Annals of Operations Research 127, 21–144, 2004

An Annotated Bibliography of Personnel Scheduling and Rostering

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Abstract. Computational methods for rostering and personnel scheduling has been a subject of continued research and commercial interest since the 1950s. This annotated bibliography puts together a comprehensive collection of some 700 references in this area, focusing mainly on algorithms for generating rosters and personnel schedules but also covering related areas such as workforce planning and estimating staffing requirements. We classify these papers according to the type of problem addressed, the application areas covered and the methods used. In addition, a short summary is provided for each paper.

Keywords: staff scheduling, personnel scheduling, rostering

1. Introduction

For most organisations the ability to have the right staff on duty at the right time is a critically important factor when attempting to satisfy their customers' requirements. Personnel scheduling and rostering is defined as the process of constructing optimised work timetables for staff. It has received increasing attention over the past few years.

In a general sense, the rostering problem involves allocating suitably qualified staff to meet a time dependent demand for different services while observing industrial workplace agreements and attempting to satisfy individual work preferences. These are typically highly constrained and complex optimisation problems. The particular requirements of different industries result in quite diverse rostering models and, in turn, these models require very different solution techniques in order to provide what are considered good and realistic solutions.

Our annotated bibliography contains reviews of over 700 papers, the earliest being a discussion (Edie, 1954) of the use of probability theory to calculate the number of toll booths, and hence the number of operators, required to provide a specified level of service at different times of the day, and an associated letter (Dantzig, 1954) outlining the use of linear programming to schedule the tool booth operators.

While the world of work appears to have become more complicated, the complexity of *actual* rostering problems has probably not increased substantially over the in-

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tervening half century. However, advances in exact and heuristic optimisation methods, coupled with the increased availability of powerful computers, has seen the development of much more realistic models and associated solution techniques for these problems. In most cases these advances relate to the process of developing planned rosters for a specified time period; more recently some attention has been focused on disruption management in which rapid redeployment of staff is needed to cover changed circumstances.

The purpose of this paper is to provide a resource that contains a comprehensive review of the major research directions, modelling and solution methods, and applications, in an area of great importance to companies attempting to staff their operations in a manner that is cost effective, observes industrial regulations and satisfies individuals' work preferences.

1.1. The contents and structure of the bibliography

The papers included for review relate to the different stages involved in the rostering process. These stages: *demand modelling*, *days off scheduling*, *shift scheduling*, *line of work construction*, *task assignment*, and *staff assignment*, are discussed more fully in the survey paper (Ernst et al., 2004). For definitions of these terms as well as other definitions, we refer the reader to (Ernst et al., 2004). We did not review papers that are related to, though not strictly part of, the rostering process unless they contained a direct application to one of these stages. Among these are papers relating to timetabling, and to the sociological, psychological, ergonomic and safety impacts of different work patterns.

We selected the papers for this bibliography using searches based on a selection of 60 keywords for identifying the different classes of problems, application areas, and solution methods, associated with personnel scheduling.

We carried out the search for papers using our own CSIRO libraries and through them a wide range of libraries across the world, the CSIRO electronic journal collections, the Web of science and other Web based citation indexes, the EI compendex, general Web searches and direct communication with authors. Some relevant publications such as Ph.D. theses, papers in conference proceedings, and internal technical reports, for which we could not obtain information, are not included.

Each paper is categorised according to its *classification* (section 2), its *application area* (section 3), and its *solution method* (section 4). Again, these categories follow the approach introduced in (Ernst et al., 2004). In addition to this categorisation, each paper contains a brief review in the reference listing. These reviews are not abstracts, we read each paper and then wrote a brief description of its contents. We did not categorize the collected papers according to importance of their contributions to the area of personnel scheduling and rostering. We contacted those authors for whom we had an email address and asked them to comment on our classification and review of their papers.

As an example, the paper (Caprara et al., 1997) is categorised as

Classification: Crew Scheduling and Crew Rostering.
Application area: Railways.
Solution method: Integer Programming, Lagrangian Relaxation, Set Covering and Constructive Heuristic;

with the review:

> This paper deals with rail crew scheduling and rail crew rostering where train trips, that need to be crewed, are drawn from a repeating daily schedule. Both problems are formulated as one of finding a min-cost collection of circuits of a graph covering each node (trips or duties) once. For the Italian Railways, the crew scheduling model is formulated as a set covering problem, whose variables are associated with the circuits of the graph, and solved using an iterative Lagrangean heuristic procedure. Given a set of duties that need to be performed, the crew rostering phase is modelled as an integer linear program, whose variables are associated with the edges of the graph, that is solved by Lagrangean relaxation and a heuristic method.

1.2. Earlier reviews

The developments in personnel scheduling and rostering research can be traced through earlier review papers. Some of the reviews that have appeared at different times are found in the publications by the following authors: (Aggarwal, 1982a; Alfares, 2004; Arabeyre et al., 1969; Baker, 1976; Barnhart et al., 1998, 1999; Bodin et al., 1983; Bradley and Martin, 1991; Burke et al., 2002; Day, 1989; Elms, 1988; Ernst et al., 2004; Freling et al., 1999; Gans et al., 2003; Grossman et al., 1999; Gunes, 1999; Hartley, 1981; Hershey et al., 1981; Howick and Pidd, 1990; Hung, 1995b, 1997a; Johnson et al., 1997; Marsten and Shepardson, 1981; Mehrotra, 1997; Ramli et al., 2002; Rushmeier et al., 1995; Siferd and Benton, 1992; Silvestro and Silvestro, 2000; Sitompul and Radhawa, 1990; Spyropoulos, 2000; Thompson, 2002; Tien and Kamiyama, 1982; Warner, 1976a; Wren, 1968, 1974, 1981a, 1981b, 1996; Wren and Rousseau, 1995).

1.3. Further development of the bibliography

A number of commercial rostering products containing advanced solution methods[1] have been developed for specific industries, but much more research is needed before easy to use decision support tools that allow for the complex goals and constraints of real rostering systems are readily available for use by the staff typically responsible for workforce scheduling.

We hope that this current bibliography will provide a valuable resource for all those involved in these exciting and important developments, and are investigating the possibility of providing it as an online database accessed via a rostering web site. This would provide a resource to which authors could contribute relevant papers and comments, and which could be kept up to date as new papers were published.

Table 1
Categorisation of papers by rostering classification.

Classification	Papers	Classification	Papers
Crew Scheduling	219	Task Based Demand	47
Tour Scheduling	185	Demand Modelling	40
Flexible Demand	107	Task Assignment	32
Workforce Planning	99	Shift Assignment	24
Crew Rostering	76	Disruption Management	16
Shift Scheduling	64	Other Classifications	12
Cyclic Roster	62	Stint Based Roster	9
Days Off Scheduling	61	Roster Assignment	6
Shift Demand	55		

2. Rostering classifications

This section categorises papers using the classification system introduced in (Ernst et al., 2004). This classification presents the rostering process as a number of stages 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. The development of a particular roster may require only some of the stages and, in many practical implementations, several of the stages may be combined into one procedure.

Table 1 shows the keywords used to describe the classifications and lists the number of papers that relate to each classification. Note that a particular publication might belong to more than one classification. For example, a single paper could be included in the Flexible Demand, Cyclic Roster and Task Assignment classifications.

2.1. Demand modelling

Demand modelling is the process of translating some predicted pattern of incidents into associated tasks and then using the task requirements to ascertain a demand for staff. There are three broad incident categories on which staff demand can be based: task based demand, flexible demand and shift based demand. Each of these demands is discussed later in this section. In many studies, staff requirements are assumed to be given. However demand modelling is not often a trivial task and papers with significant discussions on the generation of staff requirements are referenced here.

References: (Aardal and Ari, 1987; Abernathy et al., 1973; Agnihothri and Taylor, 1991; Atlason et al., 2002, 2004; Borst, 2001; Brigandi et al., 1994; Buffa et al., 1976; Chen and Henderson, 2001; Chu et al., 1991; Gaballa and Peace, 1979; Gans et al., 2003; Green et al., 2001, 2002; Grossman et al., 1999; Hancock and Chan, 1988; Henderson et al., 1999; Ingolfsson et al., 2002a, 2002b; Isken, 1995; Jelinek et al., 1973; Khan and Callahan, 1993; Koelling and Bailey, 1984; Koutsopoulos, 1990; Kumar, 1989; Kumar and Arora, 1999; Lin, 1999; Linder, 1969; Mehrotra, 1997; Nobert and Roy, 1998; Popova and Morton, 1998; Samuelson, 1999; Sarker, 1986;

Schulmerich, 1986; Sze, 1984; Thompson, 1993, 1997b, 1998a, 1998b; Warner, 1976a; Worthington and Guy, 1988).

2.2. *Task based demand*

Here the demand for staff is obtained from lists of individual tasks to be performed. The tasks are defined in terms of an earliest starting time, a latest finishing time, a duration, and possibly the skills required to perform the task. In many situations tasks may be associated with a location. Typical applications of task based demand are crew scheduling in airlines, railways, buses, and mass transit, and other transportation systems. In many cases this demand can be obtained from timetables.

References: (Alefragis et al., 2002; Azarmi and Abdulhameed, 1995; Begur et al., 1997; Berman et al., 1997; Borndörfer et al., 2001; Bransby et al., 1976; Butchers et al., 2001; Ceder, 2002; Chabrier, 1999; Darby-Dowman and Mitra, 1985; de Silva, 2001; Dias et al., 2002; Dijkstra et al., 1991; Fahle et al., 2002; Falkner and Ryan, 1992; Fischetti et al., 2001; Focacci et al., 1997; Fores, 1996; Fores et al., 2002; Freling et al., 2004; Goumopoulos et al., 1997; Guerinik and van Caneghem, 1995; Haase et al., 2001; Halatsis et al., 1996; Kakas and Michael, 1998, 1999; Kwan and Wren, 1996; Kwan et al., 1999b; Lagerholm et al., 1997a, 2000; Lasry et al., 2000; Lewis, 1992; Li and Kwan, 2000a, 2000b; Lourenco et al., 2001a, 2002; Makri and Klabjan, 2001; Martello and Toth, 1986; Morgado and Martins, 1993; Parker and Wren, 1976, 1983; Pavlopoulou et al., 1996; Yan and Tu, 2002; Yen and Birge, 2000; Yunes, 2000; Yunes et al., 1999, 2000c, 2001; Zhao et al., 1995a).

2.3. *Flexible demand*

In the absence of known timetables or lists of tasks, the likelihood of future incidents, such as the fluctuating arrivals of customer queries to a call centre, must be modelled using forecasting techniques. The conversion from an incident forecast to staffing requirements is accomplished using techniques such as queueing theory or simulation. The outcome of such a conversion is the number of staff required at each skill level during each time period, for example hourly, over the roster planning horizon.

References: (Aggarwal, 1982a; Alvarez-Valdes et al., 1999; Atlason et al., 2002, 2004; Aykin, 1996, 1998, 2000; Azmat et al., 2004; Bailey and Field, 1985; Bailey, 1985; Bartholdi, 1981; Bartholdi and Ratliff, 1978; Beaumont, 1997a; Bechtold and Brusco, 1994a, 1994b; Bechtold and Jacobs, 1990, 1996; Bechtold and Showalter, 1985, 1987; Bechtold et al., 1991; Billionnet, 1999; Browne and Tibrewala, 1975; Brusco, 1998; Brusco and Jacobs, 1993a, 1995, 1998a, 1998b, 2000, 2001; Brusco and Johns, 1995a, 1996; Brusco and Johns, 1995b; Brusco et al., 1995; Buffa et al., 1976; Burns, 1978; Burns and Carter, 1985; Burns et al., 1998; Cezik et al., 2001; Chen, 1978; Church, 1973; Cochran et al., 1997; Dantzig, 1954; Dowling et al., 1997; Easton and Goodale, 2001; Easton and Mansour, 1999; Easton and Rossin, 1991a, 1991b, 1996, 1997; Emmons and Fuh, 1997; Eveborn and Ronnqvist, 2004; Glover and McMillan, 1986; Goodale and Thompson, 2004; Henderson and Berry, 1976; Holloran and Byrn, 1986;

Hung, 1999a, 1994b, 1994d; Ingolfsson et al., 2002b; Isken, 2004; Isken and Hancock, 1991, 1998; Jacobs and Bechtold, 1993; Jacobs and Brusco, 1996; Jarrah et al., 1994; Jaumard et al., 1998; Khoong and Lau, 1992; Koelling and Bailey, 1984; Lauer et al., 1994; Linder, 1969; Love and Hoey, 1990; Mabert, 1979; Mabert and Watts, 1982; Maier-Rothe and Wolfe, 1973; Mason, 1999; Mason and Smith, 1998; Mason et al., 1998; McGinnis et al., 1978; Mehrotra et al., 2000; Miller and Franz, 1996; Monroe, 1970; Morris and Showalter, 1983; Nachreiner et al., 1991; Narasimhan, 1996; Nobert and Roy, 1998; Ozkarahan, 1991a, 1991b; Panton and Ryan, 1999; Pedrosa and Constantino, 2001; Poliac et al., 1987; Rekik et al., 2004; Rothstein, 1972; Samuelson, 1999; Schindler and Semmel, 1993; Shepardson and Marsten, 1980; Taylor and Huxley, 1989; Thompson, 1995a, 1995b, 1997b, 1999b; Tibrewala et al., 1972; Topaloglu and Ozkarahan, 1998, 2000; VanOudheusden and Wen-Jenq, 1982; Vohra, 1987; Willis and Huxford, 1991; Wilson and Willis, 1983).

2.4. Shift based demand

In this case demand is obtained directly from a specification of the number of staff that are required to be on duty during different shifts. A shift is often defined as a day's work for a worker. Shift based demand is often the basis for nurse scheduling.

References: (Abdennadher and Schlenker, 1999; Altman et al., 1971; Bailey et al., 1997; Balakrishnan and Wong, 1990; Bodin, 1973a, 1973b; Burns and Koop, 1987; Butler and Maydell, 1979; Cheng et al., 1996; Chew, 1991; Chun et al., 2000; Danko and Gulewicz, 1994; Darmoni et al., 1995; Eitzen, 1999; Gopalakrishnan et al., 1993; Hagberg, 1985; Hao et al., 2004; Hare, 2001; Harris and Bohle, 1998; Meyer auf'm Hofe, 2001; Hung, 1993, 1994c, 1997c; Hung and Emmons, 1993; Kendall et al., 2002; Kolesar et al., 1975; Koop, 1988; Krajewski et al., 1980; Kusumoto, 1996; Laporte, 1999; Laporte et al., 1980; Lau, 1994, 1996a, 1996b; Lau and Lau, 1997; Lee and Vairaktarakis, 1997; Lin, 1999; Lin et al., 2000; Mason and Nielsen, 1999a, 1999b; Meisels and Kaplansky, 2001; Meisels and Lusternik, 1997; Meisels and Schaerf, 2003; Meisels et al., 1997; Miller et al., 1979; Moz and Pato, 2004; Musliu et al., 2000; Ozkarahan, 1989; Ozkarahan and Bailey, 1988; Panton, 1991; Raggl and Slany, 1998; Vairaktarakis et al., 2002; Vandenberg and Panton, 1994; Weil et al., 1995).

2.5. Days off scheduling

The main concern in days off scheduling is to determine the off-work days for each worker over the rostering planning horizon, rather than to assign the worker particular shifts on working days. Days off scheduling often arises in rostering problems with flexible and shift based demand.

References: (Aggarwal, 1982b; Alfares, 1998; Azmat et al., 2004; Bailey and Field, 1985; Baker, 1974a, 1974b, 1976; Baker and Magazine, 1977; Baker et al., 1979b; Bartholdi, 1981; Bartholdi and Ratliff, 1978; Bartholdi et al., 1980; Beaumont, 1997b; Bechtold, 1981, 1988; Bechtold and Brusco, 1994a; Bechtold and Showalter, 1985, 1987; Berrada et al., 1996; Billionnet, 1999; Browne and Tibrewala, 1975; Brownell and Lowerre, 1976; Brusco and Jacobs, 1998b; Buffa et al., 1976; Burke et al., 2002; Burns, 1978; Burns and Carter, 1985; Burns and Koop, 1987; Burns et al., 1998; Chen, 1978; Cochran et al., 1997; Day and Ryan, 1997; Emmons, 1985; Emmons and Burns, 1991; Emmons and Fuh, 1997; Gaballa and Peace, 1979; Gartner et al., 1998, 2001; Gierl and Pollwein, 1993; Gunes, 1999; Hung, 1991b, 1994a, 1994d, 1999b; Jelinek et al., 1973; Koop, 1986; Lowerre, 1977; Mabert and Raedels, 1977; McGinnis et al., 1978; Morris and Showalter, 1983; Narasimhan, 1996; Okada and Okada, 1988; Panton, 1991; Pedrosa and Constantino, 2001; Rothstein, 1972; Smith et al., 1979a; Tibrewala et al., 1972; Topaloglu and Ozkarahan, 2000; Vohra, 1987; Warner, 1976a; Wermus and Pope, 1994).

2.6. *Shift scheduling*

Shift scheduling involves selecting a set of the best shifts from a (large) pool of candidate shifts on a single day. It is similar to crew scheduling in transportation systems.

References: (Atlason et al., 2002, 2004; Aykin, 1996, 1998, 2000; Bailey and Field, 1985; Bailey et al., 1997; Baker, 1976; Bechtold and Brusco, 1994a; Bechtold and Jacobs, 1990, 1996; Bechtold and Showalter, 1985, 1987; Brigandi et al., 1994; Brusco and Jacobs, 1998b; Buffa et al., 1976; Burke et al., 2002; Byrne and Potts, 1973; Chen and Yeung, 1992; Dantzig, 1954; Easton and Mansour, 1999; Eitzen, 2002; Gaballa and Peace, 1979; Gartner and Wahl, 1998b; Gartner et al., 1998, 2001; Glover and McMillan, 1986; Grossman et al., 1999; Henderson and Berry, 1976, 1977; Ingolfsson and Cabral, 2002; Jelinek et al., 1973; Keith, 1979; Koelling and Bailey, 1984; Kostreva and Jennings, 1991; Mabert, 1979; Mason et al., 1998; Mehrotra et al., 2000; Millar and Kiragu, 1998; Miller et al., 1976; Moondra, 1976; Morris and Showalter, 1983; Nobert and Roy, 1998; Ozkarahan, 1991a, 1991b; Panton and Ryan, 1999; Poliac et al., 1987; Rekik et al., 2004; Rothstein, 1973; Schaerf and Meisels, 1999; Schindler and Semmel, 1993; Segal, 1974; Shepardson and Marsten, 1980; Thompson, 1995a, 1995b, 1996a, 1996b, 1997b; Topaloglu and Ozkarahan, 1998, 2000; VanOudheusden and Wen-Jenq, 1982; Warner, 1976a; Willis and Huxford, 1991; Wilson and Willis, 1983).

2.7. *Tour scheduling*

Tour scheduling integrates days off and shift scheduling. The process involves both choosing the off days for the workers and allocating shifts for each of their working days over the rostering horizon. Tour scheduling reduces to shift scheduling when the rostering horizon is one day and to days-off scheduling when only a single shift exists on each day.

References: (Abdennadher and Schlenker, 1999, 2002; Aggarwal, 1982a; Aickelin, 1999; Aickelin and Dowsland, 2000; Aickelin and White, 2004; Aitken and Hayyen, 2000; Alfares, 1988, 2004; Alvarez-Valdes et al., 1999; Arthur and Ravindran, 1981; Ashley, 1995; Bailey, 1985; Bailey and Field, 1985; Bailey et al., 1995; Balakrishnan and Wong, 1990; Bard et al., 2003; Baxter and Mosby, 1988; Beaulieu et al., 2000; Beaumont, 1997a; Bechtold and Brusco, 1994a, 1994b; Bechtold and Showalter, 1985, 1987; Bechtold et al., 1991; Begur et al., 1997; Berrada et al., 1996; Blau and Sear, 1983; Bodin, 1973a, 1973b; Bradley and Martin, 1991; Brusco, 1998; Brusco and Jacobs, 1993a, 1995, 1998a, 1998b, 2000, 2001; Brusco and Johns, 1995a, 1995b, 1996; Brusco et al., 1995; Burke et al., 1998, 2001a, 2001b, 2001c, 2002; Butler and Maydell, 1979; Cai and Li, 2000; Carter and Lapierre, 2001; Cavique et al., 1999; Cezik et al., 2001; Cheng et al., 1996, 1997; Chew, 1991; Chow and Hui, 1991, 1993; Chun et al., 2000; Darmoni et al., 1995; Dowling et al., 1997; Dowsland, 1998; Dowsland and Thompson, 2000; Easton and Goodale, 2001; Easton and Rossin, 1991a, 1991b, 1996, 1997; Easton and Mansour, 1999; Eitzen, 1999, 2002; Eitzen et al., 2004; Eveborn and Ronnqvist, 2004; Fahle and Bertels, 2002; Franz and Miller, 1993; Franz et al., 1989; Gartner and Wahl, 1998a; Gartner et al., 2001, 2002; Glover et al., 1985; Goodale and Thompson, 2004; Gopalakrishnan et al., 1993; Gunes, 1999; Haase, 1999; Hagberg, 1985; Hao et al., 2004; Hare, 2001; Harris and Bohle, 1998; Hershey et al., 1981; Meyer auf'm Hofe, 2000, 2001; Holloran and Byrn, 1986; Huarng, 1999, 2001; Hung, 1992, 1993, 1994b, 1994c, 1995a, 1997c, 1999a; Hung and Emmons, 1993; Ingolfsson et al., 2002b; Isken, 1995, 2004; Isken and Hancock, 1991, 1998; Jackson and Havens, 1997; Jacobs and Bechtold, 1993; Jacobs and Brusco, 1996; Jarrah et al., 1994; Jaumard et al., 1998; Johns, 1995; Kataoka and Komaya, 1998; Kendall et al., 2002; Khoong and Lau, 1992; Koop, 1988; Kostreva and Genevier, 1989; Kostreva and Jennings, 1991; Kragelund and Mayoh, 1999; Kusumoto, 1996; Kwan et al., 2001; Laporte, 1999; Laporte et al., 1980; Lau, 1994, 1996a, 1996b; Lau and Lau, 1997; Lauer et al., 1994; Lazaro and Aristondo, 1995; Li et al., 1991; Lin, 1999; Lin et al., 2000; Loucks and Jacobs, 1991; Love and Hoey, 1990; Lucic and Teodorovic, 1999; Lukman et al., 1991; Mabert and Watts, 1982; Mason, 1999, 2001; Mason and Nielsen, 1999a, 1999b; Mason and Smith, 1998; Mason et al., 1998; McGinnis et al., 1978; Meisels and Kaplansky, 2001; Meisels and Lusternik, 1997; Meisels and Schaerf, 2003; Meisels et al., 1997; Miller et al., 1979; Mills and Panton, 1992; Monfroglio, 1996; Monroe, 1970; Morris and Showalter, 1983; Moz and Pato, 2004; Musa and Saxena, 1984; Musliu et al., 2000; Nachreiner et al., 1991; Nooriafshar, 1995; Okada et al., 1991; Owens, 2001; Owens et al., 2001; Ozkarahan, 1989; Ozkarahan and Bailey, 1988; Panton, 1991; Raggl and Slany, 1998; Randhawa and Sitompul, 1993; Rekik et al., 2004; Schneeweiß et al., 1996; Scott, 1998; Sinuany-Stern and Teomi, 1986; Smith, 1976; Taylor and Huxley, 1989; Thompson, 1995b, 1996b, 1997a, 1997b, 1999b; Thornton and Sattar, 1996; Topaloglu and Ozkarahan, 1998, 2000, 2003; Tsang and Voudouris, 1997; Valouxis and Housos, 2000; Venkataraman and Brusco, 1996; Warner, 1976b; Warner and Prawda, 1972; Weil et al., 1995).

