling problems have been solved using an SA framework in [40,45]. An SA approach for airport ground staff has been developed in [75] which attempts to solve the whole rostering problem of days off, shift scheduling and tour scheduling within the SA framework. SA has been applied to airline crew scheduling in [4,82,123] and to train crew rostering in [85]. A SA algorithm for solving a large set covering integer programming formulation is used in [112] to develop rosters for a mix of permanent and casual health sector staff.

GAs have also been used to find solutions for personnel scheduling problems, subproblems and their variants [8,48,132,172]. GA's have been used in nurse rostering [7] and in bus driver scheduling [59,192].

Combined SA and GA metaheuristic methods have been successfully employed in [2,24] for solving staff scheduling and manpower allocation problems.

4.5. Mathematical programming approaches

In mathematical programming approaches, scheduling and rostering problems are formulated as linear programs or linear integer programs, or general mathematical programs. The commonly used model for both scheduling and rostering problems is the famous Dantzig *set covering* formulation [64] or its variations.

Algorithms based on a mathematical programming approach generally achieve the lowest cost solutions. However there are a number of difficulties with these approaches that prevent them from being universally applied:

- In many cases a column generation method is applied which hides much of the complexity of the problem in the definition of the columns. Hence the pricing problem usually becomes the real challenge and often this subproblem has to be solved heuristically. In that case the advantage of using an exact method for the master problem may be lost.

- Mathematical programming formulations are more limiting in what constraints and objectives can be expressed easily. Hence these approaches are more commonly applied to simplified versions of the real world rostering problem or where there are few complications in the original problem.
- Implementing a good integer programming method for a particular crew scheduling and rostering problem, is relatively difficult and time consuming. This is only justified when the extra benefit through the reduced cost of solutions obtained is significant and when the rostering rules and regulations are relatively static over time.

The set covering/partitioning model is so general that many problems in staff scheduling and rostering can be described in this unified format. Days-off, shift, tour scheduling [32], crew scheduling [17] and crew rostering [66,94] are such examples. A useful variation of the set covering model is the elastic set partitioning model which allows both under and over coverage. In order to discourage unnecessary under and over coverage, the associated terms are usually penalised in the objective. Over coverage is particularly useful when deadheading is unavoidable. Both the set covering model and the elastic set partitioning model allow over coverage, but the flexibility of allowing under coverage in the latter may result in very cost effective solutions.

In real life applications, a number of side constraints are added to the set covering model and its variations in order to take different practical considerations into account. These constraints may include governmental and industrial regulations, and personal preferences.

Large scale linear integer programs usually arise from the set covering model and its variations. Even with today's computational technology, it is still a formidable, if not impossible task to efficiently solve large linear integer programs with millions or even billions variables to optimality. Two different methods have been developed to try and overcome the exponential explosion in size of set covering formulations: generating a limited number of columns and forming a reasonably sized formulation [88,100], and partially generating all possible columns using column generation approaches [70,117].

In the first method, a limited number of columns can be generated either randomly or by using some intuitive criteria, or iteratively by solving a sequence of set covering formulations. The idea behind the second method is to generate good columns to form restricted versions of the set covering formulation. If the optimality condition for the full version of the set covering formulation is satisfied, then the problem is solved, otherwise, subproblems are solved. Additional good columns based on reduced cost or similar criteria are priced out and added to the existing restricted version of the set covering formulation. It is computationally expensive to calculate reduced costs for all columns since the number of columns is extremely large. Instead, subproblems are formulated and solved to find new columns. In typical crew scheduling and rostering applications, this subproblem is a resource constrained shortest path problem [70].

A set covering model needs to be solved in both the column generation version of the set covering formulation and its smaller sized variant. The set covering model can be solved using either exact or heuristic algorithms. The best known exact algorithm for linear integer programs is the branch-and-bound method. Upper bounds can be calculated using any simple or advanced heuristic. Lower bounds can be found by solving linear programming relaxations [88,109] or Lagrangian relaxations [184]. Branching on single variables may not be efficient. Branching on constraints have been proved to be more efficient. One such example is the so-called "follow-on" branching strategy [88], based on a determination of whether or not one task must follow another in a duty/shift/pairing.

If exploration of the branch-and-bound search tree is too time consuming, then heuristic rules can be used to terminate the search. These heuristic rules include: termination after finding the first, or a good, integer solution [66,95,156], and partially exploring the search tree by fixing fractional variables [95]. The Lagrangian heuristic is a very popular and efficient way for solving the set covering model arising from crew scheduling and crew rostering [35,49,184]. Branch-and-cut [109], and branch-and-price [30,94] approaches are emerging as powerful techniques for solving large scale linear integer programs arising from crew scheduling and crew rostering.