2.8. *Workforce planning*

Workforce planning is more about strategic decisions than operational ones. It involves the determination of the staff levels required if an organisation is to achieve its goals. As an example, a workforce planning problem for airlines is to decide how many pilots will be employed.

References: (Abboud et al., 1998; Abernathy et al., 1973; Agnihothri and Taylor, 1991; Aitken and Hayyen, 2000; Al-Tabtabai and Alex, 1997, 1998; Al-Zubaidi and Christer, 1997; Alfares and Bailey, 1997; Alivizatos, 1981; Andrews and Parsons, 1989, 1993; Baker, 1974a; Baker and Magazine, 1977; Baker et al., 1979b; Bechtold, 1981, 1988; Begur et al., 1997; Billionnet, 1976; Bodin, 1973a; Browne and Tibrewala, 1975; Brownell and Lowerre, 1976; Brusco and Jacobs, 2001; Burns, 1978; Burns and Carter, 1985; Burns and Koop, 1987; Burns et al., 1998; Castaline, 1992; Cezik et al., 2001; Chen, 2000; Chu et al., 1991; Cochran et al., 1997; Dijkstra et al., 1991; Drexl and Haase, 1999; DuCote and Malstrom, 1999; Duder and Rosenwein, 2001; Edie, 1954; Emmons, 1985; Emmons and Burns, 1991; Emmons and Fuh, 1997; Faaland and Schmitt, 1993; Freeman, 1992; Gans et al., 2003; Gass, 1991; Glen, 1975; Gunes, 1999; Haase, 1999; Hancock et al., 1984; Hanssmann and Hess, 1960; Henderson and Mason, 1999; Henderson et al., 1998; Hershey et al., 1974, 1981; Hong et al., 1989; Howick and Pidd, 1990; Hung, 1994d, 1997b, 1999a, 1999b; Iskander and Chou, 1985; Jelinek and Kavois, 1992; Jennings et al., 1996; Khan, 1991; Koop, 1988; Koutsopoulos, 1990; Koutsopoulos and Wilson, 1987; Krajewski et al., 1980; Kress and Golany, 1994; Kumar and Arora, 1999; Li and Li, 2000; Li et al., 1991; Littler and Whitaker, 1997; Lowerre, 1977; Mabert and Raedels, 1977; McHugh, 1989; Meyer and Markowitz, 1997; Moondra, 1976; Mould, 1996; Panton and Eitzen, 1997; Pedrosa and Constantino, 2001; Quinn et al., 1991; Reeves and Reid, 1999; Rising et al., 1973; Ritzman et al., 1976; Rogers et al., 1997; Rothstein, 1972; Ryan et al., 1975; Sarin and Aggarwal, 2001; Schulmerich, 1986; Siferd and Benton, 1994; Silvestro and Silvestro, 2000; Taylor and Huxley, 1989; Tibrewala et al., 1972; Valls et al., 1996; VanGilder and Usher, 1996; Venkataraman and Brusco, 1996; Verbeek, 1991; Vohra, 1987; Wilson et al., 1988; Wolfe and Young, 1965a, 1965b).

2.9. Task assignment

Task assignment is the process of allocating a set of tasks, with specified start and end times and skill requirements, between a group of workers who have typically already been assigned to a set of working shifts.

References: (Al-Tabtabai and Alex, 1998; Awad and Chinneck, 1998; Azarmi and Abdulhameed, 1995; Bailey et al., 1995; Bean and Bean, 1985; Booler, 1975; Campbell, 2002; Collins and Sisley, 1994; Duffuaa and Al-Sultan, 1999; Feiring, 1993; Franz and Miller, 1993; Gans et al., 2003; Grayson and Yuan, 1997; Hsu, 1984; Kilby, 2001; Krishnamoorthy and Ernst, 1999; Kroon et al., 1997; Lesaint et al., 1998, 2000; Liang and Buclatin, 1988; Loucks and Jacobs, 1991; Maier-Rothe and Wolfe, 1973; Meyer and Markowitz, 1997; Miller and Franz, 1996; Roberts and Escudero, 1983a, 1983b; Schaerf and Meisels, 1999; Stern and Hersh, 1980; Tharmmaphornphilas and Norman, 2004; Trivedi and Warner, 1976; Tsang and Voudouris, 1997; Wright, 1991; Yang, 1996).

2.10. Shift assignment

This is a special case of tour scheduling in which work and rest (off) days are given as inputs.

References: (Alvarez-Valdes et al., 1999; Arthur and Ravindran, 1981; Awad and Chinneck, 1998; Bailey, 1985; Bailey and Field, 1985; Chew, 1991; Hung, 1993, 1994b, 1994c, 1997c; Hung and Emmons, 1993; Khoong and Lau, 1992; Lau, 1994, 1996a, 1996b; Morgado and Martins, 1992; Okada, 1992; Okada and Okada, 1988; Ozkarahan, 1989, 1991a; Panton, 1991; Randhawa and Sitompul, 1993; Vandenberg and Panton, 1994; Warner et al., 1991).

2.11. Roster assignment

Roster assignment is the process of assigning lines of work to staff. A line of work defines the complete work schedule for an individual over the rostering horizon.

References: (Alvarez-Valdes et al., 1999; Dowling et al., 1997; Gamache and Soumis, 1998; Gamache et al., 1998; Goodale and Thompson, 2004; Ritzman et al., 1976).

2.12. Crew scheduling

Crew scheduling, typically applied in transportation systems, involves the selection of a best set of duties. Duties are sometimes called pairings or roundtrips. A related problem is the generation of feasible duties. Constructing duties is often a fairly complicated task since many industrial and organisation rules must be met. Crew scheduling is one of the dominant areas in personnel scheduling and rostering. Many published papers are concerned with crew scheduling in airlines, trains and buses. Crew scheduling is analogous to shift scheduling in non-transportation systems.

References: (Alefragis et al., 1998, 2000, 2002; Anbari, 1987; Anbil et al., 1991, 1992, 1993, 1998, 1999; Andersson et al., 1997; Arabeyre et al., 1969; Baker et al., 1979a; Baker and Fischer, 1981; Ball and Benoit-Thompson, 1988; Ball and Roberts, 1985; Ball et al., 1981, 1983, 1985; Banihashemi and Haghani, 2001; Barnhart et al., 1994, 1995, 1999; Beasley and Cao, 1996; Bennett and Potts, 1968; Bertram and Winckler, 1988; Bianco et al., 1992; Blais and Rousseau, 1988; Blais et al., 1990; Bodin et al., 1983; Bohoris and Thomas, 1995; Booler, 1975; Borndörfer et al., 2001; Borret and Roes, 1981; Boschetti et al., 2004; Bransby et al., 1976; Butchers et al., 2001; Capra et al., 1973, 1997, 1999, 2001; Carraresi and Gallo, 1984b; Carraresi et al., 1982, 1988, 1995; Catanas and Paixao, 1995; Ceder, 2002; Ceder et al., 1988; Chabrier, 1999; Chebalov and Klabjan, 2002; Chu and Chan, 1998; Chu et al., 1997; Clement and Wren, 1995; Crainic and Rousseau, 1987; Curtis et al., 1999, 2000; Daduna and Mojsilovic, 1988; Darby-Dowman and Mitra, 1985; Darby-Dowman et al., 1988; Desaulniers et al., 1997, 1998, 1999; de Sousa, 1991; Desrochers and Soumis, 1988, 1989; Desrochers et al., 1992; de Silva, 2001; Dias et al., 2002; Doerner et al., 2002; Dupuis, 1985; Eitzen, 2002; Elms, 1988; Emden-Weinert and Proksch, 1999; Ernst et al., 1999b, 2001a, 2001b; Eusebio et al., 1988; Falkner and Ryan, 1987, 1988; Ferreira and Guimaraes, 1995; Fischetti et al., 2001; Focacci et al., 1997; Fores, 1996; Fores and Proll, 1998; Fores et al., 1998, 1999, 2001, 2002; Forsyth and Wren, 1997; Freling et al., 1999, 2001a, 2001b, 2003, 2004; Gaffi and Nonato, 1999; Garnier, 1985; Gershkoff, 1989; Goumopoulos et al., 1997; Graves et al., 1993; Haase, 1999; Haase and Friberg, 1999; Haase et al., 2001; Ho et al., 1998; Hoffman and Padberg, 1993; Hoffstadt, 1981, 1988; Housos, 1997; Howard and Moser, 1985; Jorvang, 1992; Klabjan and Schwan, 2001; Klabjan et al., 2001a, 2001b, 2002a, 2002b; Kroon and Fischetti, 2001; Kwan and Wren, 1996; Kwan et al., 1988, 1992, 1993, 1996a, 1996b, 1999a, 1999b, 2000; Kwok et al., 1995; Lagerholm et al., 1997a, 1997b, 2000; Lamont, 1988; Landis, 1981; Lasry et al., 2000; Lavoie et al., 1988; Layfield et al., 1999; Leprince and Mertens, 1985; Lessard et al., 1981; Levine, 1996; Lewis, 1992; Li, 1985; Li and Kwan, 2000a, 2000b; Lourenco et al., 2001a, 2001b, 2002; Luedtke, 1985; Makri and Klabjan, 2001; Marsten and Shepardson, 1981; Marsten et al., 1979; Martello and Toth, 1986; Mateus and Casimiro, 2002; Mellouli, 2001; Mingozzi et al., 2000; Mitra and Darby-Dowman, 1985; Mitra and Welsh, 1981; Morgado and Martins, 1992; Mott and Fritsche, 1988; Paias and Paixao, 1993; Paixao and Pato, 1989; Paixao et al., 1986; Parker and Smith, 1981; Parker and Wren, 1976, 1983; Parker et al., 1995; Patrikalakis and Xerocostas, 1992; Piccione et al., 1981; Rousseau and Desrosiers, 1995; Rousseau et al., 1985; Rubin, 1973; Rushmeier et al., 1995; Ryan and Falkner, 1988; Ryan and Foster, 1981; Sanders et al., 1999; Schaefer et al., 2001; Shen and Kwan, 2001, 2000; Shepardson, 1985; Smith and Wren, 1984, 1988; Smith et al., 1998; Sodhi, 2003; Söhngen, 1988; Stojković and Soumis, 2001a, 2001b; Stojković et al., 1998; Tajima and Misono, 1997; Tosini and Vercellis, 1988; Tykulsker et al., 1985; Valouxis and Housos, 2002; Vance et al., 1997; Volker and Schutze, 1995; Wallis, 1985; Ward et al., 1981; Wark et al., 1997; Weaver and Wren, 1970; Wedelin, 1995; Wei et al., 1997; Willers et al., 1995; Williamson, 1985; Wren, 1975a, 1975b, 1976, 1981a, 1981b, 1987, 1994; Wren and Beecken, 1992; Wren and Chamberlain, 1988; Wren and Gualda, 1999; Wren and Kwan, 1999; Wren and Rousseau, 1995; Wren and Smith, 1988; Wren and Wren, 1995; Wren et al., 1985, 1994; Yan and Chang, 2002; Yan and Tu, 2002; Yan et al., 2002; Yen and Birge, 2000; Yunes, 2000; Yunes et al., 2000a, 2000d, 2001; Zhao et al., 1995a).

2.13. Crew rostering

Crew rostering is largely applied in transportation systems. The optimal duties obtained from crew scheduling are sequenced, in some optimal fashion, to form feasible lines of work. Crew rostering is then the process of choosing a set of the best lines of work for all employees. Tour scheduling in non-transportation systems is similar to crew rostering.

References: (Abdelghany et al., 2004; Anantaram et al., 1993; Arabeyre et al., 1969; Barnhart et al., 1999; Beasley and Cao, 1998; Belletti et al., 1985; Bertram and Winckler, 1988; Blais and Rousseau, 1988; Bodin et al., 1983; Butchers et al., 2001; Caprara et al., 1997, 1998a, 1998b, 1999, 2001; Carraresi and Gallo, 1984a, 1984b;

Cavique et al., 1999; Christou et al., 1999; Constantino et al., 2002; Daduna and Mojsilovic, 1988; Dawid et al., 2001; Day and Ryan, 1997; Desaulniers et al., 1998; Desrosiers, 2001; Dillion and Kontogiorgis, 1999; Doerner et al., 2002; Eitzen, 2002; Ernst et al., 1998, 1999b, 2001a, 2001b; Fahle et al., 2002; Falkner and Ryan, 1988; Freling et al., 2004; Gamache and Soumis, 1998; Gamache et al., 1998, 1999; Guerinik and van Caneghem, 1995; Halatsis et al., 1996; Hoffstadt, 1981; Jachnik, 1981; Jarrah and Diamond, 1997; Jones, 1989; Junker et al., 1999; Kakas and Michael, 1998, 1999; Kohl and Karisch, 2004; König and Strauss, 2000; Kwan et al., 1992; Lamont, 1988; Lasry et al., 2000; Marsten et al., 1979; Mateus and Casimiro, 2002; Morgado and Martins, 1993; Mott and Fritsche, 1988; Nicoletti, 1975; Onodera, 1989; Pavlopoulou et al., 1996; Rousseau et al., 1985; Ryan, 1992; Sherali and Rios, 1984; Sklar et al., 1990; Smith and Wren, 1984; Sodhi, 2003; Söhngen, 1988; Teodorovic, 1998; Tingley, 1979; Townsend, 1988; Tykulsker et al., 1985; Volker and Schutze, 1995; Weir and Johnson, 2004; Yunes, 2000; Yunes et al., 1999, 2000c, 2001).

2.14. Cyclic roster

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.

References: (Ahuja and Sheppard, 1975; Alfares, 1998; Baker, 1974b, 1976; Bartholdi, 1981; Bartholdi et al., 1980; Baxter and Mosby, 1988; Beaumont, 1997b; Bechtold, 1981; Bell et al., 1986; Brusco and Jacobs, 1993a, 1993b; Burke et al., 2002; Caprara et al., 2001; Cezik et al., 2001; Chew, 1991; Cochran et al., 1997; Constantino et al., 2002; Emmons, 1985; Ernst et al., 1998, 2001a; Ferreira and Guimaraes, 1995; Gartner and Wahl, 1998b; Gartner et al., 1998, 2001, 2002; Hao et al., 2004; Hare, 2001; Hoffmann, 1979; Hung, 1991a, 1991b, 2002; Hung and Emmons, 1993; Jachnik, 1981; Koop, 1986, 1988; Laporte, 1999; Laporte et al., 1980; Lowerre, 1977; Maier-Rothe and Wolfe, 1973; Mason, 1999; Mason et al., 1998; Mazzolla and Oppenheimer, 1973; Megeath, 1978; Millar and Kiragu, 1998; Mills and Panton, 1992; Monfroglio, 1996; Monroe, 1970; Morgado and Martins, 1993; Morrish and O'Conner, 1970; Musliu et al., 2000; Panton, 1991; Pedrosa and Constantino, 2001; Rosenbloom and Goertzen, 1987; Scott and Simpson, 1998; Smith, 1976; Smith and Wiggins, 1977; Sodhi, 2003; Vandenberg and Panton, 1994; Vohra, 1987, 1988; Wermus and Pope, 1994).

2.15. Stint based roster

Stints are patterns of shift work over consecutive days with one shift allocated per day. For example, using D, N and O to represent day, night and off shifts, respectively, DDNN is a working stint with two day shifts followed by two night shifts, and OOO is a rest stint with three consecutive days off. A stint based roster is a sequence of stints. In stint based rosters good stints, defining approved work patterns, are used to build rosters by applying allowed stint transition rules.

References: (Bell et al., 1986; Eitzen, 2002; Ernst et al., 1999a; Gartner and Wahl, 1998b; Koop, 1988; Laporte et al., 1980; Schneeweiß et al., 1996; Sodhi, 2003; Valouxis and Housos, 2000).

2.16. Disruption management

Most existing approaches to personnel scheduling and rostering do not take disruptions and delays into account. Disruptions may cause many problems and increase operating costs dramatically if planned schedules are very rigid. The aim of disruption management is to create robust schedules to minimise the impact of possible disruptions.

References: (Abdelghany et al., 2002, 2004; Chebalov and Klabjan, 2002; Desaulniers et al., 1998; Klabjan et al., 2001b; Lesaint et al., 1998, 2000; Moz and Pato, 2004; Schaefer et al., 2001; Stojković and Soumis, 2001a, 2001b; Stojković et al., 1998; Thompson, 1996a, 1999a; Wei et al., 1997; Yen and Birge, 2000).

2.17. Other classifications

Papers that do not fall into any of the above categories, for example, determination of annual hours, on call scheduling, scheduling to increase productivity, and so on, are collected here.

References: (Andrews and Cunningham, 1995; Ballantyne, 1979; Bechtold, 1991; Bechtold and Thompson, 1993; Corominas et al., 2004; Evans, 1988; Gartner and Popkin, 1999; Hosios and Rousseau, 1980; Hung, 1997a; Liang and Thompson, 1987; Norby et al., 1977; Seitman, 1994).

3. Application areas

This section categorises the publications by application area. Table 2 shows the keywords used to describe the application areas and lists the number of papers relating to each area. The application areas and number of papers do not represent a one-to-one mapping; for example, a publication might relate to both the bus and railway application areas.

3.1. Airlines

Because of its economic scale and impact, airline crew scheduling and rostering has attracted much attention from researchers. Almost all the world's major airlines now use some form of crew scheduling and rostering software to assist creating crew pairings and crew rosters for pilots and/or crew attendants. Some major airlines have departments dedicated to crew management.

References: (Abdelghany et al., 2002, 2004; Aitken and Hayyen, 2000; Alefragis et al., 2002; Anantaram et al., 1993; Anbil et al., 1991, 1992, 1993, 1998, 1999; Andersson et al., 1997; Arabeyre et al., 1969; Baker and Fischer, 1981; Baker et al., 1979a;

Table 2
Categorisation of papers by application.

Application	Papers	Application	Papers
Buses	129	Civic Services and Utilities	22
Nurse Scheduling	103	Venue Management	19
Airlines	99	Protection and Emergency Services	16
Railways	37	Other Applications	14
Call Centres	37	Transportation Systems	12
General	33	Hospitality and Tourism	7
Manufacturing	29	Financial Services	6
Mass Transit	28	Sales	3
Health Care Systems	23		

Ball and Roberts, 1985; Barnhart et al., 1994, 1995, 1999; Bodin et al., 1983; Brusco et al., 1995; Butchers et al., 2001; Chabrier, 1999; Chebalov and Klabjan, 2002; Chow and Hui, 1991, 1993; Christou et al., 1999; Chu et al., 1997; Crainic and Rousseau, 1987; Dawid et al., 2001; Day and Ryan, 1997; Desaulniers et al., 1997, 1998, 1999; Desrosiers, 2001; Dillion and Kontogiorgis, 1999; Doerner et al., 2002; Emden-Weinert and Proksch, 1999; Fahle et al., 2002; Freling et al., 2004; Gamache and Soumis, 1998; Gamache et al., 1998, 1999; Gershkoff, 1989; Goumopoulos et al., 1997; Graves et al., 1993; Halatsis et al., 1996; Ho et al., 1998; Hoffman and Padberg, 1993; Hong et al., 1989; Housos, 1997; Jarrah and Diamond, 1997; Jones, 1989; Junker et al., 1999; Kakas and Michael, 1998, 1999; Klabjan et al., 2001a, 2001b, 2002a, 2002b; Kohl and Karisch, 2004; König and Strauss, 2000; Kress and Golany, 1994; Kwok et al., 1995; Lagerholm et al., 1997a, 1997b, 2000; Lasry et al., 2000; Lavoie et al., 1988; Levine, 1996; Lucic and Teodorovic, 1999; Makri and Klabjan, 2001; Marsten and Shepardson, 1981; Marsten et al., 1979; Mellouli, 2001; Nicoletti, 1975; Onodera, 1989; Pavlopoulou et al., 1996; Rubin, 1973; Rushmeier et al., 1995; Ryan, 1992, 2000; Schaefer et al., 2001; Sherali and Rios, 1984; Sklar et al., 1990; Stojković and Soumis, 2001a, 2001b; Stojković et al., 1998; Tajima and Misono, 1997; Teodorovic, 1998; Tingley, 1979; Vance et al., 1997; Verbeek, 1991; Wark et al., 1997; Wei et al., 1997; Weir and Johnson, 2004; Yan et al., 2002; Yan and Chang, 2002; Yan and Tu, 2002; Yen and Birge, 2000).

3.2. Buses

Bus driver scheduling is another of the most popular areas in crew scheduling and rostering. Several bus driver scheduling systems have been developed in a number of countries including the UK, Germany, Canada and America. A large amount of research has been presented in workshops and proceedings relating to computer-aided scheduling in passenger transport.

References: (Ball and Benoit-Thompson, 1988; Ball et al., 1981, 1983; Belletti et al., 1985; Bertram and Winckler, 1988; Bianco et al., 1992; Blais et al., 1990; Bodin et al., 1983; Bohoris and Thomas, 1995; Borndörfer et al., 2001; Borret and Roes, 1981;

Bransby et al., 1976; Campbell, 1988; Capra et al., 1973; Carraresi and Gallo, 1984a; Carraresi et al., 1982, 1988, 1995; Ceder et al., 1988; Chamberlain and Wren, 1992; Clement and Wren, 1995; Curtis et al., 1999, 2000; Darby-Dowman and Mitra, 1985; Darby-Dowman et al., 1988; de Silva, 2001; Desrochers and Soumis, 1988; Desrochers et al., 1992; Dias et al., 2002; Dupuis, 1985; Elms, 1988; Eusebio et al., 1988; Falkner and Ryan, 1987, 1988, 1992; Ferreira and Guimaraes, 1995; Fores, 1996; Fores and Proll, 1998; Fores et al., 1998, 1999, 2001, 2002; Forsyth and Wren, 1997; Freling et al., 1999, 2001a, 2003; Garnier, 1985; Guerinik and van Caneghem, 1995; Haase and Friberg, 1999; Hamer and Seguin, 1992; Hartley, 1981; Hildyard and Wallis, 1981; Hoffstadt, 1981; Howard and Moser, 1985; Jachnik, 1981; Jorvang, 1992; Koutsopoulos, 1990; Kwan and Wren, 1996; Kwan et al., 1988, 1992, 1993, 2000, 2001; Lamont, 1988; Landis, 1981; Layfield et al., 1999; Leprince and Mertens, 1985; Lessard et al., 1981; Lewis, 1992; Li, 1985; Lourenco et al., 2001a, 2001b, 2002; Luedtke, 1985; Manington and Wren, 1975; Marsten and Shepardson, 1981; Martello and Toth, 1986; Meilton, 2001; Mitchell, 1985; Mitra and Darby-Dowman, 1985; Mitra and Welsh, 1981; Paias and Paixao, 1993; Paixao and Pato, 1989; Paixao et al., 1986; Parker and Smith, 1981; Parker and Wren, 1976, 1983; Patrikalakis and Xerocostas, 1992; Piccione et al., 1981; Rousseau and Blais, 1985; Rousseau et al., 1985; Ryan and Foster, 1981; Shen and Kwan, 2000, 2001; Shepardson, 1985; Shepardson and Marsten, 1980; Smith and Wren, 1984, 1988; Smith et al., 1998; Townsend, 1988; Valouxis and Housos, 2002; Wallis, 1985; Ward et al., 1981; Weaver and Wren, 1970; Willers et al., 1995; Williamson, 1985; Wren, 1968, 1974, 1975a, 1975b, 1976, 1981a, 1981b, 1987, 1994; Wren and Beecken, 1992; Wren and Chamberlain, 1988; Wren and Gualda, 1999; Wren and Kwan, 1999; Wren and Rousseau, 1995; Wren and Smith, 1988; Wren and Wren, 1995; Wren et al., 1985; Yunes et al., 1999, 2000a, 2000c, 2000d, 2001; Zhao et al., 1995a, 1995b).

3.3. Railways

Compared with airline and bus crew scheduling and rostering, train driver and train crew scheduling is a more recent area of research in public transportation systems. Most of the work to date in this area has come from European researchers.

References: (Anbari, 1987; Blais et al., 1990; Caprara et al., 1997, 1998a, 1998b, 1999, 2001; Cavique et al., 1999; Chu and Chan, 1998; Constantino et al., 2002; Ernst et al., 1998, 1999b, 2001a, 2001b; Focacci et al., 1997; Fores et al., 2001, 2002; Freling et al., 2001b, 2004; Kataoka and Komaya, 1998; Kroon and Fischetti, 2001; Kwan et al., 1996a, 1996b, 1999a, 2000; Leprince and Mertens, 1985; Monfroglio, 1996; Morgado and Martins, 1992, 1993; Parker et al., 1995; Shen and Kwan, 2000, 2001; Smith et al., 1998; Sodhi, 2003; Tykulsker et al., 1985; Wren and Kwan, 1999; Wren et al., 1994).

3.4. Mass transit

Buses, trains, aeroplanes and ferries transport large numbers of people and as such are forms of mass transit. Here we use the category mass transit to refer to metropolitan systems such as underground rail. Crew scheduling and rostering in mass transit systems often involves both drivers and security guards.

References: (Ball et al., 1985; Banihashemi and Haghani, 2001; Bennett and Potts, 1968; Bianco et al., 1992; Blais and Rousseau, 1988; Bodin et al., 1983; Borndörfer et al., 2001; Carraresi and Gallo, 1984b; Castaline, 1992; Chu and Chan, 1998; Daduna and Mojsilovic, 1988; Dahl et al., 1985; de Sousa, 1991; Desrochers and Soumis, 1989; Freling et al., 2003; Gaffi and Nonato, 1999; Haase et al., 2001; Hoffstadt, 1988; Koutsopoulos, 1990; Koutsopoulos and Wilson, 1987; Mateus and Casimiro, 2002; Mott and Fritsche, 1988; Rousseau and Desrosiers, 1995; Ryan and Foster, 1981; Tosini and Vercellis, 1988; Volker and Schutze, 1995; Wren and Beecken, 1992; Yunes, 2000).

3.5. General transportation systems

This section contains references to publications that relate to generalised transportation systems and that could be applicable to a number of the areas above. Two common features of rostering applications in transport are that demand is typically generated from timetables, and that geographical considerations make the scheduling process more complicated.

It is also worth mentioning one reference relating to shipping (Wermus and Pope, 1994).

References: (Alefragis et al., 1998; Booler, 1975; Boschetti et al., 2004; Carraresi et al., 1995; Catanas and Paixao, 1995; Haase, 1999; Hagberg, 1985; Kwan et al., 1999b; Mingozzi et al., 2000; Pedrosa and Constantino, 2001; Ryan and Falkner, 1988).

3.6. Call centres

There is an increasing interest in personnel scheduling and rostering in call centres. Given the fluctuating nature of the workload, incident forecasting and demand modelling are essential stages in the development of call centre rosters, though many papers assume that incident forecasts and demand for staff requirements are given.

References: (Andrews and Cunningham, 1995; Andrews and Parsons, 1989, 1993; Atlason et al., 2004; Borst, 2001; Brigandi et al., 1994; Brusco and Jacobs, 2000, 2001; Buffa et al., 1976; Cezik et al., 2001; Chen, 2000; Chen and Henderson, 2001; Church, 1973; Duder and Rosenwein, 2001; Eveborn and Ronnqvist, 2004; Gaballa and Peace, 1979; Gans et al., 2003; Green et al., 2002; Grossman et al., 1999; Henderson and Berry, 1976, 1977; Henderson et al., 1998, 1999; Holloran and Byrn, 1986; Keith, 1979; Lin, 1999; Lin et al., 2000; Linder, 1969; McGinnis et al., 1978; Mehrotra, 1997; Quinn et al., 1991; Samuelson, 1999; Segal, 1974; Sze, 1984; Thompson, 1997a; VanOudheusden and Wen-Jenq, 1982; Willis and Huxford, 1991; Wilson and Willis, 1983).

3.7. Nurse scheduling

Given the importance of health care, and the difficulty of the work, there is an extensive body of work relating to nurse scheduling. Mathematical programming approaches are not dominant in nurse scheduling. Many sophisticated heuristic approaches have been developed to deal with the complex individual work preferences that are a very important aspect of developing good rosters for nurses.

References: (Abdennadher and Schlenker, 1999, 2002; Abernathy et al., 1973; Ahuja and Sheppard, 1975; Aickelin, 1999; Aickelin and Dowsland, 2000; Aickelin and White, 2004; Alivizatos, 1981; Arnold and Mills, 1983; Arthur and Ravindran, 1981; Bailey et al., 1997; Ballantyne, 1979; Begur et al., 1997; Bell et al., 1986; Berrada et al., 1996; Blau and Sear, 1983; Bradley and Martin, 1991; Burke et al., 1998, 2001a, 2001b, 2001c, 2002; Campbell, 2002; Chen and Yeung, 1992; Cheng et al., 1996, 1997; Chun et al., 2000; Darmoni et al., 1995; Dowsland, 1998; Dowsland and Thompson, 2000; Hare, 2001; Hershey et al., 1974, 1981; Meyer auf'm Hofe, 2000, 2001; Huarng, 1999, 2001; Hung, 1991a, 1995b, 1997b; Isken and Hancock, 1991; Jaumard et al., 1998; Jelinek and Kavois, 1992; Jelinek et al., 1973; Kendall et al., 2002; Khan, 1991; Kostreva and Genevier, 1989; Kostreva and Jennings, 1991; Kragelund and Mayoh, 1999; Kumar, 1989; Kusumoto, 1996; Lazaro and Aristondo, 1995; Lukman et al., 1991; Maier-Rothe and Wolfe, 1973; Mason and Smith, 1998; McHugh, 1989; Megeath, 1978; Meisels and Kaplansky, 2001; Meisels and Lusternik, 1997; Meisels and Schaerf, 2003; Meisels et al., 1997; Millar and Kiragu, 1998; Miller et al., 1976, 1979; Morrish and O'Conner, 1970; Moz and Pato, 2004; Musa and Saxena, 1984; Nooriafshar, 1995; Norby et al., 1977; Okada, 1992; Okada and Okada, 1988; Okada et al., 1991; Ozkarahan and Bailey, 1988; Ozkarahan, 1989, 1991a, 1991b; Randhawa and Sitompul, 1993; Rosenbloom and Goertzen, 1987; Ryan et al., 1975; Schulmerich, 1986; Scott, 1998; Scott and Simpson, 1998; Siferd and Benton, 1992, 1994; Silvestro and Silvestro, 2000; Sitompul and Radhawa, 1990; Smith, 1976; Smith and Wiggins, 1977; Smith et al., 1979a, 1979b; Spyropoulos, 2000; Thornton and Sattar, 1996; Trivedi and Warner, 1976; Valouxis and Housos, 2000; Venkataraman and Brusco, 1996; Warner, 1976a, 1976b; Warner and Prawda, 1972; Warner et al., 1991; Weil et al., 1995; Wilson et al., 1988; Wolfe and Young, 1965a, 1965b; Worthington and Guy, 1988).

3.8. Health care systems

This section contains references to publications that deal with rostering health professionals other than nurses.

References: (Agnihothri and Taylor, 1991; Al-Zubaidi and Christer, 1997; Beaulieu et al., 2000; Carter and Lapierre, 2001; Day, 1989; Fahle and Bertels, 2002; Franz and Miller, 1993; Franz et al., 1989; Gierl and Pollwein, 1993; Hancock and Chan, 1988; Hancock et al., 1984; Hoffmann, 1979; Isken, 1995, 2004; Isken and Hancock, 1998; Khan and Callahan, 1993; Li and Li, 2000; Mazzolla and Oppenheimer, 1973; Meyer and Markowitz, 1997; Rising et al., 1973; Rothstein, 1973; Seitman, 1994; Spyropoulos, 2000).

3.9. Protection and emergency services

This area covers police, ambulance, fire brigade, security, and emergency road breakdown services. An important objective in these areas is to deal with incidents within a specified response time. The demand for service is dynamic, and not known ahead of time. As a result, incident forecasting and demand modelling are typically required to be part of the overall scheduling process. While the variability in demand is similar to that experienced in call centres, the geographical aspect of the calls for service must be taken into account when dealing with these systems.

References: (Alfares, 2001; Balakrishnan and Wong, 1990; Beaumont, 1997a; Butler and Maydell, 1979; Chu et al., 1991; Ernst et al., 1999a; Freeman, 1992; Henderson and Mason, 1999; Hung, 1995a; Jackson and Havens, 1997; Kolesar et al., 1975; Laporte, 1999; Laporte et al., 1980; Mills and Panton, 1992; Panton, 1991; Sinuany-Stern and Teomi, 1986; Taylor and Huxley, 1989).

3.10. Civic services and utilities

National, state and local governments operate a large number of labour intensive services such as libraries, post offices, universities, toll booths and power supply utilities. In some of these areas services are provided 24 hours per day and the demand for service varies with the time of day. Efficient staffing is important from both a customer perspective and from the perspective of providing a cost effective service.

References: (Al-Zubaidi and Christer, 1997; Altman et al., 1971; Ashley, 1995; Awad and Chinneck, 1998; Bard et al., 2003; Bean and Bean, 1985; Bodin, 1973b; Byrne and Potts, 1973; Danko and Gulewicz, 1994; Dantzig, 1954; Edie, 1954; Eitzen, 2002; Jacobs and Brusco, 1996; Jarrah et al., 1994; Johns, 1995; Laporte, 1999; Lauer et al., 1994; Lesaint et al., 1997, 1998, 2000; Mabert, 1979; Ritzman et al., 1976; Tsang and Voudouris, 1997).

3.11. Venue management

There are many different types of operations in which workers perform a variety of tasks at the same location. The workload changes over time. Some typical examples are ground, cargo and maintenance services in airports. Other examples include casinos, sport centres and special events.

References: (Alfares, 1988; Alvarez-Valdes et al., 1999; Brusco and Jacobs, 1998a, 1998b; Chew, 1991; Dijkstra et al., 1991; Dowling et al., 1997; Duffuaa and Al-Sultan, 1999; Evans, 1988; Hao et al., 2004; Holloran and Byrn, 1986; Lau and Lau, 1997; Littler and Whitaker, 1997; Mason et al., 1998; Nobert and Roy, 1998; Sarin and Aggarwal, 2001; Schindler and Semmel, 1993; Stern and Hersh, 1980; Wright, 1991).

3.12. Financial services

The publications referenced here relate to rostering clerical workers in service industries such as banking and insurance. One aspect of the development of rosters for bank counter officers is the occurrence of demand peaks, often at lunchtime, that are serviced with part-time staff.

References: (Krajewski et al., 1980; Li et al., 1991; Mabert and Raedels, 1977; Mabert and Watts, 1982; Moondra, 1976; Mould, 1996).

3.13. Hospitality and tourism

Staffing is a significant part of the overall costs in hotels, tourist resorts and restaurants. Again the demand for services is generally not known with certainty ahead of time. Workers may need to work at night-time or on weekends. Some staff have multiple skills and can perform different tasks. Efficient scheduling and rostering can save a significant amount of money by minimising the staff needed to provide services at an acceptable level.

References: (Eveborn and Ronnqvist, 2004; Glover and McMillan, 1986; Loucks and Jacobs, 1991; Love and Hoey, 1990; Poliac et al., 1987; Thompson, 1996a, 1996b).

3.14. Sales

Personnel scheduling and rostering has received little attention for retail business in the literature.

References: (Abboud et al., 1998; Glover et al., 1985; Haase, 1999).

3.15. Manufacturing

The dynamic demand for different products forces manufacturers to revise their production levels from time to time in order to maintain a suitable balance between supply, demand and inventory. As a result, dynamic manpower requirements must be managed to operate production lines efficiently.

References: (Aardal and Ari, 1987; Al-Tabtabai and Alex, 1997, 1998; Alfares and Bailey, 1997; Baxter and Mosby, 1988; Berman et al., 1997; Cochran et al., 1997; Faaland and Schmitt, 1993; Gartner and Wahl, 1998b; Gartner et al., 1998; Glen, 1975; Gopalakrishnan et al., 1993; Hanssmann and Hess, 1960; Hsu, 1984; Hung, 1997b; Iskander and Chou, 1985; Kumar and Arora, 1999; Lee and Vairaktarakis, 1997; Panton and Eitzen, 1997; Popova and Morton, 1998; Raggl and Slany, 1998; Roberts and Escudero, 1983a, 1983b; Sarker, 1986; Schneeweiß et al., 1996; Tharmmaphornphilas and Norman, 2004; Vairaktarakis et al., 2002; Valls et al., 1996; VanGilder and Usher, 1996).

3.16. Other applications

This section includes publications that consider rostering in disparate areas, for example, maintenance engineering, that have received only limited attention in the literature.

References: (Billionnet, 1976; Collins and Sisley, 1994; Corominas et al., 2004; Drexl and Haase, 1999; Eitzen, 1999; Feiring, 1993; Gass, 1991; Grayson and Yuan, 1997; Howick and Pidd, 1990; Liang and Buclatin, 1988; Liang and Thompson, 1987; Lowerre, 1977; Reeves and Reid, 1999; Yang, 1996).

3.17. General

The publications referenced here contain algorithms whose nature, their authors suggest, make them suitable for a number of application areas.

References: (Aggarwal, 1982a; Aykin, 1996; Bailey et al., 1995; Bechtold and Jacobs, 1990, 1996; Bechtold et al., 1991; Bodin, 1973a; Brusco and Jacobs, 1993b; Cai and Li, 2000; Campbell, 2002; DuCote and Malstrom, 1999; Easton and Mansour, 1999; Fischetti et al., 2001; Green et al., 2001; Hosios and Rousseau, 1980; Hung, 1997a; Ingolfsson et al., 2002b; Jacobs and Bechtold, 1993; Jennings et al., 1996; Kilby, 2001; Loucks and Jacobs, 1991; Mason, 1999, 2001; Mason and Nielsen, 1999a, 1999b; Mehrotra et al., 2000; Owens, 2001; Owens et al., 2001; Rogers et al., 1997; Schaerf and Meisels, 1999; Thompson, 1995b, 1998a, 1998b; Vohra, 1988).

4. Methods

This section categorises papers according to the solution techniques employed for rostering problems. The list is not exhaustive but is comprehensive and representative. The reader may feel that some methods are special cases of more general methods. For example, linear programming and integer programming are special cases of mathematical programming. However, we think that it is appropriate to identify these individual methods in order to indicate their importance as rostering solution techniques.

Table 3 shows the keywords used to describe the methods and lists the number of papers relating to each. Again, an individual paper may consider a number of solution methods. For example, a publication might use Set Covering, Column Generation and Lagrangian Relaxation techniques for solving a given problem.

4.1. Enumeration

This is a simple method in which a complete or partial enumeration of all possible solutions is carried out.

References: (Arabeyre et al., 1969; Bailey et al., 1995; Caprara et al., 1999; Cezik et al., 2001; Dawid et al., 2001; Hung, 1991a; Klabjan and Schwan, 2001; König and Strauss, 2000; Maier-Rothe and Wolfe, 1973; Mazzolla and Oppenheimer, 1973; Megeath, 1978; Seitman, 1994; Smith, 1976).

Table 3
Categorisation of papers by solution method.

Method	Papers	Method	Papers
Branch-and-Bound	14	Lagrangean Relaxation	32
Branch-and-Cut	9	Linear Programming	35
Branch-and-Price	30	Matching	36
Column Generation	48	Mathematical Programming	27
Constraint Logic Programming	46	Network Flow	38
Constructive Heuristic	133	Other Meta-Heuristic	11
Dynamic Programming	17	Other Methods	35
Enumeration	13	Queueing Theory	32
Evolution	4	Set Covering	58
Expert Systems	15	Set Partitioning	72
Genetic Algorithms	28	Simple Local Search	39
Goal Programming	19	Simulated Annealing	20
Integer Programming	139	Simulation	31
Iterated Randomised Construction	5	Tabu Search	16

4.2. Artificial intelligence

Artificial Intelligence (AI) is the simulation of certain human intelligence processes using machines, especially computer systems. These processes include learning (the acquisition of information and rules for using the information), reasoning (using the rules to reach approximate or definite conclusions), and self-correction. While Expert Systems are a particular application of AI, we list this method as a separate category. Fuzzy logic is included in the Artificial Intelligence category referenced here.

References: (Andersson et al., 1997; Burke et al., 2002; Kakas and Michael, 1998, 1999; Kumar and Arora, 1999; Kwan et al., 1992; Morgado and Martins, 1992, 1993; Okada, 1992; Okada and Okada, 1988; Onodera, 1989; Raggl and Slany, 1998; Spyropoulos, 2000; Teodorovic, 1998; Zhao et al., 1995a).

4.3. Expert systems

An expert system is a computer program that simulates the judgement and behaviour of a human, or organisation, with expert knowledge and experience in a particular field. Typically, such a system contains a knowledge base storing accumulated experience and a set of rules for applying the knowledge base to a particular situation when it is described to the expert system. In the context of personnel scheduling and rostering, such rules are used to construct duty pairings and rosters.

References: (Anantaram et al., 1993; Burke et al., 2002; Carraresi et al., 1988; Chen and Yeung, 1992; Chow and Hui, 1991, 1993; Gierl and Pollwein, 1993; Jones, 1989; Kwan et al., 1988; Kwok et al., 1995; Lukman et al., 1991; Meisels et al., 1997; Meyer and Markowitz, 1997; Morgado and Martins, 1992; Okada et al., 1991).

4.4. *Constraint logic programming*

Constraint Logic Programming (CLP) is a programming technology for solving complex combinatorial problems. Data representing a problem are described by domain variables. Each variable has an associated domain, which is the set of its potentially feasible values. Constraints describe the different relationships that must be met by a set of variables. Constraint logic programming provides a powerful tool for finding feasible solutions to many scheduling and rostering problems in which complex rules are very hard to model as mathematical equations. This technique is particularly useful when the problem is highly constrained and/or when any feasible (non-optimal) solution will suffice. A recent trend has been to integrate constraint programming with mathematical programming.

References: (Abdennadher and Schlenker, 1999, 2002; Azarmi and Abdulhameed, 1995; Burke et al., 2002; Caprara et al., 1998a; Chabrier, 1999; Cheng et al., 1996, 1997; Chun et al., 2000; Curtis et al., 1999; Darmoni et al., 1995; Dawid et al., 2001; de Silva, 2001; Fahle and Bertels, 2002; Fahle et al., 2002; Focacci et al., 1997; Guerinik and van Caneghem, 1995; Halatsis et al., 1996; Hare, 2001; Meyer auf'm Hofe, 2000, 2001; Junker et al., 1999; König and Strauss, 2000; Kusumoto, 1996; Kwan et al., 2000; Lau and Lau, 1997; Layfield et al., 1999; Lazaro and Aristondo, 1995; Lesaint et al., 1998, 2000; Meisels and Kaplansky, 2001; Meisels and Lusternik, 1997; Meisels et al., 1997; Owens, 2001; Owens et al., 2001; Pavlopoulou et al., 1996; Scott and Simpson, 1998; Sellmann et al., 2000; Smith et al., 1998; Weil et al., 1995; Yang, 1996; Yunes, 2000; Yunes et al., 1999, 2000a, 2000c, 2000d, 2001).

4.5. *Constructive heuristic*

In practice it is sometimes more important to get a sensible feasible solution quickly than to expend a great deal of computational effort to obtain an optimal or near optimal solution. Simple but fast heuristic algorithms provide a means to this end. This is particularly true in the early stages of developing computational approaches for some problems. Moreover, feasible solutions from simple heuristic algorithms often offer a good starting point for obtaining better solutions. Manual solutions for scheduling and rostering can be categorised simple heuristic algorithms.

References: (Aggarwal, 1982b; Alivizatos, 1981; Arthur and Ravindran, 1981; Awad and Chinneck, 1998; Azarmi and Abdulhameed, 1995; Bailey, 1985; Baker, 1974a, 1974b; Baker and Fischer, 1981; Baker and Magazine, 1977; Baker et al., 1979a, 1979b; Ball and Roberts, 1985; Ball et al., 1981; Bartholdi, 1981; Bechtold, 1981, 1988, 1991; Bechtold and Brusco, 1994a, 1994b; Bechtold and Showalter, 1985, 1987; Bechtold et al., 1991; Begur et al., 1997; Bell et al., 1986; Bertram and Winckler, 1988; Bianco et al., 1992; Blais et al., 1990; Bransby et al., 1976; Browne and Tibrewala, 1975; Brownell and Lowerre, 1976; Brusco and Jacobs, 1998a, 1998b; Brusco and Johns, 1995b, 1996; Burke et al., 2002; Burns, 1978; Burns and Carter, 1985; Burns and Koop, 1987; Burns et al., 1998; Caprara et al., 1997, 1999; Chen, 1978; Chew, 1991; Chun et al., 2000; de Sousa, 1991; Dijkstra et al., 1991; Easton and Mansour, 1999; Emmons, 1985; Emmons and Burns, 1991; Emmons and Fuh, 1997; Ernst et al., 1999a;

Fores et al., 2002; Franz and Miller, 1993; Gaffi and Nonato, 1999; Glover et al., 1985; Goodale and Thompson, 2004; Gopalakrishnan et al., 1993; Haase, 1999; Hancock and Chan, 1988; Henderson and Berry, 1976; Meyer auf'm Hofe, 2001; Hosios and Rousseau, 1980; Howard and Moser, 1985; Hsu, 1984; Hung, 1991b, 1993, 1994b, 1994c, 1994d, 1997c, 1999a, 1999b, 2002; Hung and Emmons, 1993; Jachnik, 1981; Jarrah et al., 1994; Johns, 1995; Khoong and Lau, 1992; Kilby, 2001; Kohl and Karisch, 2004; Kroon and Fischetti, 2001; Kroon et al., 1997; Lau, 1994, 1996a, 1996b; Lessard et al., 1981; Li and Kwan, 2000a, 2000b; Li et al., 1991; Lin, 1999; Loucks and Jacobs, 1991; Lowerre, 1977; Mabert and Raedels, 1977; Martello and Toth, 1986; Mason et al., 1998; Mateus and Casimiro, 2002; McGinnis et al., 1978; Miller and Franz, 1996; Monroe, 1970; Morris and Showalter, 1983; Mott and Fritsche, 1988; Narasimhan, 1996; Nicoletti, 1975; Okada, 1992; Okada and Okada, 1988; Ozkarahan, 1991b; Paixao et al., 1986; Parker and Smith, 1981; Parker and Wren, 1976; Pedrosa and Constantino, 2001; Randhawa and Sitompul, 1993; Ritzman et al., 1976; Sarker, 1986; Schaerf and Meisels, 1999; Schulmerich, 1986; Scott, 1998; Sherali and Rios, 1984; Smith and Wiggins, 1977; Smith and Wren, 1988; Thompson, 1997a; Tibrewala et al., 1972; Tosini and Vercellis, 1988; Tykulsker et al., 1985; Valouxis and Housos, 2000, 2002; Vohra, 1987, 1988; Ward et al., 1981; Wermus and Pope, 1994; Willers et al., 1995; Worthington and Guy, 1988; Wright, 1991).