The set covering model and its variations represents a dominant approach employed in over one hundred articles, to solving crew scheduling problems. Nevertheless other mathematical modelling techniques have also proved to be useful.

In nurse scheduling, a few approaches are reviewed in [168] for creating both cyclic and non-cyclic rosters. Goal programming [146] is a viable approach when multiple objectives are taken into account. Stochastic programming [3] can be used to model stochastic demand. A network model based on the concept of the stint is considered in [131].

Other methodologies employed in crew scheduling and rostering are the network model [26], the multi-commodity network flow approach [36], dynamic programming [31], and the matching model [27]. Various methods have also been developed for general days-off, shift and tour scheduling. For example, an alternative to the set covering formulation is its equivalent but much more compact implicit formulation [33].

Decomposition techniques for airline crew rostering are reviewed in [94]. In these decomposition techniques, the overall rostering problem is decomposed into subproblems in various ways and subproblems may be solved using different mathematical programming approaches. Rosters can be constructed by assigning highest-priority activities to highest-priority employees [97,127]. The model presented in [140] is to generate rosters by solving assignment problems for each day of the rostering horizon. An extension of this model is to generate subrosters for subperiods of the rostering horizon [49,66]. Another model proposed in [47] is to construct rosters sequentially. Any employee's roster, once constructed, remains unchanged throughout the process, and the rosters for remaining employees are generated from pairings/duties that have not yet been assigned to any employee. The above decomposition techniques can be combined to remove the drawbacks associated with any individual approach.

Integrated models for both crew scheduling and crew rostering are considered in [36,92]. It is pointed out in [177] that the set covering model suffers from "a single period paradigm" for labour scheduling, in particular for shift scheduling and tour scheduling. Basically, demand requirements and workforce scheduling are dealt with independently. As a result, the accurate calculation of workforce requirements and optimal workforce scheduling would not give an overall optimal or near optimal solution. Therefore, two integrated approaches have been proposed in [177] to consider demand modelling and staff scheduling simultaneously.

Improvements can be obtained if crew scheduling and crew rostering are combined into a single global method. Some progress in this direction is reported in [51,84].

5. Future trends and conclusions

As can be seen from this review, a large amount of work has already been done in the area of rostering and personnel scheduling. Nevertheless there is still significant room for improvements in this area. We see improvements occurring not only in the area of rostering algorithms, but also in the wider applicability of rostering because of the flexibility that more sophisticated rostering software tools will be able to provide in the future. Here we single out a few key areas that, in our opinion, are likely to occupy people working in this area over the near to medium term.

The first area of integration applies mainly to applications where rostering is already well established such as the transportation sector in general and the aviation industry in particular. Here the main challenge is to obtain greater efficiency gains not by improving algorithms for solving any one aspect of the problem but by integrating more of the steps outlined in Section 2.1 into a single problem. Furthermore it may be possible to consider at least some aspects of the rostering problem in other scheduling problems. For example it is likely that staffing costs for an airline could be reduced if the rostering is considered (at least at a fairly high level) during the timetabling and scheduling of aircraft.

Another important area requiring further work is generalisation of models and methods. Currently, models and algorithms often require significant modification when they are to be transferred to a different application area, or to accommodate changes within an organisation. In a continually changing environment it is not desirable to have an organisation's internal structures, processes and work policies hard-wired into models, algorithms and software for personnel scheduling. New models need to be formulated that provide more flexibility to accommodate individual workplace practices. This can then lead to the development of more general algorithms that will be more robust to changes in the rostering requirements.

Technology transfer in the area of roster preparation is partly driven by the issues related to algorithmic inflexibility. There are many application areas where manual rostering practices persist. This is partly due to a perception that existing rostering software is not flexible enough to deal with specific individual workplace practices. Another challenge is to integrate existing rostering algorithms and software with industry standard Enterprise Resource Planning and Human Resource systems to make them more accessible to a larger number of users.

As the modern workplace becomes more complex and as enterprise bargaining agreements become more focussed on the individual, rather than on a group or team, it is likely that roster solutions will also need to cater to individual preferences. In other words, roster algorithms and rostering applications will need to involve individual-centric work constraints, preferences and business rules. While this feature has the potential to increase roster personalisation, and hence personal job satisfaction in the workplace, this clearly impacts on the complexity of the resulting rostering problems.

As a result of changing work environments and conditions, it is likely that rostering algorithms will need to be more general in the future. Given the resulting flexibility that will be required of the algorithms, it is likely that we will see a more integrated approach to roster solution developments. For example, it will be necessary to consider integrated solution frameworks that include CP, heuristic search, integer programming and simulation approaches to solve a multitude of subproblems within the context of solving the complex rostering problems of the future.

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