4.6. Simple local search

Local search is used to improve solution quality by iteratively exploring feasible solutions in the neighbourhood of the current solution. Simple local search methods do not use the complicated moving strategies employed in many meta-heuristic approaches such as simulated annealing and tabu search. Hill-climbing and descent are two examples of simple local search.

References: (Azarmi and Abdulhameed, 1995; Baker et al., 1979a; Ball and Roberts, 1985; Bennett and Potts, 1968; Blau and Sear, 1983; Bohoris and Thomas, 1995; Burke et al., 2001c; Campbell, 2002; Carraresi et al., 1982; Ceder et al., 1988; Chow and Hui, 1991, 1993; Chu and Chan, 1998; Collins and Sisley, 1994; Drexl and Haase, 1999; Easton and Rossin, 1991a; Meyer auf'm Hofe, 2000, 2001; Hong et al., 1989; Howard and Moser, 1985; Jachnik, 1981; Jackson and Havens, 1997; Jones, 1989; Krishnamoorthy and Ernst, 1999; Meisels and Schaerf, 2003; Miller et al., 1976, 1979; Raggl and Slany, 1998; Schaerf and Meisels, 1999; Sklar et al., 1990; Smith and Wren, 1984; Tajima and Misono, 1997; Thompson, 1997a; Tosini and Vercellis, 1988; Tsang and Voudouris, 1997; Valouxis and Housos, 2002; Wark et al., 1997; Weaver and Wren, 1970; Wright, 1991).

4.7. Simulated annealing

Simulated Annealing (SA) is a meta-heuristic algorithm that attempts to find global optimal solutions. The idea comes from the energy minimising processes that occur in the slow physical cooling of metals. At high temperatures, the algorithm accepts worse solutions with a certain probability as a means of escaping locally optimal solutions. As the temperature is decreased, this probability converges to zero. Local searches are applied at each temperature level.

References: (Abboud et al., 1998; Bailey et al., 1997; Brusco and Jacobs, 1993a, 1993b, 1995; Brusco et al., 1995; Burke et al., 2002; Dowling et al., 1997; Easton and Mansour, 1999; Emden-Weinert and Proksch, 1999; Ernst et al., 1998; Goodale and Thompson, 2004; Isken and Hancock, 1991; Kragelund and Mayoh, 1999; Lesaint et al., 1998, 2000; Lucic and Teodorovic, 1999; Owens, 2001; Owens et al., 2001; Thompson, 1996b).

4.8. Tabu search

Tabu Search (TS) is a popular and efficient meta-heuristic algorithm. The basic concept is to avoid becoming trapped in cyclic moves by forbidding or penalising moves that give solutions in regions of the solution space that have been visited in the recent past. These recent solution regions are maintained in a tabu list and the tabu list is dynamically updated.

References: (Alvarez-Valdes et al., 1999; Berrada et al., 1996; Burke et al., 1998, 2001a, 2002; Carter and Lapierre, 2001; Cavique et al., 1999; Dowsland and Thompson, 2000; Dowsland, 1998; Easton and Mansour, 1999; Glover and McMillan, 1986; Lourenco et al., 2001a, 2001b, 2002; Shen and Kwan, 2000, 2001; Valouxis and Housos, 2000).

4.9. Iterated randomised construction

There are several types of meta-heuristic that start with a simple greedy constructive heuristic which is randomised and used repeatedly in order to search for better solution. While there is no standard terminology for this type of method, we have grouped these types of algorithms together as iterated randomised construction heuristic.

Greedy random adaptive search procedure
Greedy Random Adaptive Search Procedure (GRASP) is probably the most widely known meta-heuristic of this type in the operations research community. It is a multi-start or iterative process, in which each iteration consists of two phases. First, a feasible solution is produced by the randomised construction phase. Then in the local search phase, a local optimal solution is sought in the neighbourhood of the constructed solution.

References: (Abboud et al., 1998; Aickelin, 1999; Aickelin and Dowsland, 2000; Aickelin and White, 2004; Al-Tabtabai and Alex, 1997, 1998; Awad and Chinneck, 1998; Bailey et al., 1997; Burke et al., 2001a, 2002; Cai and Li, 2000; Clement and Wren, 1995; Dias et al., 2002; Easton and Mansour, 1999; Ingolfsson et al., 2002b; Kwan and Wren, 1996; Kwan et al., 1993, 1999b, 2000, 2001; Levine, 1996; Li and Kwan, 2000b; Lourenco et al., 2001a, 2001b, 2002; Meisels and Lusternik, 1997; Monfroglio, 1996; Wren and Wren, 1995; Wren et al., 1994).

Ant colony optimisation
Ant Colony Optimisation (ACO) is an independently developed variant of GRASP that derives its inspiration from the behaviour of ant colonies. In ACO the results of the randomised constructive heuristic are used to modify the probabilities with which elements of the solution are selected in order to reinforce good solutions. The process is intended to mimic the depositing and evaporation of pheromones by ants which allow them to determine the shortest paths between the nest and a food source.

Reference: (Forsyth and Wren, 1997).

Problem space search
Problem Space Search differs from the above two methods by using an entirely deterministic constructive heuristic but introducing variation by perturbing the problem data on which the constructive heuristic operates. A genetic algorithm or similar technique is then used to search through the space of possible problem data sets.

References: (Li and Kwan, 2000b).

4.10. Evolution

Evolutionary algorithm is an umbrella term used to describe a class of meta-heuristic algorithms based on the use of evolutionary mechanisms to design and implement algorithms. Genetic algorithms are specials examples referenced separately in section 4.11.

References: (Christou et al., 1999; Kataoka and Komaya, 1998; Li and Kwan, 2000a; Wren, 1994).

4.11. Genetic algorithm

The genetic algorithm is also a special meta-heuristic algorithm which derives its behaviour from a metaphor of some of the evolutionary mechanisms found in nature. The procedure involves the creation, with a suitable data representation, of a population of individuals representing feasible solutions. The population is constantly updated by generating new members of the population from existing members, and removing the weakest members using fitness functions. After many iterations, the best member in the population will potentially be the optimal, or close to optimal, solution to the problem.

References: (Abboud et al., 1998; Aickelin, 1999; Aickelin and Dowsland, 2000; Aickelin and White, 2004; Al-Tabtabai and Alex, 1997, 1998; Awad and Chinneck, 1998; Bailey et al., 1997; Burke et al., 2001a, 2002; Cai and Li, 2000; Clement and Wren, 1995; Dias et al., 2002; Easton and Mansour, 1999; Ingolfsson et al., 2002b; Kwan and Wren, 1996; Kwan et al., 1993, 1999b, 2000, 2001; Levine, 1996; Li and Kwan, 2000b; Lourenco et al., 2001a, 2001b, 2002; Meisels and Lusternik, 1997; Monfroglio, 1996; Wren and Wren, 1995; Wren et al., 1994).

4.12. Other meta-heuristics

We use the term Meta-Heuristic to define any algorithm that follows a general framework which is adapted to the specific problem to be solved. This includes any local search method applying complex techniques to explore and guide neighbourhood searches, neural network approaches and others. Examples of meta-heuristics referenced separately include simulated annealing, tabu search, evolutionary algorithms, genetic algorithms and iterated randomised construction (GRASP, ant colony optimisation, problem space search). Any paper using meta-heuristics other than these are referenced here.

References: (Burke et al., 2001b, 2001c, 2002; Carter and Lapierre, 2001; Curtis et al., 2000; Fahle and Bertels, 2002; Ferreira and Guimaraes, 1995; Hao et al., 2004; Kendall et al., 2002; Lagerholm et al., 1997a, 2000).

4.13. Simulation

Simulation is a technique for imitating the behaviour of a real system by means of an analogous computer model. The cause-and-effect relationships of a system are captured in the simulation model which is then used to predict the behaviour of the system. One of the main uses of simulation is to carry out what-if analyses on different system scenarios. In personnel scheduling and rostering, simulation modelling is mainly used for demand modelling.

References: (Abernathy et al., 1973; Al-Zubaidi and Christer, 1997; Atlason et al., 2002, 2004; Brigandi et al., 1994; Cochran et al., 1997; Danko and Gulewicz, 1994; Freeman, 1992; Gaballa and Peace, 1979; Goodale and Thompson, 2004; Hancock et al., 1984; Henderson and Mason, 1999; Hershey et al., 1974; Koelling and Bailey, 1984; Kumar, 1989; Li and Li, 2000; Lin et al., 2000; Linder, 1969; Littler and Whitaker, 1997; Mabert, 1979; Mabert and Watts, 1982; Mason et al., 1998; McHugh, 1989; Mehrotra, 1997; Mould, 1996; Nooriafshar, 1995; Rising et al., 1973; Schaefer et al., 2001; Siferd and Benton, 1994; Thompson, 1993, 1995b).

4.14. Queueing theory

Queueing theory is the study of the behaviour of the queues arising, in the context of rostering demand, from calls to a call centre, customer arrivals at bank counters, patient arrivals at a medical facility, and so on. Queueing theory can be used to analyse service performance using measures such as queue length and waiting time, and to determine possible improvements in performance arising from changes to service times or the number and configuration of available servers. Queueing theory is mainly used for demand modelling in personnel scheduling and rostering systems that have dynamic demand. It can be used as an alternative to simulation in some cases.

References: (Agnihothri and Taylor, 1991; Andrews and Parsons, 1989, 1993; Borst, 2001; Brigandi et al., 1994; Buffa et al., 1976; Chen, 2000; Chen and Henderson, 2001; Chu et al., 1991; Church, 1973; Duder and Rosenwein, 2001; Edie, 1954; Gans et al., 2003; Green et al., 2001, 2002; Henderson et al., 1998, 1999; Hong et al., 1989; Ingolfsson et al., 2002a, 2002b; Jennings et al., 1996; Khan and Callahan, 1993; Koelling and Bailey, 1984; Kolesar et al., 1975; Lin, 1999; Lin et al., 2000; Linder, 1969; Mehrotra, 1997; Quinn et al., 1991; Samuelson, 1999; Sze, 1984; Thompson, 1993, 1998b).

4.15. Dynamic programming

Papers using dynamic programming techniques are included in this section. In many column generation applications dynamic programming is used to solve the shortest path problem or the constrained shortest path problem. A new neighbourhood search technique is also included here. The method uses dynamic programming to search an exponential size neighbourhood in polynomial time. This technique is called *dynasearch* and is another meta-heuristic.

References: (Alefragis et al., 2002; Alfares and Bailey, 1997; Beasley and Cao, 1996, 1998; Chu et al., 1991; Desaulniers et al., 1999; Desrochers and Soumis, 1989; Desrochers et al., 1992; Easton and Rossin, 1997; Eveborn and Ronnqvist, 2004; Freling et al., 2001b; Glen, 1975; Henderson et al., 1998, 1999; Paias and Paixao, 1993; Yunes et al., 2000a, 2001).

4.16. Goal programming

Many rostering problems have a number of different objectives that need to be satisfied. In some cases the different aims are combined into a single weighted objective. However, a number of authors have modelled them using goal programming techniques.

References: (Arthur and Ravindran, 1981; Brusco and Johns, 1995b; Burke et al., 2002; Chen and Yeung, 1992; Easton and Rossin, 1996; Franz et al., 1989; Gass, 1991; Grayson and Yuan, 1997; Huarng, 1999, 2001; Loucks and Jacobs, 1991; Musa and Saxena, 1984; Ozkarahan and Bailey, 1988; Sinuany-Stern and Teomi, 1986; Thompson, 1996a, 1997a; Topaloglu and Ozkarahan, 2000, 2003; Venkataraman and Brusco, 1996).

4.17. Mathematical programming

The term mathematical programming is sometimes used as a synonym for optimisation, in which we seek to minimise or maximise an objective subject to a set of constraints. Linear programming, integer linear programming, and many network flow problems are special cases of mathematical programming and are treated as individual solution methods. The mathematical programming publications referenced here are those that do not use these particular techniques.

References: (Altman et al., 1971; Bechtold, 1991; Bechtold and Brusco, 1994a; Bechtold and Thompson, 1993; Bianco et al., 1992; Billionnet, 1976; Brusco and Johns, 1995b; Burke et al., 2002; Carraresi et al., 1982; Chu and Chan, 1998; Chu et al., 1991; Duffuaa and Al-Sultan, 1999; Easton and Goodale, 2001; Easton and Rossin, 1996; Eitzen, 2002; Gass, 1991; Kostreva and Genevier, 1989; Mabert, 1979; Miller et al., 1976; Mingozzi et al., 2000; Morgado and Martins, 1992; Popova and Morton, 1998;

Reeves and Reid, 1999; Ryan and Foster, 1981; Smith and Wren, 1984; Topaloglu and Ozkarahan, 1998; Yen and Birge, 2000).

4.18. Linear programming

The publications referenced here use linear programming approaches to solve rostering problems.

References: (Aardal and Ari, 1987; Abdennadher and Schlenker, 1999, 2002; Azarmi and Abdulhameed, 1995; Barnhart et al., 1995; Bennett and Potts, 1968; Berman et al., 1997; Blais et al., 1990; Booler, 1975; Burke et al., 2002; Byrne and Potts, 1973; Campbell, 2002; Caprara et al., 1998a; Chabrier, 1999; Cheng et al., 1996, 1997; Chun et al., 2000; Curtis et al., 1999; Dantzig, 1954; Darmoni et al., 1995; Dawid et al., 2001; de Silva, 2001; Fahle and Bertels, 2002; Fahle et al., 2002; Focacci et al., 1997; Freling et al., 2003; Guerinik and van Caneghem, 1995; Halatsis et al., 1996; Hanssmann and Hess, 1960; Hare, 2001; Henderson and Berry, 1976; Meyer auf'm Hofe, 2000, 2001; Isken and Hancock, 1991; Junker et al., 1999; König and Strauss, 2000; Koutsopoulos and Wilson, 1987; Krajewski et al., 1980; Kusumoto, 1996; Kwan et al., 1999a, 2000; Lau and Lau, 1997; Layfield et al., 1999; Lazaro and Aristondo, 1995; Lesaint et al., 1998, 2000; Li, 1985; Lin, 1999; Lourenco et al., 2001b; Meisels and Kaplansky, 2001; Meisels and Lusternik, 1997; Meisels et al., 1997; Mitra and Welsh, 1981; Moondra, 1976; Nobert and Roy, 1998; Owens, 2001; Owens et al., 2001; Ozkarahan, 1989, 1991a; Paixao et al., 1986; Parker and Smith, 1981; Pavlopoulou et al., 1996; Rothstein, 1973; Schneeweiß et al., 1996; Scott and Simpson, 1998; Sellmann et al., 2000; Sklar et al., 1990; Smith et al., 1998; Townsend, 1988; Weil et al., 1995; Willers et al., 1995; Wolfe and Young, 1965b; Yang, 1996; Yunes, 2000; Yunes et al., 1999, 2000a, 2000c, 2000d, 2001).

4.19. Integer programming

These publications employ integer linear programming models but do not use specialised branch-and-bound algorithms as part of the solution method. As can be seen later in this section, integer linear programming models with well-known special structures such as set covering and set partitioning will be treated separately.

References: (Abdelghany et al., 2002, 2004; Alfares, 1988, 1998; Alfares and Bailey, 1997; Anbil et al., 1993; Arabeyre et al., 1969; Arthur and Ravindran, 1981; Ashley, 1995; Atlason et al., 2002, 2004; Aykin, 1996, 1998, 2000; Azmat et al., 2004; Bailey and Field, 1985; Bailey et al., 1997; Ball et al., 1983; Bard et al., 2003; Bean and Bean, 1985; Beaulieu et al., 2000; Beaumont, 1997a, 1997b; Bechtold, 1988; Bechtold and Brusco, 1994a; Bechtold and Jacobs, 1990; Berrada et al., 1996; Bianco et al., 1992; Billionnet, 1999; Bodin, 1973b; Brusco and Jacobs, 1995, 1998a, 1998b, 2000, 2001; Brusco and Johns, 1996; Burke et al., 2002; Campbell, 2002; Caprara et al., 1997, 1999; Carraresi and Gallo, 1984a; Chen, 2000; Chen and Yeung, 1992; Chew, 1991; Cochran et al., 1997; Corominas et al., 2004; Desrochers and Soumis, 1989; Desrosiers, 2001; Dillion and Kontogiorgis, 1999; Drexl and Haase, 1999; Eitzen, 2002;

Eitzen et al., 2004; Ernst et al., 2001a, 2001b; Fahle and Bertels, 2002; Falkner and Ryan, 1988; Fischetti et al., 2001; Fores and Proll, 1998; Fores et al., 1999, 2001; Franz et al., 1989; Freling et al., 2001a, 2003; Graves et al., 1993; Grayson and Yuan, 1997; Henderson and Berry, 1977; Ho et al., 1998; Hoffstadt, 1981; Housos, 1997; Ingolfsson and Cabral, 2002; Ingolfsson et al., 2002b; Isken, 1995, 2004; Isken and Hancock, 1991; Jacobs and Bechtold, 1993; Jacobs and Brusco, 1996; Jarrah et al., 1994; Johnson et al., 1997; Khan, 1991; Khoong and Lau, 1992; Klabjan et al., 2001a, 2002a, 2002b; Kolesar et al., 1975; Kostreva and Jennings, 1991; Koutsopoulos, 1990; Krishnamoorthy and Ernst, 1999; Kwan and Wren, 1996; Kwan et al., 1993, 1996b, 1999a, 1999b, 2000; Laporte et al., 1980; Lauer et al., 1994; Lessard et al., 1981; Li and Li, 2000; Liang and Buclatin, 1988; Lin et al., 2000; Love and Hoey, 1990; Mabert and Raedels, 1977; Mason et al., 1998; Millar and Kiragu, 1998; Miller and Franz, 1996; Mills and Panton, 1992; Mitra and Welsh, 1981; Moz and Pato, 2004; Nobert and Roy, 1998; Ozkarahan, 1989, 1991a, 1991b; Rekik et al., 2004; Roberts and Escudero, 1983a, 1983b; Rosenbloom and Goertzen, 1987; Rushmeier et al., 1995; Ryan and Foster, 1981; Sanders et al., 1999; Shepardson, 1985; Sodhi, 2003; Stern and Hersh, 1980; Taylor and Huxley, 1989; Tharmmaphornphilas and Norman, 2004; Thompson, 1995a, 1995b; Thornton and Sattar, 1996; Topaloglu and Ozkarahan, 1998; Valouxis and Housos, 2000, 2002; VanOudheusden and Wen-Jenq, 1982; Warner, 1976b; Warner and Prawda, 1972; Wedelin, 1995; Weir and Johnson, 2004; Willers et al., 1995; Willis and Huxford, 1991; Wilson and Willis, 1983; Wren and Kwan, 1999; Yunes, 2000; Yunes et al., 2000c).

4.20. Lagrangean relaxation

Lagrangean relaxation is used to find good bounds for mathematical, typically linear and integer linear, programs. This is accomplished by relaxing (removing) some constraints and incorporating them as penalised functions in the objective. The relaxed problems are easier to solve than the original problem and the best bound can be found by iteratively updating the objective penalty coefficients.

References: (Alefragis et al., 1998, 2000; Anbil et al., 1998, 1999; Balakrishnan and Wong, 1990; Ball and Benoit-Thompson, 1988; Beasley and Cao, 1996, 1998; Borndörfer et al., 2001; Boschetti et al., 2004; Campbell, 2002; Caprara et al., 1997, 1998a, 1998b, 1999; Carraresi et al., 1982, 1988, 1995; Chebalov and Klabjan, 2002; Dijkstra et al., 1991; Freling et al., 2001a, 2003; Gaffi and Nonato, 1999; Kroon and Fischetti, 2001; Kroon et al., 1997; Mason, 2001; Mateus and Casimiro, 2002; Paias and Paixao, 1993; Paixao and Pato, 1989; Shepardson, 1985; Shepardson and Marsten, 1980; Vairaktarakis et al., 2002).

4.21. Column generation

Column generation is a computational technique for solving large-scale integer linear programming problems or linear programming problems. Column generation formulations normally have tighter linear programming relaxations than other more compact formulations for the same problem. This tightness is used to reduce the computational burden of exploring the branch-and-bound tree when solving integer linear programs. Only papers using column generation for a linear programming relaxation are listed here. The papers that use column generation in all nodes of the search tree are collected in section 4.24.

References: (Alefragis et al., 1998; Anbil et al., 1991, 1992, 1993; Barnhart et al., 1995; Borndörfer et al., 2001; Boschetti et al., 2004; Carraresi et al., 1995; Catanas and Paixao, 1995; Chabrier, 1999; Chu et al., 1997; Crainic and Rousseau, 1987; de Silva, 2001; Desrochers and Soumis, 1989; Easton and Rossin, 1991b, 1997; Eitzen, 1999, 2002; Fahle et al., 2002; Fores, 1996; Fores and Proll, 1998; Fores et al., 1998, 1999, 2001, 2002; Freling et al., 2001a, 2001b, 2003; Haase and Friberg, 1999; Junker et al., 1999; Krishnamoorthy and Ernst, 1999; Kroon and Fischetti, 2001; Lavoie et al., 1988; Makri and Klabjan, 2001; Mason, 2001; Mason and Nielsen, 1999a, 1999b; Mason and Smith, 1998; Panton and Ryan, 1999; Pedrosa and Constantino, 2001; Rousseau and Desrosiers, 1995; Sarin and Aggarwal, 2001; Sellmann et al., 2000; Stojković et al., 1998; Valouxis and Housos, 2002; Yunes et al., 1999, 2000a, 2000d).

4.22. Branch and bound

Branch and bound schemes are usually used for solving integer linear programs. Publications that use customised branch and bound schemes are referenced here.

References: (Beasley and Cao, 1996, 1998; Beaulieu et al., 2000; Booler, 1975; Brusco, 1998; Capra et al., 1973; Haase and Friberg, 1999; Isken, 1995; Schneeweiß et al., 1996; Shepardson and Marsten, 1980; Trivedi and Warner, 1976; Valls et al., 1996; Wei et al., 1997; Yen and Birge, 2000).

4.23. Branch and cut

Publications that explore the use of customised branch and bound schemes in conjunction with cutting planes are referenced here.

References: (Aykin, 1998; Ernst et al., 1999b; Fischetti et al., 2001; Gamache et al., 1998; Haase, 1999; Haase et al., 2001; Hoffman and Padberg, 1993; Johnson et al., 1997; Mason, 1999).

4.24. Branch and price

Branch and price is a specialised branch and bound method in which column generation is employed at all nodes of the branch-and-bound tree. In these papers, so-called constraint branching rules are used in order to efficiently to solve pricing subproblems at each node of the search tree.

References: (Anbil et al., 1999; Barnhart et al., 1994, 1998, 1999; Desaulniers et al., 1997, 1998; Desrochers and Soumis, 1988; Eitzen, 2002; Eitzen et al., 2004; Ernst et al., 1999b; Eveborn and Ronnqvist, 2004; Freling et al., 2001b, 2004; Gamache and Soumis, 1998; Gamache et al., 1998, 1999; Haase, 1999; Haase et al., 2001; Jaumard et al., 1998; Johnson et al., 1997; Lasry et al., 2000; Mehrotra et al., 2000; Stojković and Soumis, 2001a, 2001b; Vance et al., 1997; Yan et al., 2002; Yan and Chang, 2002; Yunes, 2000; Yunes et al., 2000c, 2001).

4.25. Set covering

In rostering, set covering refers to models in which the objective is to cover the demand for staff. In most cases set covering models are solved using integer programming, and possibly column generation, methods. Set covering and set partitioning models are widely used in personnel scheduling, particularly in crew scheduling and crew rostering problems.

References: (Alefragis et al., 1998, 2000, 2002; Andersson et al., 1997; Barnhart et al., 1994; Bartholdi, 1981; Bartholdi et al., 1980; Bechtold et al., 1991; Borndörfer et al., 2001; Brusco, 1998; Brusco and Johns, 1995b; Brusco et al., 1995; Caprara et al., 1997, 1999, 2001; Carraresi et al., 1982; Crainic and Rousseau, 1987; Desrochers and Soumis, 1988; Easton and Rossin, 1996, 1997; Eitzen, 1999, 2002; Eusebio et al., 1988; Fores and Proll, 1998; Fores et al., 1999, 2001, 2002; Freling et al., 2001a; Gaballa and Peace, 1979; Kroon and Fischetti, 2001; Kwan et al., 1999a, 1999b, 2000; Lavoie et al., 1988; Mabert and Watts, 1982; Mason and Smith, 1998; Mateus and Casimiro, 2002; Morris and Showalter, 1983; Ozkarahan, 1991a; Paixao and Pato, 1989; Paixao et al., 1986; Panton and Ryan, 1999; Pedrosa and Constantino, 2001; Rousseau and Desrosiers, 1995; Rubin, 1973; Sanders et al., 1999; Schindler and Semmel, 1993; Shepardson, 1985; Smith and Wren, 1988; Thompson, 1996a, 1997b; Tykulsker et al., 1985; Wedelin, 1995; Willers et al., 1995; Wren and Kwan, 1999; Wren et al., 1985, 1994; Yan et al., 2002).

4.26. Set partitioning

Set partitioning refers to models in which the aim is to match the demand for staff, though it can also be used more flexibly by allowing penalised under or over coverage. Set partitioning is a variation of set covering and uses similar solution methods.

References: (Alefragis et al., 2000; Anbil et al., 1992, 1998; Bailey, 1985; Ball et al., 1983; Barnhart et al., 1999; Bartholdi et al., 1980; Bean and Bean, 1985; Borret and Roes, 1981; Boschetti et al., 2004; Butchers et al., 2001; Chebalov and Klabjan, 2002; Chu et al., 1997; Darby-Dowman and Mitra, 1985; Day and Ryan, 1997; Desaulniers et al., 1998; Easton and Goodale, 2001; Ernst et al., 1999b; Eveborn and Ronnqvist, 2004; Fahle et al., 2002; Falkner and Ryan, 1987, 1988, 1992; Fores and Proll, 1998; Fores et al., 1998, 1999; Freling et al., 2004; Gaballa and Peace, 1979; Gaffi and Nonato, 1999; Gamache and Soumis, 1998; Gamache et al., 1998, 1999; Gershkoff, 1989; Graves et al., 1993; Guerinik and van Caneghem, 1995; Haase and Friberg, 1999; Haase et al., 2001; Halatsis et al., 1996; Hoffman and Padberg, 1993; Jarrah and Diamond, 1997; Keith, 1979; Klabjan et al., 2001a, 2002b; Koelling and Bailey, 1984; Kohl and Karisch, 2004; Lasry et al., 2000; Marsten and Shepardson, 1981; Marsten et al., 1979; Mason, 1999; Mason and Nielsen, 1999a, 1999b; Mellouli, 2001; Mingozzi et al., 2000; Mitra and Darby-Dowman, 1985; Patrikalakis and Xerocostas, 1992; Pavlopoulou et al., 1996; Piccione et al., 1981; Rothstein, 1972; Rushmeier et al., 1995; Ryan, 1992; Ryan and Falkner, 1988; Ryan and Foster, 1981; Sanders et al., 1999; Sarin and Aggarwal, 2001; Shepardson and Marsten, 1980; Tajima and Misono, 1997; Wedelin, 1995; Willers et al., 1995; Yan and Chang, 2002; Yunes et al., 2000a, 2000d, 2001).

4.27. Network flow

In some cases a personnel scheduling or rostering problem can be naturally cast as a network model and network flow methods are used to solve complete problems or subproblems that arise from this approach. Network models are also used to solve subproblems that arise in column generation methods.

References: (Balakrishnan and Wong, 1990; Ball and Benoit-Thompson, 1988; Banihashemi and Haghani, 2001; Barnhart et al., 1994; Bartholdi et al., 1980; Billionnet, 1976; Blais et al., 1990; Borndörfer et al., 2001; Carraresi and Gallo, 1984b; Carraresi et al., 1988; Cezik et al., 2001; Dowsland and Thompson, 2000; Ernst et al., 1999a; Gans et al., 2003; Gass, 1991; Jarrah et al., 1994; Jaumard et al., 1998; Khan, 1991; Koop, 1988; Kress and Golany, 1994; Kroon et al., 1997; Liang and Buclatin, 1988; Liang and Thompson, 1987; Love and Hoey, 1990; Mason, 1999; Mason and Smith, 1998; Mellouli, 2001; Millar and Kiragu, 1998; Moz and Pato, 2004; Nicoletti, 1975; Panton and Ryan, 1999; Patrikalakis and Xerocostas, 1992; Pedrosa and Constantino, 2001; Segal, 1974; Sodhi, 2003; Tingley, 1979; Vandenberg and Panton, 1994; Wilson and Willis, 1983; Yan and Tu, 2002).

4.28. Matching

Matching algorithms can be applied to many rostering problems or to subproblems arising as part of the solution method for these problems. Assignment algorithms are also included in this category.

References: (Abdelghany et al., 2004; Ahuja and Sheppard, 1975; Alvarez-Valdes et al., 1999; Ball and Benoit-Thompson, 1988; Ball and Roberts, 1985; Ball et al., 1981, 1983, 1985; Bard et al., 2003; Bartholdi and Ratliff, 1978; Belletti et al., 1985; Bennett and Potts, 1968; Bianco et al., 1992; Blais et al., 1990; Caprara et al., 1998b; Carraresi and Gallo, 1984a, 1984b; Chu and Chan, 1998; Constantino et al., 2002; Corominas et al., 2004; Evans, 1988; Franz and Miller, 1993; Hagberg, 1985; Hoffstadt, 1981; Howard and Moser, 1985; Kohl and Karisch, 2004; Lee and Vairaktarakis, 1997; Lessard et al., 1981; Mott and Fritsche, 1988; Ozkarahan, 1989; Randhawa and Sitompul, 1993; Rousseau et al., 1985; Seitman, 1994; Tosini and Vercellis, 1988; Vairaktarakis et al., 2002; Valouxis and Housos, 2002; Wark et al., 1997).

4.29. Other methods

Specialised methods, not covered by any of the methods listed previously, are referenced here. Some of the methods include specialised backtracking and other iteration procedures, parallel computing and policy evaluation techniques.

References: (Alefragis et al., 2002; Andrews and Cunningham, 1995; Baxter and Mosby, 1988; Bodin, 1973a, 1973b; Butler and Maydell, 1979; Castaline, 1992; Faaland and Schmitt, 1993; Gartner and Wahl, 1998b; Gartner et al., 1998; Goumopoulos et al., 1997; Ingolfsson and Cabral, 2002; Ingolfsson et al., 2002a; Iskander and Chou, 1985; Jacobs and Bechtold, 1993; Kostreva and Genevier, 1989; Lagerholm et al., 1997b; Lee and Vairaktarakis, 1997; Lin et al., 2000; Morrish and O'Conner, 1970; Musliu et al., 2000; Norby et al., 1977; Poliac et al., 1987; Popova and Morton, 1998; Ryan et al., 1975; Sinuany-Stern and Teomi, 1986; Sitompul and Radhawa, 1990; Taylor and Huxley, 1989; Thompson, 1998b; Vairaktarakis et al., 2002; Valls et al., 1996; VanGilder and Usher, 1996; Warner et al., 1991; Wilson et al., 1988; Wolfe and Young, 1965b).

Note

1. Here we are ignoring the many good rostering products that provide bookkeeping functionality for what remain essentially manual staffing procedures.

References

Aardal, K. and A. Ari. (1987). "Decomposition Principles Applied to the Dynamic Production and Work-Force Scheduling Problem." *Engineering Costs and Production Economics* 12(1–4), 39–49.
Notes. This paper discusses the determination of demand for staff in a manufacturing environment. Given a profile for costs and benefits the linear program determines an optimal inventory level and at the same time demand for staffing. Decomposition methods Benders, Dantzig–Wolfe, and cross decomposition are discussed and comments are made on how problem structure is exploited by these methods.

Abboud, N., M. Inuiguchi, M. Sakawa, and Y. Uemura. (1998). "Manpower Allocation Using Genetic Annealing." *European Journal of Operational Research* 111, 405–420.
Notes. The paper considers the problem of allocating sales staff over the branches of a company in order to best meet the sales predictions at the different branches. Various examples, the largest being to assign 215 sales representatives to 33 branches, were considered when testing the solution algorithms. The main focus of the paper is to evaluate different GA SA hybrid forms in terms of providing efficient solution techniques.

Abdelghany, K., A. Abdelghany, G. Ekollu, and S. Raina. (2002). "An Integrated Real-Time Decision Support Tool for Airline Recovery under Irregular Operation Conditions." Working Paper.
Notes. This paper presents an integrated real-time decision support tool for airline recovery under irregular operation conditions. It fully automates the recovery process. It allows detections of potential system breaks ahead of their occurrence. It generates an integrated recovery plan to fix these projected breaks. It implements a greedy simulation-optimization approach in a rolling framework. The recovery problem at each stage is formulated as an integer linear program.

Abdelghany, A., G. Ekollu, R. Narasimhan, and K. Abdelghany. (2004). "A Proactive Crew Recovery Decision Support Tool for Commercial Airlines during Irregular Operations." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 309–331.

Notes. This paper describes a decision support tool that automates crew recovery during irregular operations for large-scale commercial airlines. The system proactively recovers crew problems ahead of time before their occurrence. It also gives the user wide flexibility to react to the different operation scenarios. Recovering actions include delaying flights, using standby and reserve crew, crew swapping and deadheads. The crew recovering problem is formulated as an integer linear program and is solved using a rolling approach in which a sequence of optimization assignment problems are solved to recover flights in chronological order of their departure. In each assignment problem, the objective is to recover as many flights as possible while minimizing total system cost and flight delays. The solutions of assignment problems are inputs for generating new rosters.

Abdennadher, S. and H. Schlenker. (1999). "Nurse Scheduling Using Constraint Logic Programming." In *Proceedings of the 11th Conference on Innovative Applications of Artificial Intelligence*, pp. 838–843.
Notes. This paper describes a standard three shifts per day problem, with typical hours, coverage, and break time constraints. The solution technique is based on splitting the scheduling into days off scheduling and shift scheduling phases. Of interest is the discussion of pre-allocation of nurses to shifts and the need for interactivity for acceptance of the software.

Abdennadher, S. and H. Schlenker. (2002). "Nurse Rostering Using Constraint Programming." Working Paper.
Notes. In this paper, the nurse scheduling problem is discussed and a specific system, INTERDIP, is presented, that assists a human planner in scheduling the nurse working shifts for a hospital ward. INTERDIP is an advanced industrial prototype that supports semi-automatic creation of rosters. Using constraint based programming, INTERDIP imitates certain aspects of manual planning.

Abernathy, W., N. Baloff, J. Hershey, and S. Wandel. (1973). "A Three-Stage Manpower Planning and Scheduling Model: A Service Sector Example." *Operations Research* 22(3), 693–711.
Notes. This paper presents a planning model for workforce planning of nursing staff. Decision problems discussed include: the number of number of nurses to fix in a ward or have in a floating pool, when to make transfers, and satisfying training requirements.

Aggarwal, S. (1982a). "A Focused Review of Scheduling in Services." *European Journal of Operational Research* 9(2), 114–121.
Notes. This paper provides a review and classification of 25 papers specific to service industry personnel scheduling. It provides a description of typical industry specific constraints and solution techniques.

Aggarwal, S. (1982b). "Two Methods of Labor Scheduling for Shift Operations." *Production and Inventory Management* 23(2), 36–44.
Notes. Two constructive algorithms are designed to generate rosters for two types of days off scheduling. In one case, no part time worker is allowed and therefore, off days are scheduled on days with lower demands. In another case, part time workers are employed to cover days with larger demands.

Agnihothri, S. and P. Taylor. (1991). "Staffing a Centralized Appointment Scheduling Department in Lourdes Hospital." *Interfaces* 21(5), 1–11.
Notes. The paper looks at applying an M/M/C queue model to determine the number of staff needed at different times of the day to handle phone calls for patient appointments in a large hospital. The paper also provides an easy-to-reference generalized queueing table to aid other managers.

Ahuja, H. and R. Sheppard. (1975). "Computerized Nurse Scheduling." *Industrial Engineering* 7(10), 24–29.
Notes. The paper looks at developing four-week cyclic rosters. Individual nurse preferences are allowed for. Computer implementation as at 1975, superseded by later approaches.

Aickelin, U. (1999). "Genetic Algorithm for Multiple-Choice Optimisation Problem." Ph.D. Thesis, University of Wales Swansea.
Notes. This thesis investigates the use of problem-specific knowledge to enhance a genetic algorithm approach to the nurse scheduling problem among others. The algorithm allows construction of a feasible nurse roster that considers as many requests as possible. The main theme of this work is to balance feasibility and the cost of solutions. The standard genetic algorithm generates poor results. To over-

come this, problem-specific information is added in a variety of ways, some of which is designed to increase the number of feasible solutions found whilst other modifications are intended to improve the quality of such solutions. The most successful variant of the proposed algorithm has a more than 99% chance of finding a feasible solution which is either optimal or within a few percentage points of optimality.

Aickelin, U. and K. Dowsland. (2000). "Exploiting Problem Structure in a Genetic Algorithm Approach to a Nurse Rostering Problem." *Journal of Scheduling* 3, 139–153.
Notes. The paper provides a very good description of how a GA implementation must be carefully designed to solve nurse scheduling problems. The problem looked at in the paper is described as a multiple-choice set covering problem. Multiple-choice refers to the fact that higher grade nurses can carry out the duties of lower grade nurses, though at a higher cost.

Aickelin, U. and P. White. (2004). "Building Better Nurse Scheduling Algorithms." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 159–177.
Notes. The paper contains an excellent description of a typical nurse rostering problem and presents an integer programming formulation which is solved by a number of evolutionary algorithms. The main focus of the paper, however, is to address the problem of how to tune an evolutionary algorithm to solve difficult problems, as typified by nurse rostering, in which feasible solutions are sparsely distributed in a large search space. To this end the authors describe a method for statistically comparing the performance of implementations of similar algorithms. The method allows rapid identification of the processes needed to improve the solution method for a given problem using the results from a set of candidate algorithmic implementations. This statistical comparison technique may be applied to other problems in which a set of similar algorithms could be used to find a solution.

Aitken, S. and R. Hayyen. (2000). "Gate Gourmet London Gatwick Operations." `http://www.e-optimization.com`: Case study.
Notes. This report extols the benefits of the ROST1MA software as a decision support tool of which little technical detail is provided.

Al-Tabtabai, H. and A. Alex. (1997). "Manpower Scheduling Optimization Using Genetic Algorithm." In *Proceedings of the 1997 4th Congress on Computing in Civil Engineering*, Philadelphia, pp. 702–709.
Notes. The paper discusses how GA methods might be applied to a problem in which a workforce needs to be assigned to different units of a construction company engaged in multiple projects.

Al-Tabtabai, H. and A. Alex. (1998). "Resource Allocation in Construction Projects Using Genetic Algorithms." *Kuwait Journal of Science and Engineering* 25(1), 145–162.
Notes. The paper discusses the use of GA methods for assigning different tradespeople to jobs for a construction company engaged in multiple projects. The employees are assigned according to the critical paths and priorities of jobs in the projects.

Al-Zubaidi, H. and A. Christer. (1997). "Maintenance Manpower Modelling for a Hospital Building Complex." *European Journal of Operational Research* 99, 603–618.
Notes. The paper uses simulation modelling to evaluate different workforce planning scenarios to meet the maintenance requirements at a large public hospital. The model uses estimated demand for tradesmen, expected holidays and sick leave, materials costs, and so on, to evaluate scenarios representing different employment policies.

Alefragis, P., C. Goumopoulos, E. Housos, P. Sanders, T. Takkula, and D. Wedelin. (1998). "Parallel Crew Scheduling in PAROS." In *European Conference on Parallel Processing*, pp. 1104–1113.
Notes. This paper describes the authors efforts to parallelize their crew scheduling algorithm (mostly superseded by (Alefragis et al., 2000)). The basic algorithm solves a set covering formulation with additional base capacity constraints using a Lagrangean heuristic and column generation. The column generation can easily be spread over multiple computers. A more difficult task is to parallelize the Lagrangean multiplier update. Two techniques are suggested for this part. Computational results with up to 5000 rows and 400,000 columns show that a near linear speed up can be achieved with 1–4 processors.

Alefragis, P., P. Sanders, T. Takkula, and D. Wedelin. (2000). "Parallel Integer Optimization for Crew Scheduling." *Annals of Operations Research* 99(1), 141–166.

Notes. This paper describes how the Lagrangean relaxation heuristic introduced in (Wedelin, 1995) can be improved and parallelized. This algorithm solves set covering/partitioning problems as they arise in crew scheduling and rostering by relaxing all of the constraints and using cost perturbations to obtain a primal feasible solution. An active set method is introduced to reduce the number of columns considered in each iteration. Ways of splitting the algorithm over multiple processors based on partitioning the set of variables and the constraints are presented and analysed. Numerical results indicate a significant speed up of the basic algorithm can be achieved.

Alefragis, P., K. Papoutsis, C. Valouxis, and E. Housos. (2002). "A Parallel Column Generation Approach in Solving the Crew Pairing Problem." Working Paper.

Notes. In this paper, a solution approach is developed for solving large-scale set covering models arising from crew scheduling problems. This new approach combines a column generation scheme with an external legality system for generating pairings, a Lagrangean based heuristic integer optimizer and distributed parallel processing algorithms over a network of workstations. Computational results from problem instances from a large European airline demonstrate that distributed parallel processing techniques speedup the solution process without sacrificing solution quality.

Alfares, H. (1988). "Aircraft Maintenance Workforce Scheduling: A Case Study." *Journal of Quality in Maintenance Engineering* 5(2), 78–88.

Notes. This is a case study describing the generation of a weekly roster for aircraft maintenance staff of Saudi Aramco. There are two possible shifts per day with a weekly pattern of demand. Simple IP models are provided, which determine the minimum number of staff required and the optimal assignment of days off and shifts.

Alfares, H. (1998). "An Efficient Two-Phase Algorithm for Cyclic Days-off Scheduling." *Computers and Operations Research* 25(11), 913–923.

Notes. Days-off scheduling with exactly five consecutive working days for each employee can be modelled as a simple integer program. By adding one cut to the formulation, optimal solutions can be found more quickly. This additional cut specifies the minimum workforce size that can be obtained from an analytical formula.

Alfares, H. (2001). "Staffing and Workforce Scheduling for a Security Gate." *International Journal of Operations & Quantitative Management* 7(4), 281–293.

Alfares, H.K. (2004). "Survey, Categorization, and Comparison of Recent Tour Scheduling Literature." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 145–175.

Notes. The literature published since 1990 is reviewed and classified according to solution techniques. These techniques are classified into ten categories: manual solution, integer programming, implicit modeling, decomposition, goal programming, working set generation, LP-based solution, construction and improvement, metaheuristics, and other methods. Different techniques are compared. Future research directions are also identified.

Alfares, H. and J. Bailey. (1997). "Integrated Project Task and Manpower Scheduling." *IIE Transactions* 29(9), 711–717.

Notes. This paper discusses project scheduling for construction. In which the system is to produce a project plan which is on time and minimum cost. The compression of the project plan is achieved via adjustments to the manpower assigned to activities. An integer programming formulation is presented as well as a dynamic programming heuristic.

Alivizatos, M. (1981). "A New Concept in Scheduling for Nurses." *Supervisor Nurse*, pp. 20–22.

Notes. Replace the traditional working pattern of eight hours each day and five days each week by a new working pattern in which lengths of shifts can vary and the number of working days varies too.

Altman, S., E. Beltrami, S. Rappaport, and G. Schoepele. (1971). "Nonlinear Programming Model of Crew Assignments for Household Refuse Collection." *IEEE Transactions on Systems, Man, and Cybernetics* 1, 289–297.

Notes. This paper presents a model for calculating manpower requirements for refuse collection. A non-linear mathematical programming model is used to transform refuse tonnage for each day of the week into a requirement for trucks and therefore staffing levels.

Alvarez-Valdes, R., E. Crespo, and J. Tamarit. (1999). "Labour Scheduling at an Airport Refuelling Installation." *Journal of the Operational Research Society* 50(3), 211–218.

Notes. The problem of creating rosters for aircraft refuelling staff at airports in Spain is presented together with a heuristic algorithm for creating good solutions. The problem is characterised by variable demand and relatively flexible shift times though shifts are categorised into three types. The planning horizon can be short term (one week) through to long term (whole year with given leave blocks). The solution method proceeds in three phases: first all feasible weekly patterns of night, morning, evening and rest shifts are generated and from these a suitable subset covering demand are selected. Next these worklines are assigned to staff. Finally actual shifts are assigned to each day.

Anantaram, C., P. Joshi, K. Deshpande, and P. Trivedi. (1993). "Crew Rostering System an Expert System for Scheduling Crew for Indian Airlines." In *Proceedings of the 9th Conference on Artificial Intelligence for Applications*, pp. 63–70.

Notes. This paper discusses the crew rostering problem for the monthly activity of an Indian airline. An expert system is used to represent the rules and heuristics specified by the experts and implements a search for a roster. The system is also used for disruption management. The system is started to be able to avoid backtracking and produce solutions conforming to given constraints. However, little is said about the quality of the solutions or how the 24 hour execution time compares with other systems.

Anbari, F. (1987). "Train and Engine Crew Management System." In T. Murthy, B. Mellitt, and J. Korber (eds.), *Computers in Railway Operations*, pp. 267–284. WIT Press.

Notes. This paper provides an overview of a train and engine crew management system implemented at Amtrak railways.

Anbil, R., E. Gelman, B. Patty, and R. Tanga. (1991). "Recent Advances in Crew-Pairing Optimization at American Airlines." *Interfaces* 21(1), 62–74.

Notes. This case study describes current crew scheduling methods at American Airlines. It details how the methods have evolved since the 1970s and how improvements to individual sub-algorithms have improved overall performance.

Anbil, R., R. Tanga, and E. Johnson. (1992). "A Global Approach to Crew-Pairing Optimization." *IBM Systems Journal* 31, 71–78.

Notes. This paper reports on a joint study by American Airlines and IBM to improve the quality of American Airlines' crew scheduling solutions. This was achieved by generating a much bigger set of columns than was previously considered (5.5 million), but only solving LP subproblems with about 5000 columns and then pricing the remaining columns to form the next subproblem. Integer solutions were found by successively fixing follow on segments where the same crew need to fly both segments. This exercise has reportedly resulted in significant cost savings.

Anbil, R., C. Barnhart, L. Hatay, E. Johnson, and V. Ramakrishnan. (1993). "Crew-Pairing Optimization at American Airlines Decision Technologies." In T. Ciriani and R. Leachman (eds.), *Optimization in Industry: Mathematical Programming and Modeling Techniques in Practice*, pp. 31–36. Chichester: Wiley.

Notes. This paper gives a brief description of the crew scheduling practices at American Airlines. In particular it describes the differences in approach that are necessary in order to deal with the long-haul and domestic crew scheduling problems.

Anbil, R., J. Forrest, and W. Pulleyblank. (1998). "Column Generation and the Airline Crew Pairing Problem." *Documenta Mathematica*, pp. 677–686.

Notes. This brief paper starts by summarising the crew scheduling problem and outlines the usual column generation approach to solving the set partitioning formulation. It then describes several tricks for improving the ability to solve large problems, some of which are already given in more detail elsewhere (e.g. (Anbil et al., 1992)). A new idea is the use of the volume algorithm (a variant of Lagrangean relaxation) to generate columns and then to use the dual solution to crash the dual simplex method.

Numerical results indicate significant performance improvements over using the dual simplex method by itself.

Anbil, B., F. Barahona, L. Ladanyi, R. Rushmeier, and J. Snowdon. (1999). "Airline Optimization." *OR/MS Today* 26(6), 26–29.

Notes. A high level overview is given in this paper of IBM's work in the area of OR for airlines. This includes crew scheduling, disruption management for crew trips and simulation of passenger flow. The techniques used include the volume algorithm (Lagrangean relaxation variant), Branch-and-Cut-and-Price and simulation.

Andersson, E., E. Housos, N. Kohl, and D. Wedelin. (1997). "Crew Pairing Optimization." In G. Yu (ed.), *OR in Airline Industry*, pp. 1–31. Boston, MA: Kluwer Academic.

Notes. This paper starts with a nice review of the crew scheduling literature and the differences between the American and European airlines. It then presents the Carmen crew scheduling system. This produces crew schedules over a weekly horizon or longer by iteratively optimizing one day with the remaining pairings fixed. Crew optimisation is done by a combination of tricks, heuristics and LP. A special feature of Carmen is the rulebase for crew pairings which allows rules to be written which can be used to test if a pairing or partial pairing is feasible.

Andrews, B. and S. Cunningham. (1995). "L.L. Bean Improves Call-Center Forecasting." *Interfaces* 25(6), 1–13.

Notes. This is one of a few forecasting papers we collected since its main role is to provide inputs for call centre scheduling. The ARIMA/transfer function methodology is used to do forecasting because time series data exhibit seasonal patterns but strongly in fluenced by independent variables including holiday and advertising interventions.

Andrews, B. and H. Parsons. (1989). "L.L. Bean Chooses a Telephone Agent Scheduling System." *Interfaces* 19(6), 1–9.

Notes. This paper mainly discusses the evaluation of several vendors of workforce planning software for call centres. A description is also included, of the queueing model and testing regime used to evaluate the software.

Andrews, B. and H. Parsons. (1993). "Establishing Telephone-Agent Staffing Levels through Economic Optimization." *Interfaces* 23(2), 14–20.

Notes. This paper builds existing work by the authors (Andrews and Parsons, 1989) regarding call centre staffing levels. Additional work has been done to formalise the requirements for staffing levels. This includes incorporating costs for abandonments as well as direct costs incurred by staffing levels.

Arabeyre, J., J. Fearnley, F. Steiger, and W. Teather. (1969). "The Airline Crew Scheduling Problem: A Survey." *Transportation Science* 3, 140–163.

Notes. This paper provides a summary current state of the art as it was in the late 1960s for crew scheduling. It contains an interesting comparison of the actual practices at a variety of airlines including the constraints, types of costs and solution approaches used. The solution methods always consist of some form of (limited) enumeration of pairings, which are then reduced heuristically and optimised using a LP based branch and bound scheme. The largest problem solved appears to be 300 legs and 3000 pairings.

Arnold, B. and M. Mills. (1983). "Core 12: Implementation of Flexible Scheduling." *The Journal of Nursing Administration*, pp. 9–14.

Notes. This paper explores benefits of a new shift pattern that has a length of around 12 hours to replace either 10 hour or eight hour shifts.

Arthur, J. and A. Ravindran. (1981). "A Multiple Objective Nurse Scheduling Model." *AIIE Transactions* 13(1), 55–60.

Notes. The paper describes a goal programming method for nurse rostering. The objectives are formulated in terms of minimum staff levels, desired staff levels, nurse preferences and nurse special requests. The method is applied to a problem involving three shifts per day over two weeks, for three grades of nurses. An IP is used to solve the goal programming problem of determining days of work for the nurses a heuristic is then used to assign the shifts for each day.

Ashley, D. (1995). “A Spreadsheet Optimization System for Library Staff Scheduling.” *Computers and Operations Research* 22(6), 615–624.

Notes. This paper discusses staffing a library desk at a university. The desk may be attended by staff and students, each with individual availability requirements. An assignment problem style formulation is used to assign time-slots to individuals. The implementation and interface are both implemented using a spreadsheet.

Atlason, J., M. Epelman, and S. Henderson. (2002). “Combining Simulation and Cutting Plane Methods in Service Systems.” In *Proceedings of the 2002 National Science Foundation Design, Service and Manufacturing Grantees Conference*.

Notes. Traditionally demand for staff has been modelled by queueing theory or simulation to determine minimum staffing levels that are then fed into a rostering problem. This paper suggests that these two phases can be integrated. It provides an formulation that includes both scheduling constraints and the service levels. The latter is a non-linear, stochastic function of the staff schedule. The proposed method involves iteratively building up a piecewise linear approximation to the service level function. In each iteration a simulation is run to provide a point estimate of the service levels and a sub-gradient of this function for a given schedule. Some theoretical results on convergence are provided based on fairly general assumptions such as concavity of the service level function. Unfortunately no numerical experience is reported so it is not clear whether this idea is practical. (See also (Henderson and Mason, 1998).)

Atlason, J., M.A. Epelman, and S.G. Henderson. (2004). “Call Center Staffing with Simulation and Cutting Plane Methods.” *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 333–358.

Notes. The paper discusses the use of a hybrid simulation/IP approach to the problem of minimising staffing costs in a call centre subject to maintaining a specified service level over a specified number of time periods. At each iteration an IP is solved and the resulting staffing levels are fed to a simulation. The simulation checks to see whether the service standard is met and, if not, delivers a set of new cuts (constraints) to the IP. This process is iterated until service standards, requiring that a specified percentage of customers is served within some time from arrival into the system, are met. A simple example is given and used to discuss the performance of the algorithm. See also (Atlason et al., 2002) for additional discussion of this algorithm.

Awad, R. and J. Chinneck. (1998). “Proctor Assignment at Carleton University.” *Interfaces* 28(2), 58–71.

Notes. This paper considers examinations for a university that take place every day (three exams per day) over a fortnight. These are supervised by contracted examiners who need to be scheduled. The examiners are classified on the basis of their experience. Examiners have preferences for work periods and also buddies that they would like to work with. About 50 exams are scheduled in any time slot and each exam requires at least one examiner. Some exam schedules are seen as unfavourable (for example, involving split shifts, short exams and continuous exams). The goal is to produce a shift pattern so that all exams are covered and unfavourable shifts are distributed evenly. The paper presents a genetic algorithm which is used in conjunction with a constructive heuristic.

Aykin, T. (1996). “Optimal Shift Scheduling with Multiple Break Windows.” *Management Science* 42(4), 591–602.

Notes. A new integer programming formulation for the shift scheduling problem with multiple breaks and break windows is proposed. Because breaks are modelled implicitly, the resulting formulation has a much smaller size than the classical set covering model for the same problem. The numerical results show that this formulation is very useful in solving large shift scheduling problems optimally.

Aykin, T. (1998). “A Composite Branch and Cut Algorithm for Optimal Shift Scheduling with Multiple Breaks and Break Windows.” *Journal of the Operational Research Society* 49(6), 603–615.

Notes. This paper presents a branch and cut algorithm for solutions of shift scheduling with multiple breaks and break time windows. The proposed method is applied to an implicit formulation that is developed in (Aykin, 1996). Cuts are generated from solutions of the linear programming relaxation. Cuts are added into the linear programming relaxation and upper bounds of variables are updated.

Large-sized test problems can be solved to optimality.

Aykin, T. (2000). "A Comparative Evaluation of Modeling Approaches to the Labor Shift Scheduling Problem." *European Journal of Operational Research* 125, 381–397.
Notes. Two new implicit modelling approaches are proposed for shift scheduling with multiple rest and lunch breaks, and disjoint break windows. These are extensions of the implicit modelling approaches described in (Aykin, 1996; Bechtold and Jacobs, 1990), respectively. Extensive computational results demonstrate that the model based on (Aykin, 1996) outperforms the one based on (Bechtold and Jacobs, 1990).

Azarmi, N. and W. Abdulhameed. (1995). "Workforce Scheduling with Constraint Logic Programming." *BT Technology Journal* 13(1), 81–94.
Notes. This paper describes a CLP construction heuristic for assigning geographically situated tasks to engineers. Additionally, a repair (hill climbing) algorithm is used to improve the initial solution found by the construction heuristic. Discussion of a TSP based constraint solver indicates improved task allocation is possible through (near) optimal sequencing of the tasks for an engineer.

Azmat, C.S., T. Hürlimann, and M. Widmer. (2004). "Mixed Integer Programming to Schedule a Single-Shift Workforce under Annualized Hours." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 199–215.
Notes. This paper presents several mixed integer linear programming models which solve the workforce scheduling problem considering a single-shift. In order to offer scheduling flexibility, the annualized hour arrangement and two different scenarios to select holiday weeks are discussed. The objective is to generate a workforce schedule which minimizes the overtime hours and balances the employee's workload over a year.

Bailey, J. (1985). "Integrated Days off and Shift Personnel Scheduling." *Computers and Industrial Engineering* 9(4), 395–404.
Notes. An elastic set partitioning model with side constraints is presented for a tour scheduling in which the total workforce size and off days for each staff are given. The model is solved using linear programming relaxations and a heuristic algorithm. Under cover and over cover possibilities are also considered along with constraints on the total workforce size and on the number of days off per worker. A rounding heuristic is used to round off non-integer variables and a construction heuristic is used for assigning shifts.

Bailey, J. and J. Field. (1985). "Personnel Scheduling with Flexshift Models." *Journal of Operations Management* 5(3), 327–338.
Notes. The tour scheduling problem is solved by decomposing it into separate shift scheduling and days-off scheduling problems that are formulated as set covering models. Numerical experiments suggest that a large proportion of the labour cost can be saved from using flexible lengths of shifts.

Bailey, J., H. Alfares, and W. Lin. (1995). "Optimization and Heuristic Models to Integrate Project Task and Manpower Scheduling." *Computers and Industrial Engineering* 29, 473–476.
Notes. The paper describes a method for scheduling a workforce in order to meet due dates in a project. The paper is a conference outline and gives very little information about the methods used.

Bailey, R., K. Garner, and M. Hobbs, (1997). "Using Simulated Annealing and Genetic Algorithms to Solve Staff Scheduling Problems." *Asia–Pacific Journal of Operational Research* 14(2), 27–43.
Notes. The paper compares the results from using SA and GA to schedule 27 nurses over six weeks with three shifts per day. Each nurse is assigned to one of four teams and categorised into one of three skill levels. An IP formulation is also given.

Baker, K. (1974a). "Scheduling a Full-Time Workforce to Meet Cyclic Staffing Requirements." *Management Science* 20(12), 1561–1568.
Notes. A constructive heuristic is developed for generating a days-off schedule given a cyclic seven-day demand pattern. Each employee has exactly two off days each week. The objective is to minimize the number of employees required. All the calculations can be done by hand.

Baker, K. (1974b). “Scheduling Full-Time and Part-Time Staff to Meet Cyclic Staffing Requirements.” *Operational Research Quarterly* 25(1), 65–76.

Notes. This paper studies a cyclic days-off scheduling problem. It is required to allocate staff to meet variable daily demand exactly. The workforce is a mixture of full-time and part-time staff where full-time staff have two consecutive days off each week. The objective is to minimize the number of part-time employees. A simple algorithm is developed for this purpose and solutions can be found using hand calculations.

Baker, K. (1976). “Workforce Allocation in Cyclical Scheduling Problems: A Survey.” *Operations Research Quarterly* 27(1), 155–167.

Notes. This paper reviews some basic mathematical models for both shift scheduling and days-off scheduling problems.

Baker, E. and M. Fischer. (1981). “Computational Results for Very Large Air Crew Scheduling Problems.” *Omega* 9, 613–618.

Notes. The crew scheduling methods at Federal Express Corp. are described in this paper. The approach consists of several constructive heuristic and an improvement method for merging two solutions to obtain a better one. The methods are generalized to allow multiple crew domiciles. Problems with up to 3000 flight legs and 15000 trips were solved using these methods.

Baker, K. and M. Magazine. (1977). “Workforce Scheduling with Cyclic Demands and Day-off Constraints.” *Management Science* 24(2), 161–167.

Notes. Several versions of a days-off scheduling problem are exploited by considering different scenarios on off days patterns and weekend patterns. For each scenario, a formula for the minimum workforce size is derived and a constructive algorithm is designed for optimal schedules.

Baker, E., L. Bodin, W. Finnegan, and R. Ponder. (1979a). “Efficient Heuristic Solutions to an Airline Crew Scheduling Problem.” *IIE Transactions* 11(2), 79–85.

Notes. This paper describes the crew scheduling system developed by the authors for Federal Express Corp. The software uses a constructive heuristic followed by an improvement phase using several local search operators derived from vehicle scheduling. Some results for a 1000 leg data set from Federal Express are discussed.

Baker, K., R. Burns, and M. Carter. (1979b). “Staff Scheduling with Day-off and Workstretch Constraints.” *AIIE Transactions* 11(4), 286–292.

Notes. Simple expressions of calculating minimum workforce sizes are derived for a simple days-off scheduling in which staff requirements remain the same during the week, each worker must have two consecutive off days, and each worker must have a certain number weekends off within given weeks. Optimal schedules are also generated from a scheduling algorithm.

Balakrishnan, A. and R. Wong. (1990). “A Network Model for the Rotating Workforce Scheduling Problem.” *Networks* 20, 25–42.

Notes. The problem of determining optimal fixed shift schedules is discussed in this paper. The authors present a network flow (shortest path) formulation based on a shift-time graph. The staffing requirements for each shift are dualised so that a lower bound can be obtained with a Lagrangean relaxation approach. Finally, an optimal primal solution is found by enumerating the K-shortest paths. Results are presented for three police rostering problems from the literature.

Ball, M. and H. Benoit-Thompson. (1988). “A Lagrangian Relaxation Based Heuristic for the Urban Transit Crew Scheduling Problem.” In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 54–67. Springer.

Notes. The crew scheduling problem can be solved by iteratively solving a shortest path problem and a matching problem. A shortest path problem solves the block partitioning problem and a matching problem solves the run generation problem. The crew scheduling problem is then one that minimises costs while achieving good block partitions and generates good runs. This paper solves the combined problem using Lagrangean relaxation.

Ball, M. and A. Roberts. (1985). "A Graph Partitioning Approach to Airline Crew Scheduling." *Transportation Science* 19(2), 107–126.

Notes. The authors present an alternative approach for crew scheduling to the traditional column generation method based on a set partitioning formulation. They initially construct a set of pairings by solving a sequence of assignment problems that augment the set of paths (pairings) until all flights are covered. These pairings are then improved by considering all ways to improve the solution through combining (and then splitting) two pairings. The best set of such improvements are selected by solving another assignment problem. Results for United Airlines data sets with up to 1000 flights are presented.

Ball, M., L. Bodin, and R. Dial. (1981). "Experimentation with a Computerized System for Scheduling Mass Transit Vehicles and Crews." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 313–334. Amsterdam: North-Holland.

Notes. The problem of simultaneously generating vehicle schedules and crew schedules is considered in this paper. The method proposed consists of iteratively solving assignment problems to combine small work pieces into larger ones, and large work pieces into duties. At various points in the algorithm the user is given the opportunity to eliminate infeasible combinations or to make other manual adjustments.

Ball, M., L. Bodin, and R. Dial. (1983). "A Matching Based Heuristic for Scheduling Mass Transit Crews and Vehicles." *Transportation Science* 17(1), 4–31.

Notes. This paper models and solves the problem of scheduling mass transit crews and vehicles simultaneously. It includes the lengths and placement of relief breaks. An IP formulation is provided for the crew/vehicle scheduling problem. The problem, which is formulated using a network representation, is modelled as a partitioning problem on an acyclic graph. This is solved using a decomposition of the problem. A matching sub-problem is accompanied with an improvement phase and combining work pieces to form a 'run.' The algorithms are tested for one division of the Baltimore MTA bus system which includes nearly 1000 trips.

Ball, M., L. Bodin, and J. Greenberg. (1985). "Enhancements to the RUCUS-II Crew Scheduling Systems." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 279–293. North-Holland.

Notes. In this paper the authors provide an update on developments to the RUCUS II software for crew scheduling in mass transit operations. The enhancements are concentrated on two modules, both based on a matching approach. The first interchanges pieces among allocated crew runs and the second modifies relief points.

Ballantyne, D. (1979). "A Computerized Scheduling System with Centralized Staffing." *Journal of Nursing Administration*, 38–45.

Notes. A centralized nurse scheduling system aided by computer is described. Key features of this system include its flexibility of allowing for personnel requests, shift rotation and alterations among others.

Banihashemi, M. and A. Haghani. (2001). "A New Model for the Mass Transit Crew Scheduling Problem." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 1–16. Springer.

Notes. This paper presents a new, multi commodity flow formulation for the mass transit crew scheduling problem. There are variables associated with tasks that need to be performed and their compatibilities. The model is solved through an iterative constraint and variable generation approach.

Bard, J., C. Binici, and A. de Silva. (2003). "Staff Scheduling at the United States Postal Service." *Computers & Operations Research* 30(5), 745–771.

Notes. This paper describes a methodology for developing weekly schedules for workers at mail processing facilities and involves finding work days, shift lengths and start times, and breaks, for both full and part time workers. The problem is formulated as a large-scale integer program solved using CPLEX. The output from the IP stage gives staff levels and shifts and is post-processed to assign days off and breaks in the schedules. The authors consider the effects on solution quality of a number of model extensions including consecutive days off, different classes of shifts, variable start times, and ratios of full time to part time workers. The paper gives detailed results for a US postal processing and distribution centre that operates 24 hours a day, 7 days a week, and employs a mix of around 130 full time and part time workers.

Barnhart, C., E. Johnson, R. Anbil, and L. Hatay. (1994). "A Column Generation Technique for the Long-Haul Crew Assignment Problem." In T. Ciriani and R. Leachman (eds.), *Optimization in Industry 2*, pp. 7–24. Chichester: Wiley.

Notes. The crew scheduling problem for long-haul operations of an airline is discussed in this paper. The authors describe a column generation method that uses a shortest-path algorithm to generate new pairings. Methods for making this shortest path subproblem manageable are discussed in some detail. Results are reported for problems of up to 833 flights.

Barnhart, C., L. Hatay, and E. Johnson. (1995). "Deadhead Selection for the Long-Haul Crew Pairing Problem." *Operations Research* 43(3), 491–499.

Notes. In long-haul crew scheduling, a significant problem in generating pairings is to determine a good set of deadhead legs to include for consideration. This paper describes a method for selecting a small set of deadheads that is likely to improve the incumbent solution using dual prices from the current LP relaxation. Through some sophisticated processing a lower bound on the reduced cost of any pairing using a potential deadhead is obtained. This allows the most promising deadheads to be selected.

Barnhart, C., E. Johnson, G. Nemhauser, M. Savelsbergh, and P. Vance. (1998). "Branch-and-Price: Column Generation for Solving Huge Integer Programs." *Operations Research* 46, 316–329.

Notes. This tutorial paper provides a good summary of branch and price algorithms for solving integer programs in general, with particular emphasis on the sorts of set partitioning and set covering models that are commonly used in crew rostering and crew scheduling. The discussion covers formulation of problems, pricing, branching and a range of computational issues that need to be considered in implementing a branch and price algorithm.

Barnhart, C., E. Johnson, G. Nemhauser, and P. Vance. (1999). "Crew Scheduling." In R. Hall (ed.), *Handbook of Transportation Science*, pp. 493–521. Norwell: Kluwer Academic.

Notes. This is an introductory chapter covering the area of crew scheduling and rostering in particular as they arise in the airline industry. It describes these problems. The discussion of solution strategies emphasises branch and price methods based on set partitioning formulations with constrained shortest path subproblems.

Bartholdi, J. (1981). "A Guaranteed-Accuracy Round-off Algorithm for Cyclic Scheduling and Set Covering." *Operations Research* 29, 501–510.

Notes. A constructive heuristic algorithm is proposed for solving a special set covering model arising from a days-off scheduling problem. The author shows a heuristic based on solving a related linear program and the rounding off in a special way. The absolute error of the heuristic solution can be bounded in a way that relates naturally to the work schedule.

Bartholdi, J. and H. Ratliff. (1978). "Unnetworks, with Applications to Idle Time Scheduling." *Management Science* 24, 850–858.

Notes. A days-off scheduling problem with two consecutive days off for each worker can be formulated as a simple set covering problem. Some special cases can be solved using a matching algorithm to a complementary reformulation of the problem.

Bartholdi, J., J. Orlin, and H. Ratliff. (1980). "Cyclic Scheduling via Integer Programs with Circular Ones." *Operations Research* 28(5), 1074–1085.

Notes. Days-off scheduling problems are formulated as either a set covering model or a set partitioning model depending on applications. By exploiting special structures of the constraint matrix, it is possible to solve the integer linear program exactly as a series of network flow problems as a linear program. The solution is rounded off in a special way. Special polynomial time algorithms based on network flow problems are designed for solving these set covering/partitioning models.

Baxter, J. and M. Mosby. (1988). "Generating Acceptable Shift-Working Schedules." *Journal of the Operational Research Society* 39(6), 537–542.

Notes. This paper discusses a simple tour scheduling problem to allocate people to shifts in a manufacturing environment. A randomised heuristic performs the days off scheduling first then shift scheduling second. A rotation is formed from the individual rosters. A number of schedules is produced and best is retained.

Bean, J. and M. Bean. (1985). "An Integer Programming Approach to Reference Staff Scheduling." *Information Processing and Management* 21(5), 459–464.

Notes. This paper describes assignment of shifts at libraries. A basic set partitioning formulation is used to divide the duties between the employees. Unusually, no objective function is provided even though it is solved using standard integer programming software.

Beasley, J. and B. Cao. (1996). "A Tree Search Algorithm for the Crew Scheduling Problem." *European Journal of Operational Research* 94, 517–526.

Notes. This paper appears to be superseded by (Beasley and Cao, 1998). The authors consider an abstracted version of the crew scheduling problem in which the only constraint on pairing generation is the maximum length (duration) of the pairing. They develop Lagrangean relaxation method where the task assignment constraints are relaxed to yield a subproblem of finding the K least cost, time constrained, shortest paths (where K is the number of crew). The sub-problems are solved using dynamic programming and a custom branch and bound scheme is provided. Computational results for randomly generate data sets of up to 500 tasks and 200 crews are reported.

Beasley, J. and B. Cao. (1998). "A Dynamic Programming Based Algorithm for the Crew Scheduling Problem." *Computers and Operations Research* 25(7–8), 567–582.

Notes. This paper introduces the generic crew rostering problem and a dynamic programming based method for obtaining lower bounds which is used in a branch and bound method to find optimal solutions. The lower bound is based on Lagrangean relaxation of the set partitioning constraints. By solving constrained shortest path problems a set of worklines is found for each crew with the correct total number of duties but possibly some under or over cover. This is then resolved by branching. Results for randomly generated data of up to 500 duties are presented.

Beaulieu, H., J. Ferland, B. Gendron, and P. Michelon. (2000). "A Mathematical Programming Approach for Scheduling Physicians in the Emergency Room." *Health Care Management Science* 3, 193–200.

Notes. An integer program model with multiple objectives is presented for scheduling physicians in the emergency room arising from a real world application. The model is solved using a specialized branch and bound method.

Beaumont, N. (1997a). "Scheduling Staff Using Mixed Integer Programming." *European Journal of Operational Research* 98(3), 473–484.

Notes. A tour scheduling problem arising from an emergency service company is formulated as an integer program. The main objectives are to determine the workforce size and shift starting times. Satisfactory solutions are found.

Beaumont, N. (1997b). "Using Mixed Integer Programming to Design Employee." *Journal of the Operational Research Society* 48(6), 585–590.

Notes. A cyclic roster is constructed by solving an integer program. The problem can be viewed as a days-off scheduling problem with constraints imposing on consecutive on/off days and weekly workload and others. Numerical experiments are carried out on a real-world application and satisfactory solutions are found.

Bechtold, S. (1981). "Work Force Scheduling for Arbitrary Cyclic Demand." *Journal of Operations Management*, 205–214.

Notes. This paper is concerned with determination of the minimum number of full-time employees that meet variable cyclic demand. It also determines two cases of cyclic rosters. In the first case, one off day is allowed in the roster. In the second case, exactly two consecutive days off is allowed. Two simple constructive heuristic approaches are developed for the above two problems, respectively. Computational comparisons with the algorithms proposed in (Baker, 1974a; Tibrewala et al., 1972) are made in terms of computational time and variations of surplus demand across the planning horizon.

Bechtold, S. (1988). “Implicit Optimal and Heuristic Labor Staffing in a Multiobjective, Multiallocation Environment.” *Decision Sciences* 19(2), 353–373.

Notes. In this paper only the days off scheduling is considered with the only restriction on any person’s roster being a limit on the minimum and maximum number of days worked. This problem is easy when there is only a single location for which there is a given demand of number of staff required each day. The more complex scenario where there are multiple locations (or positions) that need to be filled can be solved in two steps: determining the number of staff at each location as well as the number of multi-location staff, then create rosters for each location separately using the basic constructive algorithm for single location problems. The author shows how the staffing numbers can be determined using an IP that can minimise the number of multi-location staff, the total number staff or a weighted combination of the two. A constructive heuristic is provided for the special case where staff can only work 2 or 3 days over the rostering horizon.

Bechtold, S. (1991). “Optimal Work–Rest Schedules with a Set of Fixed-Duration Rest Periods.” *Decision Sciences* 22, 157–172.

Notes. Workers’ productivity decreases as a function of time. Breaks are used to recover workers’ productivity. The objective of this study is to maximum workers’ productivity by optimally selecting break times. A quadratic programming model is presented for placing break times within a working shift. The model is solved using a constructive heuristic.

Bechtold, S. and M. Brusco. (1994a). “A Microcomputer-based Heuristic for Tour Scheduling of a Mixed Workforce.” *Computers and Operations Research* 21(9), 1001–1009.

Notes. A method for solving tour scheduling is presented. Tour scheduling is decomposed into several shift scheduling and days-off scheduling problems. Shift scheduling problems with multiple objectives are solved using two generalized set covering models, days-off scheduling problems are solved using a method in (Bechtold, 1981), and tours are constructed by a method similar to that in (Bechtold and Showalter, 1987).

Bechtold, S. and M. Brusco. (1994b). “Working Set Generation Methods for Labor Tour Scheduling.” *European Journal of Operational Research* 74, 540–551.

Notes. This paper develops two approaches for constructing a set of good potential tours that are used in formulating the set covering model for tour scheduling. The numerical results show that one method outperforms all other methods in terms that the set of tours generated from this method produces better solutions for the set covering model than the set of tours generated from the other methods.

Bechtold, S. and L. Jacobs. (1990). “Implicit Modeling of Flexible Break Assignment in Optimal Shift Scheduling.” *Management Science* 36(11), 1339–1351.

Notes. This paper presents a new implicit integer programming formulation for the inclusion of meal/rest-break flexibility for shift scheduling. Numerical results show that this new formulation outperforms the commonly used set covering model in terms of computational time and solution quality. Extensions of this work are done for tour scheduling problems (Aykin, 2000; Cezik et al., 2001; Jacobs and Brusco, 1996).

Bechtold, S. and L. Jacobs. (1996). “The Equivalence of General Set-Covering and Implicit Integer Programming Formulations for Shift Scheduling.” *Naval Research Logistics* 43(2), 233–249.

Notes. The shift scheduling problem can be formulated as integer programs either using the set covering model or the implicit formulation (Bechtold and Jacobs, 1990). This paper proves that these two formulations are in fact equivalent under certain conditions placed on break starting and finishing times.

Bechtold, S. and M. Showalter. (1985). “Simple Manpower Scheduling Methods for Managers.” *Production and Inventory Management* 26(3), 116–133.

Notes. The tour scheduling problem is solved by solving a series of shift scheduling problems (one for each day) and a series of days-off scheduling problems (one for each shift). Simple manual approaches are developed for solving both shift scheduling and days-off scheduling problems.

Bechtold, S. and M. Showalter. (1987). “A Methodology for Labor Scheduling in a Service Operating System.” *Decision Sciences* 18, 89–107.

Notes. Tour scheduling is solved by first solving shift scheduling problems and then solving days-off scheduling problems. Both subproblems are solved using simple manual heuristics. It is claimed that the manual heuristic produces solutions with less costs than some classical approaches.

Bechtold, S. and G. Thompson. (1993). "Optimal Scheduling of a Flexible-Duration Rest Period for a Work Group." *Operations Research* 41(6), 1046–1054.

Notes. This paper discusses how to select a single break period within a shift for each group of employees in order to maximize workers' productivity. A mathematical programming model is used for this purpose and solutions is found by solving a set of quadratic programs.

Bechtold, S., M. Brusco, and M. Showalter. (1991). "A Comparative Evaluation of Labor Tour Scheduling Methods." *Decision Sciences* 22, 683–699.

Notes. This paper carries out numerical experiments for several integer programming based methods and constructive heuristic approaches for tour scheduling. Relative performance of all methods is evaluated through statistical analysis.

Begur, S., D. Miller, and J. Weaver. (1997). "An Integrated Spatial DSS for Scheduling and Routing Home-Health-Care Nurses." *Interfaces* 27(4), 35–48.

Notes. The paper describes a SDSS (spatial DSS) that uses GIS software and nearest neighbourhood heuristics to schedule nurse visits to patients at home. The system determines the optimal routing of the visits. The system also balances the visit workload among the nurses. Nurse schedules and map based travel routes are displayed using the GIS component.

Bell, P., G. Hay, and Y. Liang. (1986). "A Visual Interactive Decision Support System for Workforce (Nurse) Scheduling." *INFOR* 24(2), 134–145.

Notes. The paper describes an interactive system for generating cyclic nurse rosters. A heuristic is used to develop patterns of day, night and off shifts with particular patterns representing nurse preferences for shift sequences. The system provides a simple computer screen representation of the shifts and allows the nurse manager to improve the shifts based on specific nurse requests for the planning period.

Belletti, R., A. Davini, P. Carraresi, and G. Gallo. (1985). "BDROP: A Package for the Bus Drivers' Rostering Problem." In J. Rousseau (ed.), *Computer Scheduling of Public Transport*, pp. 327–342. North-Holland.

Notes. This paper focuses on the crew rostering phase of bus driver scheduling. Given a set of shifts that satisfy some known service requirement, the crew rostering module of the BDROP package provides good rosters in such a way that there is a uniform distribution of work load amongst drivers. The modelling is based on solving a multi-level assignment problem.

Bennett, B. and R. Potts. (1967). "A Rostering Problem in Transportation." In L. Edie, R. Herman, and R. Rothery (eds.), *Proceedings of the 3rd International Symposium on Theory of Road Traffic Flow*. New York: American Elsevier.

Bennett, B. and R. Potts. (1968). "Rotating Rosters for a Transit System." *Transportation Science* 2, 14–33.

Notes. This paper presents an early approach to computerised crew schedule development at the Municipal Tramways Trust of Adelaide, Australia. LP models, an assignment-based approach and a simple local search approach are used to construct feasible days-off schedules and shift schedules.

Berman, O., R. Larson, and E. Parker. (1997). "Scheduling Workforce and Work Flow in a High Volume Factory." *Management Science* 43(2), 158–172.

Notes. This paper discuses determining the number of staff to be assigned to stations in a high volume assembly line, and the time and duration of their assignment. The assembly line may in fact be a network and work may enter the network at any station. A linear programming formulation is given which minimizes the cost of the staffing. Additional constraints are imposed to ensure a satisfactory amount of work is processed.

Berrada, I., J. Ferland, and P. Michelon. (1996). "A Multi-Objective Approach to Nurse Scheduling with Both Hard and Soft Constraints." *Socio-Economic Planning Sciences* 30(3), 183–193.

Notes. The paper develops a multi-objective model for nurse rosters using a mix of hard and soft constraints. Two different mathematical programming techniques (sequential and equivalent weights) for solving multi-objective problems are discussed along with a Tabu Search method.

Bertram, H. and J. Winckler. (1988). "Scheduling on Microcomputers Using MICROBUS." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, pp. 188–199. Springer.

Notes. This paper describes the MICROBUS software system which can be used by bus transport companies for planning, timetable planning, route planning, crew scheduling and crew rostering. The crew scheduling and duty roster modules are based on simple constructive heuristics.

Bianco, L., M. Bielli, A. Mingozzi, S. Ricciardelli, and M. Spadoni, (1992). "A Heuristic Procedure for the Crew Rostering Problem." *European Journal of Operational Research* 58(2), 272–283.

Notes. This paper develops crew schedules for mass transit rostering. The problem is one of finding a minimum cost roster over a planning horizon that covers all the work requirements according to known constraints on shift durations and rest periods. A mathematical formulation is provided first. An iterative heuristic based on solving the multilevel bottleneck assignment problem is then provided that allows a balanced workload across all crew.

Billionnet, A. (1976). "A Model for Adaptive Movements of Personnel to Planned Manpower Requirements." In M. Roubens (ed.), *Proceedings of The Second European Congress on Operations Research*, pp. 35–44. North-Holland.

Notes. This paper addresses a question of how to move and recruit workers with different skills in order to meet target manpower requirements in different skill levels at each planning period. Staff movement and staff recruitment are to accommodate staff departures. It is formulated as a mathematical programming problem and solved using an algorithm based on the minimal cost flow problem.

Billionnet, A. (1999). "Integer Programming to Schedule a Hierarchical Workforce with Variable Demands." *European Journal of Operational Research* 114(1), 105–114.

Notes. A days-off scheduling problem is formulated as an integer program. The entire workforce has a hierarchical structure and higher qualified workers can substitute for lower qualified ones. Each task requires a certain skill level. Computational results are presented in the paper.

Blais, J. and J. Rousseau. (1988). "Overview of HASTUS Current and Future Versions." In J. Daduna, and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 175–187. Springer.

Notes. This paper provides a view of the methodological improvements made to the HASTUS system, a decision support system which has been in use for vehicle scheduling, planning, timetabling, crew scheduling and duty rostering in a variety of real-world applications.

Blais, J., J. Lamont, and J. Rousseau. (1990). "The HASTUS Vehicle and Manpower Scheduling Systems at Societe de Transport de la Communate Urbalne de Montreal." *Interfaces* 20(1), 26–42.

Notes. This paper provides an applications-oriented view of the sophisticated scheduling methods in HASTUS, a decision support system for vehicle and crew scheduling. The paper deals with the implementation of HASTUS at STCUM, Montreal's public transport undertaking. Through the implementation of several smart algorithms for developing vehicle and crew schedules, the HASTUS suite of models have yielded nearly $ 4 million in savings for one Montreal's public transport operator.

Blau, R. and A. Sear. (1983). "Nurse Scheduling with a Microcomputer." *Journal of Ambulatory Care Management* 6(3), 1–13.

Notes. The paper describes a system for generating two-week rosters for nurses in a hospital unit. Generalised nurse preferences are taken into account. Paper superseded by advances in technology.

Bodin, L. (1973a). "Towards a General Model for Manpower Scheduling: Part 1." *The Journal of Urban Analysis* 1, 191–207.

Notes. This paper discusses some issues related to workforce planning and tour scheduling. A breakdown of the problem of tour scheduling is given. Discussion of the solution techniques for the sub-problems, however, is limited. This work has been superseded.

Bodin, L. (1973b). "Towards a General Model for Manpower Scheduling: Part 2." *The Journal of Urban Analysis* 1, 191–207.

Notes. This paper provides a review of papers related to scheduling refuse collection workers. The models the reviewed papers are generalised into a more realistic model. The generalised model breaks down the overall problem into shift demand calculation, days off planning, and shift scheduling. The days off planning is performed using graph algorithms and the remainder via integer programming.

Bodin, L., B. Golden, A. Assad, and M. Ball. (1983). "Routing and Scheduling of Vehicles and Crews – The State of the Art." *Computers and Operations Research* 10(2), 63–211.

Notes. This paper provides a good review of models and methods for solving airline and mass transit crew scheduling and rostering problems. The context is provided through an introduction to vehicle routing and vehicle scheduling problems, including a wide list of applications. Crew scheduling and rostering aspects are then tackled. A classification and categorization is provided followed by a review of models, algorithms and methods.

Bohoris, G. and J. Thomas. (1995). "A Heuristic for Vehicle Routing and Depot Staffing." *Journal of the Operational Research Society* 46(10), 1184–1191.

Notes. This paper presents a new and interesting depot staffing and routing application for a company operating a fleet of vehicles that collect money from vending machines and deposit these into banks. Much of the paper is devoted to describing the application context. A large part of the problem is the vehicle routing and scheduling. An important subproblem is one of determining the number of staff that are required to service the collections.

Booler, J. (1975). "A Method for Solving Crew Scheduling Problems." *Operational Research Quarterly* 26(1), 55–62.

Notes. The problem of assigning a set of tasks to workers with pre-specified shifts is presented together with a multi-commodity integer network flow formulation. A exact method involving a Dantzig–Wolfe decomposition and custom branch and bound scheme are presented together with numerical results for up to 72 jobs and 48 shifts.

Borndörfer, R., M. Grötschel, and A. Löbel. (2001). "Duty Scheduling in Public Transit." Technical Report, ZIB.

Notes. This article is about adaptive column generation techniques for the solution of duty scheduling problems in public transit. The current optimization status is exploited in an adaptive approach to guide the subroutines for duty generation, LP resolution, and schedule construction toward relevant parts of a large problem. Computational results for three European scenarios are reported.

Borret, J. and A. Roes. (1981). "Crew Scheduling by Computer: A Test on the Possibility of Designing Duties for a Certain Bus Line." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 237–253. Amsterdam: North-Holland.

Notes. The paper presents the tests made on the design of driver duties for a large bus line of the Amsterdam Urban Transport Company. The method used for crew scheduling is based on a set partitioning model in which the objective is to minimize the total duty cost.

Borst, S. (2001). "Robust Algorithms for Sharing Agents with Multiple Skills." Technical Report, Bell Laboratories.

Notes. A queueing model is presented for calculating staff requirements in call centres where multiple queues exist. Each queue is characterized by the skills required and its arrival rate. Each queue can be serviced by any one from several classes of servers. Servers are categorized by the skills that they have and each sever can provide service to customers in different queues according to his/her own skills. This class of queueing models have not received much attention in the literature. However, there is an increasing demand of such call center configurations in modern call center practice. A conservative approach and an aggressive approach are presented for calculating staff requirements for each class of servers. The paper proposes two credit schemes to determine selections of customers from various queues for service once servers are available for service. Numerical results demonstrate viability of the proposed methods.

Boschetti, M.A., A. Mingozzi, and S. Ricciardelli. (2004). "An Exact Algorithm for the Simplified Multiple Depot Crew Scheduling Problem." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 177–201.

Notes. This paper considers a simplified version of the multiple depot crew scheduling problem. The paper presents an exact method based on a set partitioning formulation with additional constraints. A new bounding procedure is introduced for generating lower bounds. The computational results show that the proposed method outperforms on the tested problems all existing methods.

Bradley, D. and J. Martin. (1991). "Continuous Personnel Scheduling Algorithms: A Literature Review." *Journal of the Society for Health Systems* 2, 8–2.

Notes. This paper reviews and classifies over 70 papers related to nurse scheduling. The papers are classified by roster structure, either cyclic or acyclic. The papers are further classified by solution technique, either heuristic, mathematical programming, or manual (self-scheduling).

Bransby, H., M. Parker, and A. Wren. (1976). "Computer Models for Scheduling Buses and Their Crews." In *Proceedings of the Eighth Annual Seminar on Public Transport Operations Research*.

Notes. The paper describes how crew scheduling is solved via a two-stage approach: generation of valid duties and partial duties, and the refining stage in which either the number of duties is reduced or the amount of unassigned tasks is decreased. The work had been used in a large number of bus undertakings in UK.

Brigandi, A., D. Dragon, M. Sheehan, and T. Spencer III. (1994). "AT&T's Call Processing Simulator (CAPS) Operation Design for Inbound Call Centers." *Interfaces* 24(1), 6–28.

Notes. This paper describes a software package CAPS for designing and evaluating inbound call centers. It is composed of four modules: The simulator for simulating call centers; Queueing models for calculating staffing requirements as well as for providing initial solutions to the simulator; The forecaster for forecasting future call volumes; and The scheduler for generating call takers' schedules. About 2000 case studies were completed using CAPS prior to 1992.

Browne, J. and R. Tibrewala. (1975). "Manpower Scheduling." *Industrial Engineering* 7(8), 22–23.

Notes. A simple constructive heuristic algorithm is designed for finding the optimal workforce size with an optimal schedule for a simple days-off scheduling problem.

Brownell, W. and J. Lowerre. (1976). "Scheduling of Workforces Required in Continuous Operations under Alternative Labor Policies." *Management Science* 22, 597–605.

Notes. This papers studies a days-off scheduling problem in which the staffing requirement on weekdays is different from weekends. The minimum workforce sizes are obtained under five different off days policies.

Brusco, M. (1998). "Solving Personnel Tour Scheduling Problems Using the Dual All-Integer Cutting Plane." *IIE Transactions* 30(9), 835–844.

Notes. A tailor-made dual all-integer cutting plane is designed for solving the set covering model of the tour scheduling problem. It is reported that the designed method substantially outperforms a commercial branch and bound code for a set of test problems.

Brusco, M. and L. Jacobs. (1993a). "A Simulated Annealing Approach to the Cyclic Staff-Scheduling Problem." *Naval Research Logistics* 40(1), 69–84.

Notes. A simulated annealing approach is presented for generating optimal cyclic rosters for tour scheduling. By comparing with other integer programming and heuristic methods, the proposed simulated annealing approach produces better quality solutions.

Brusco, M. and L. Jacobs. (1993b). "A Simulated Annealing Approach to the Solution of Flexible Labor Scheduling Problems." *Journal of the Operational Research Society* 44(12), 1191–1200.

Notes. The paper evaluates the use of SA for solving a very generalised staff scheduling problem in which the objective is to minimise cost subject to a single constraint covering the demand for employees in each time period of the planning horizon.

Brusco, M. and L. Jacobs. (1995). "Cost Analysis of Alternative Formulations for Personnel Scheduling in Continuously Operating Organizations." *European Journal of Operational Research* 86(2), 249–261.

Notes. The set covering model is used for a tour scheduling problem. A side constraint is added into the model for taking care of a correction ratio between full-time and part-time workers. By whether or not restricting starting times of tours for full-time and part-time workers, two restricted versions of the model are obtained, which are called discontinuous and continuous formulations, respectively. Numerical results show that the discontinuous formulation results in a substantial amount of excess labor cost than the continuous formulation.

Brusco, M. and L. Jacobs. (1998a). "Eliminating Redundant Columns in Continuous Tour Scheduling Problems." *European Journal of Operational Research* 111(3), 518–525.

Notes. The set covering model for tour scheduling often contains many variables/tours. It cannot be solved directly by a modern integer program solver. Strategies of eliminating redundant variables are developed in this paper. It shows that about one third of variables can be removed for an application in an airport ground station.

Brusco, M. and L. Jacobs. (1998b). "Personnel Tour Scheduling when Starting-Time Restrictions Are." *Management Science* 44(4), 534–547.

Notes. This paper extends the work of (Brusco and Jacobs, 1995) for the restricted starting-time tour scheduling problem. Solutions are found using a two-stage strategy. Two constructive heuristics in conjunction with integer programs are developed for the shift scheduling problem in Stage 1. Several simulated annealing strategies are presented for constructing tours in Stage 2. Numerical experiments with data from United Airlines airport ground stations show that the proposed approach is a valuable platform for generating near-optimal solutions.

Brusco, M. and L. Jacobs. (2000). "Optimal Models for Meal-Break and Shift-Time Flexibility in Continuous Tour Scheduling." *Management Science* 46(12), 1630–1641.

Notes. This paper presents a compact implicit integer programming formulation for a continuous tour scheduling problem with breaks and break windows. The proposed formulation extends the implicit formulation for shift scheduling studied in (Bechtold and Jacobs, 1990) and the implicit formulation for tour scheduling with break windows in (Jacobs and Brusco, 1996). The model is applied to a call centre for evaluating the various scheduling policies.

Brusco, M. and L. Jacobs. (2001). "Starting-Time Decisions in Labor Tour Scheduling: An Experimental Analysis and Case Study." *European Journal of Operational Research* 131, 459–475.

Notes. An experimental study is carried out for analyzing policies of selecting shift starting times for a specific tour scheduling problem. A feasible tour is uniquely defined by a daily shift starting time (which remains the same for each working day of the tour) and the working days during the week. An integer program is proposed for solving this problem. The objective is to minimize the total workforce size in order to meet variable demand. Numerical experiments show that restricting the number of starting times to four or five does not result in a substantial increase in workforce size. The effectiveness of this study is well supported by its application to a call centre tour scheduling problem.

Brusco, M. and T. Johns. (1995a). "The Effect of Demand Characteristics on Labour Scheduling Methods." *International Journal of Operations and Production Management* 15(1), 74.

Notes. This paper conducts numerical experiments for several approaches for solving tour scheduling under various demand patterns. Demand patterns are affected by the following factors: mean demand in each planning period, the ratio of the maximum demand over the minimum demand across the planning horizon, the shape of demand curve, and smoothness of the demand curve.

Brusco, M. and T. Johns. (1995b). "Improving the Dispersion of Surplus Labor in Personnel Scheduling Solutions." *Computers and Industrial Engineering* 28(4), 745–754.

Notes. This paper studies a tour scheduling problem with several classes of workers who are categorized according to their working productivity. The primary objective is to minimize the total staffing cost to meet dynamic demands with a sufficient proportion of full-time workers. The secondary objective is to minimize the maximum of ratios of surplus workforce for all planning periods across the entire planning horizon. Both problems are formulated as set covering models and solved using preemptive goal programming approaches.

Brusco, M. and T. Johns. (1996). "A Sequential Integer Programming Method for Discontinuous Labor Tour Scheduling." *European Journal of Operational Research* 95(3), 537–548.

Notes. Based on the commonly used set covering model, a sequential integer programming method is proposed for tour scheduling. Tours or rosters are constructed sequentially until all demands are covered. In each step, an integer program is used for finding subsets of tours and a heuristic fixes some tours to be integer values. Tours having shifts either at the beginning or the end of days are usually fixed earlier than those covering mid-day shifts. Once some tours are fixed, the demands covered by them are taken out when formulating future integer programs.

Brusco, M., L. Jacobs, R. Bongiorno, D. Lyons, and B. Tang. (1995). "Improving Personnel Scheduling at Airline Stations." *Operations Research* 43(5), 741–751.

Notes. This paper discusses the scheduling, not of airline crews, but of airline ground staff. A similar technique to aircrew scheduling is applied though. A typical set covering formulation is described and several alternative formulations are given. Also a Simulated Annealing heuristic is described.

Buffa, E., M. Cosgrove, and B. Luce. (1976). "An Integrated Work Shift Scheduling System." *Decision Sciences*, 620–630.

Notes. This paper presents an integrated system for operator scheduling in call centers. Four components of the system are forecasts of call volumes, conversion of call volumes into staffing requirements, shift scheduling, and days-off scheduling. Computational methods are discussed for problems arising from all four components.

Burke, E., P. De Causmaecker, and G. Vanden Berghe. (1998). "A Hybrid Tabu Search Algorithm for the Nurse Rostering Problem." In *Lecture Notes in Artificial Intelligence*, Vol. 1585, pp. 187–194. Springer.

Notes. The paper describes a Tabu Search algorithm for solving highly constrained nurse rostering problems. The solution methodology has been extended to include memetic algorithms as well as TS in a commercial application.

Burke, E., P. Cowling, P. De Causmaecker, and G. Vanden Berghe. (2001a). "A Memetic Approach to the Nurse Rostering Problem." *Applied Intelligence* 15(3), 199–214.

Notes. The paper describes methods for developing nurse rosters using penalty methods for the violation of soft constraints. A mix of Tabu Search and memetic variations of GA are applied to solve the problem. Algorithms from the work (over all the papers written by the authors) have formed the basis of a commercial system that has been used in over 40 hospitals in Belgium.

Burke, E., P. De Causmaecker, S. Petrovic, and G. Vanden Berghe. (2001b). "Fitness Evaluation for Nurse Scheduling Problems." In *Proceedings of the Congress on Evolutionary Computation – CEC*, Seoul, Korea, pp. 1139–1146.

Notes. The paper describes counter/numbering based system for fast, memory efficient evaluation of intermediate solutions arising from metaheuristic algorithms applied to nurse rostering problems.

Burke, E., P. De Causmaecker, S. Petrovic, and G. Vanden Berghe. (2001c). "Variable Neighbourhood Search for Nurse Rostering Problems." In *Metaheuristics International Conference – MIC'2001*, Porto, Portugal, pp. 755–760.

Notes. The paper (really an extended abstract) looks at possible problem specific extensions to the Tabu and Memetic algorithms of Burke et al. It uses neighbourhood search to provide better exploration of the search space than might be possible using just Tabu or Memetic methods.

Burke, E., P. De Causmaecker, G. Vanden Berghe, and H. Van Landeghem. (2002). "The State of the Art of Nurse Rostering." Technical Report, School of Computer Science and IT, University of Nottingham.

Notes. In this review, the authors situate nurse rostering within the global personnel scheduling problem in healthcare. The paper presents comparisons for measures that determine the complexity of nurse rostering problems. Solution approaches described range from pure operations research to artificial intelligence methods. 137 articles are reviewed in the paper.

Burns, R. (1978). "Manpower Scheduling with Variable Demand and Alternate Weekends off." *INFOR Canadian Journal of Operations Research Information Process* 16, 101–110.

Notes. This paper studies of ways for determining the minimum workforce size and finding a feasible schedule with the minimum workforce size for a days-off scheduling problem under various off days policies.

Burns, R. and M. Carter. (1985). "Work Force Size and Single Shift Schedules with Variable Demands." *Management Science* 31(5), 599–607.
Notes. A days-off scheduling problem is considered with a focus on fairness of weekends off for all employees in the rostering horizon. The minimum workforce size can be trivially calculated. A simple algorithm is presented for constructing a feasible roster with the minimum workforce size.

Burns, R. and G. Koop. (1987). "A Modular Approach to Optimal Multiple-Shift Manpower Scheduling." *Operations Research* 35(1), 100–110.
Notes. This work is an extension of (Burns and Carter, 1985) by considering multiple shifts on each day. A heuristic algorithm is proposed for finding optimal schedules that use no more than the minimum number of workers necessary for a schedule satisfying constraints that include two off days each week, a specified number of off weekends in any fixed number of consecutive weekends and others.

Burns, R., R. Narasimhan, and L. Smith. (1998). "A Set-Processing Algorithm for Scheduling Staff on 4-day or 3-day Work Weeks." *Naval Research Logistics* 45(8), 839–853.
Notes. This papers studies a days-off scheduling problem that allows either three or four working days each week, and it is similar to that in (Burns and Carter, 1985). The minimum number of workforce is sought to meet variable daily demand. Schedules can be constructed using a constructive method with the minimum workforce. Schedules must conform certain constraints such as patterns of non-working weekends, and the length of consecutive working days.

Butchers, E., P. Day, A. Goldie, S. Miller, J. Meyer, D. Ryan, A. Scott, and C. Wallace. (2001). "Optimized Crew Scheduling at Air New Zealand." *Interfaces* 31(1), 30–56.
Notes. This paper reports an extensive research for solving crew scheduling and crew rostering problems at Air New Zealand. Seven optimizers have been developed. The set partitioning model provides an underlying mathematical model to all optimizers. A large amount of savings have been achieved while providing crew rosters that better respect crew members' preferences.

Butler, D. and U. Maydell. (1979). "Manpower Scheduling in the Edmonton Police Department." *INFOR Journal* 17(4), 366–372.
Notes. This paper discusses some of the issues relating to scheduling police. Included in the discussion are fairness criteria and the difficulty of change in police organisations. The solution technique is apparently manual enumeration.

Byrne, J. and R. Potts. (1973). "Scheduling of Toll Collectors." *Transportation Science* 7(2), 224–245.
Notes. This paper discusses scheduling of toll booth operators to meet forecast demand. An integer program is given to determine the levels of full time and part time staff needed and the start times of their shifts. Rather than use branch-and-bound search, an integer solution is found by using a custom search algorithm which introduces integrality constraints in eight stages. The eight stages re flect different, problem specific groupings of the integer variables.

Cai, X. and K. Li. (2000). "A Genetic Algorithm for Scheduling Staff of Mixed Skills under Multi-Criteria." *European Journal of Operational Research* 125, 359–369.
Notes. The paper discusses a multi-criteria approach to staff scheduling where the different criteria include minimising cost, assigning as many people as possible for that cost, and minimising the variation of surplus staff.

Campbell, R. (1988). "The SEMTA Experience with Computer-Aided Scheduling." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 279–287. Springer.
Notes. This paper describes a set of processes for implementing a bus driver scheduling system. The paper also describes a set of business and operational conditions that are required for applying the software. Also described are a useful set of pre-conditions, described as questions that need to be answered. These enable successful implementation of the system.

Campbell, G. (2002). “Development and Evaluation of an Assignment Heuristic for Allocating Cross-Trained Workers.” *European Journal of Operational Research* 138, 9–20.
Notes. The paper describes methods for solving the assignment problem arising from the need to assign cross trained workers between a number of departments at the start of a shift. One application is nurse allocation between wards. The paper focuses on solution methods rather than practical applications.

Capra, R., S. Lena, and U. Santarelli. (1973). “Bus Crew Duty Cost Minimization.” *IBM Technical Disclosure Bulletin* 16(7), 2181–2185.
Notes. This paper considers the optimisation of duties for long-distance bus crews, given a bus schedule. The crew schedule minimises the number of staff used while satisfying union regulations.

Caprara, A., M. Fischetti, P. Toth, D. Vigo, and P. Guida. (1997). “Algorithms for Railway Crew Management.” *Mathematical Programming* 79(1–3), 125–141.
Notes. This paper deals with rail crew scheduling and rail crew rostering where train trips, that need to be crewed, are drawn from a repeating daily schedule. Both problems are formulated as one of finding a min-cost collection of circuits of a graph covering each node (trips or duties) once. For the Italian Railways, the crew scheduling model is formulated as a set covering problem, whose variables are associated with the circuits of the graph, and solved using an iterative Lagrangean heuristic procedure. Given a set of duties that need to be performed, the crew rostering phase is modelled as an integer linear program, whose variables are associated with the edges of the graph, that is solved by Lagrangean relaxation and a heuristic method.

Caprara, A., F. Focacci, E. Lamma, P. Mello, M. Milano, P. Toth, and D. Vigo. (1998a). “Integrating Constraint Logic Programming and Operations Research Techniques for the Crew Rostering Problem.” *Software Practice and Experience* 28(1), 49–76.
Notes. This paper discusses the application of combined constraint programming and Lagrangean relaxation for solving the crew rostering problem. Lagrangean relaxation is used to determine a bound on the number of weeks required to roster all the duties. This bound transforms the constraint optimisation problem into a constraint satisfaction problem. An incomplete labelling strategy using problem specific heuristics is then applied to find a feasible (and therefore optimal) solution. By relaxing the bound on the objective and applying a post-optimisation procedure solution time can be improved while maintaining high solution quality.

Caprara, A., P. Toth, D. Vigo, and M. Fischetti. (1998b). “Modeling and Solving the crew Rostering Problem.” *Operations Research* 46(6), 820–830.
Notes. This paper resulted from a competition conducted from Ferrovie dello Stato SpA, the Italian rail company. The paper describes a railway crew rostering approach where the main objective is the reduction in the number of crew that are used. A mathematical model is presented for the problem and a general heuristic procedure is described for its solution. This incorporates a Lagrangean lower bounding procedure based on the solution of an assignment problem.

Caprara, A., M. Fischetti, P. Guida, P. Toth, and D. Vigo. (1999). “Solution of Large-Scale Railway Crew Planning Problems: The Italian Experience.” In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 1–18. Berlin: Springer.
Notes. This paper provides a thorough overview of the sorts of crew planning problems that a typical European railway company has to undertake in the post-deregulated railway industry where track management and service operations are split. This paper highlights the particular experiences with optimization-based approaches to crew planning at the Italian state railways, who have developed, use, maintain and operate a computerized system called ALPI. The crew scheduling component is split into crew scheduling (pairing generation and pairing optimization) and crew rostering. Pairing generation is accomplished by a depth-first enumeration procedure. An iterative Lagrangean relaxation heuristic is used for solving a set covering model as part of the pairing optimization phase. A constructive heuristic procedure then patches all the pairings to form feasible crew rosters that satisfy union and business constraints.

Caprara, A., M. Monaci, and P. Toth. (2001). “A Global Method for Crew Planning in Railway Applica-

tions." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 17–36. Springer.
Notes. This paper splits the problem of rail crew roster generation into pairing generation, pairing optimization and roster optimization. The problem is one of generating cost efficient rosters that cover all timetabled train trips. A depth-first branch and bound method is first employed to enumerate all feasible pairings for all depots. Heuristics are used to reduce the feasible pairing set. The paper experimentally shows that solution quality can be substantially improved if the pairing optimization and roster optimization phases of the process can be iterated on through a feedback mechanism.

Carraresi, P. and G. Gallo. (1984a). "A Multi-Level Bottleneck Assignment Approach to the Bus Drivers' Rostering Problem." *European Journal of Operational Research* 16(2), 163–173.
Notes. This paper discusses a method for bus crew rostering which is the problem of assigning shifts to drivers such that all drivers receive an equitable distribution of shifts throughout a planning horizon. The problem is formulated as a multi-level bottleneck assignment problem where the maximum 'discomfort' to drivers is minimized. After providing an integer programming formulation of the problem and proving that the problem is NP-complete the paper provides a procedure for solving the model.

Carraresi, P. and G. Gallo. (1984b). "Network Models for Vehicle and Crew Scheduling." *European Journal of Operational Research* 16(2), 139–151.
Notes. This paper presents a review of network models that can be used for crew scheduling and crew rostering problems in mass transit applications. Apart from providing an overview of the use of network models and heuristics for vehicle scheduling across single and multiple depots, the paper also deals with crew scheduling and crew rostering. A matching approach and a Lagrangean relaxation approach are discussed for crew scheduling and a multilevel bottleneck assignment approach is discussed for crew rostering.

Carraresi, P., G. Gallo, and J. Rousseau. (1982). "Relaxation Approaches to Large Scale Bus Driver Scheduling Problems." *Transportation Research* 16B(5), 383–397.
Notes. The bus driver scheduling problem is considered in this paper. The paper presents a model for the problem that is similar to the set covering formulation of crew scheduling problems. Since the resulting models can be very large for most practical applications, the paper considers several relaxations including a neighbourhood search approach and a Lagrangean relaxation approach.

Carraresi, P., G. Gallo, N. Ciaramella, and L. Lucchesi. (1988). "BDS: A System for the Bus Drivers' Scheduling Problem Integrating Combinatorial Optimization and Logic Programming." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 68–82. Springer.
Notes. The paper considers the bus driver scheduling problem for assigning duties to bus drivers at minimal cost while satisfying demand. The approach integrates a combinatorial optimisation model and logic programming by using the Logiform expert system package. An integer programming model partitions the problem which is solved using a Lagrangean relaxation approach. This provides a lower bound and a feasible solution. The model is applied at ATAF, a transit company in France.

Carraresi, P., M. Nonato, and L. Girardi. (1995). "Network Models, Lagrangean Relaxation and Subgradient Bundle Approach in Crew Scheduling Problem." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 188–212. Springer.
Notes. The methods used by the crew scheduling software MTRAM are described in this paper. The overall algorithm consists of a master problem solved by Lagrangean relaxation with column generation. The subproblems consist of constrained shortest path problems for generating new duties. The paper describes the solution method for these subproblems in considerable detail. Computational results are provided for bus and airline crew scheduling problems with up to 1500 relief points/flights.

Carter, M. and S. Lapierre. (2001). "Scheduling Emergency Room Physicians." *Health Care Management Science* 4, 347–360.
Notes. A unified integer programming formulation is presented for constructing schedules for emer-

gency room physicians in six different hospitals. Due to different operating environments, schedules can be cyclic or acyclic or cyclic without rotations. Two case studies are presented and solutions are found by different approaches.

Castaline, A. (1992). "Work Rule Flexibility: Method to Reduce PTO Requirements." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 75–84. Springer.
Notes. This paper discusses the rules in place that restrict the way mass transit employees may be scheduled. Suggests alterations to these rules that may cut costs and improve staff morale. The author refers to use of HASTUS-MACRO for evaluating changes, but does not discuss in detail the evaluation technique.

Catanas, F. and J. Paixao. (1995). "A New Approach for the Crew Rostering Problem." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 267–277. Springer.
Notes. The authors describe a bi-criteria version of the standard crew rostering problem, in which the maximum roster duration as well as the total roster cost is to be minimized. The authors show how the complications introduced by the first part of this objective can be handled by adding side constraints to the set covering problem and by generating columns using a constrained shortest path subproblem. Results are only presented for randomly generated data sets.

Cavique, L., C. Rego, and I. Themido. (1999). "Subgraph Ejection Chains and Tabu Search for the Crew Scheduling Problem." *Journal of the Operational Research Society* 50(6), 608–616.
Notes. The paper considers two heuristics for developing crew schedules. The heuristics are based on tabu search procedures that work with the entire solution. Data from the Lisbon Underground train timetable was used to test the algorithms which are part of a DSS for managing crew schedules on the Lisbon Underground. The contractual and operational constraints consist mainly of limits of work time and meal breaks.

Ceder, A. (2002). "Public Transport Scheduling." In D. Hensher and K. Button (eds.), *Handbook: Transport Systems an Traffic Control*. Elsevier Sciences.
Notes. One of three scheduling components in public transport discussed in this paper is crew scheduling. Some works in the literature are reviewed. An example is given to describe the crew scheduling procedures and considerations.

Ceder, A., B. Fjornes, and H. Stern. (1988). "OPTIBUS: A Scheduling Package." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 212–225. Springer.
Notes. This paper describes an integrated computerised system for developing bus timetables, vehicle schedules and bus driver schedules. After determining timetables, vehicle schedules and fleet allocations, the system addresses crew scheduling using a heuristic algorithm.

Cezik, T., O. Günük, and H. Luss. (2001). "An Integer Programming Model for the Weekly Tour Scheduling Problem." *Naval Research Logistics* 48(7).
Notes. This paper studies a tour scheduling problem arising from in call centres. The proposed model allows similar starting times in all working days for each tour to be used. The model can also take days off restrictions into account and generate cyclic rosters. A nice network flow model is proposed in conjunction with an implicit formulation dealing with daily shift scheduling. A tailor-made fix and branching method is used for solving the proposed model.

Chabrier, A. (1999). "A Cooperative CP and LP Optimizer Approach for the Pairing Generation Problem." In *International Workshop on Integration of AI and OR Techniques in Constraint Programming for Combinatorial Optimization Problems*, Ferrara, Italy.
Notes. This paper provides an outline of an algorithm for using constraint programming to generate columns within a column generation approach to solving the crew scheduling problem. Discussion of the complexities of implementation and computational efficiency is limited.

Chamberlain, M. and A. Wren. (1992). "Developments and Recent Experience with the Busman and

Busman II Systems." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 1–15. Springer.
Notes. This paper is akin to a technical marketing document that presents the features of BUSMAN II, a computerised system for bus and bus crew scheduling. The paper describes the requirements of the enhancement of the original software, details some of the major upgrade features and then provides details on possible future enhancements.

Chebalov, S. and D. Klabjan. (2002). "Robust Airline Crew Scheduling: Move-up Crews." In *Proceedings of the 2002 NSF Design, Service, and Manufacturing Grantees and Research Conference*.
Notes. The authors consider the trade off between minimizing the planned crew costs and making the schedule robust to disruptions. By considering one form of disruption management, the concept of move-up crews, the authors develop a set partitioning formulation with side constraints that allows the robustness of the crew schedule to be maximised. This problem is solved by Lagrangean relaxation and column generation.

Chen, D. (1978). "A Simple Algorithm for a Workforce Scheduling Model." *AIIE Transactions* 10(3), 244–251.
Notes. A constructive heuristic algorithm is designed for solving a days-off scheduling problem with a given number of full-time workers. The main objective is to maximize the total number of workers who get two consecutive days off.

Chen, B. (2000). "Staffing Levels at the Auckland Police Communication Centre." Technical Report, Department of Engineering Science, University of Auckland.
Notes. This paper discusses the application of queueing theory to determining staffing levels and shift demand for an emergency services call centre. As the application is to emergency services the calls are broken into differing priority levels. By modelling these distinctly more efficient staffing levels can be determined. These staffing levels are transformed into shift demand using a standard integer programming formulation.

Chen, B. and S. Henderson. (2001). "Two Issues in Setting Call Centre Staffing Levels." *Annals of Operations Research*.
Notes. This paper discusses calculating the staffing levels required at a call center. Consideration is given to using approximations that make the calculations reasonable with limited computing resources. Additionally, the implications of having Poisson arrival rates with means that vary randomly from day to day are discussed.

Chen, J. and T. Yeung. (1992). "Development of a Hybrid Expert System for Nurse Shift Scheduling." *International Journal of Industrial Ergonomics* 9(4), 315–327.
Notes. The paper describes a hybrid system for nurse rostering. Rosters are developed for a two week period with three shifts per day. The expert system is used to manage the workplace rules on which the rosters are constructed. The paper also contains a discussion of some ergonomic and work stress factors related to shift patterns.

Cheng, B., J. Lee, and J. Wu. (1996). "A Constraint-Based Nurse Rostering System Using a Redundant Modeling Approach." In *Eighth IEEE International Conference on Tools with Artificial Intelligence*, pp. 140–148.
Notes. This paper discusses a nurse scheduling problem with some non-standard shift types (mainly leave related). The implementation uses a technique referred to as redundant modelling to link a standard finite domain representation with a set constraint representation. Their results show this leads to an improvement in solution time.

Cheng, B., J. Lee, and J. Wu. (1997). "A Nurse Rostering System Using Constraint Programming and Redundant Modeling." *IEEE Transactions on Information Technology in Biomedicine* 1(1), 44–54.
Notes. The paper describes a constraint programming approach to developing nurse rosters. Redundant constraints, which do not extend the definition of the problem, but which may aid the search are used to improve the solution processes. The method is applied to generate weekly rosters for 27 nurses with 11 shift types.

Chew, K. (1991). “Cyclic Schedule for Apron Services.” *Journal of the Operational Research Society* 42(12), 1061–1069.

Notes. Constructing a cyclic roster for apron crew at an airport is modelled as an integer program and solved easily using simple mathematical calculations. The problem is to use known shift start times to build cyclic lines of work for all crew so as to cover demand and provide crew with the requisite number of days off. This is a special tour scheduling problem with given shift patterns, and it is decomposed into a days-off scheduling and a shift assignment problem.

Chow, K. and C. Hui. (1991). “Knowledge-Based Approach to Airport Staff Rostering: A Case Study.” In *Proceedings of the World Congress on Expert Systems*, p. 46.

Notes. This paper describes a knowledge based system which is used to schedule airport ground staff. The knowledge based system is used to represent soft constraints and provides a heuristic for generating an initial roster for the staff. An iterative improvement algorithm is used to search for a higher quality solution. A slightly more detailed treatment is given in a more recent paper by the authors (Chow and Hui, 1993).

Chow, K. and C. Hui. (1993). “Knowledge-Based System for Rostering.” *Expert Systems with Applications* 6(3), 361–375.

Notes. The authors consider a fixed number staff members and generic duty types (including off shifts) which need to be satisfied each day of the week. The problem is to allocate duties (shifts) to each staff member so as to satisfy demand for shifts on each day, maintain equitable shift distribution, and also ensure that the total number of hours worked in a week is as close to a given number as possible. The problem is formulated as an integer programming problem but solved using a knowledge based system. This knowledge based system is used to represent soft constraints that are not easily represented as linear constraints. After the knowledge based system produces an initial roster, an iterative improvement algorithm is employee to improve the quality of the solution.

Christou, I., A. Zakarian, J. Liu, and H. Carter. (1999). “A Two-Phase Genetic Algorithm for Large-Scale Bidline-Generation Problems at Delta Air Lines.” *Interfaces* 29(5), 51–65.

Notes. The authors present a heuristic method that generates good work lines for crew at Delta Air Lines. The algorithm uses a constructive heuristic to generate an initial population. Then an evolutionary algorithm is used to search for better solutions. To deal with the complex constraints, individuals are evaluated by first performing a repair step and then a local search heuristic to improve the solution.

Chu, S. and E. Chan. (1998). “Crew Scheduling of Light Rail Transit in Hong Kong: From Modeling to Implementation.” *Computers and Operations Research* 25(11), 887–894.

Notes. This paper describes a train crew scheduling application for the Hong Kong light rail system. The crew scheduling problem is solved via a three-stage approach. The first is a shortest path model for dividing runs into smaller duties. The second is a matching problem for putting duties together. The last phase is a set of local improvement heuristics that improve on the solution.

Chu, S., C. Lin, and K. Ng. (1991). “Centralized Versus Decentralized Manpower Resource Planning. The Case of a Hong Kong Company.” *Journal of the Operational Research Society* 42(7), 525–536.

Notes. This paper considers the assignment of repairmen to different regions for carrying out services. A nonlinear programming model is presented for minimizing the weighted response time to customers. A heuristic algorithm combining with a dynamic programming approach is employed for solving the proposed model.

Chu, E., E. Gelman, and E. Johnson. (1997). “Solving Large Scale Crew Scheduling Problems.” *European Journal of Operational Research* 97, 260–268.

Notes. This paper describes work by the authors to improve the solution of large set partitioning problems that arise in airline crew scheduling. Their method starts by a column generation phase in which up to 20 million pairings are generated. The LP is then solved optimally for a subset of 2 million pairings. Finally, a new branching heuristic is used to obtain an integer solution from the best 15,000 pairings found. Results indicate a marginal improvement over the already highly optimised practices at American Airlines.

Chun, A., S. Chan, G. Lam, F. Tsang, J. Wong, and D. Yeung. (2000). "Nurse Rostering at the Hospital Authority of Hong Kong." In *Proceedings of the Twelfth Conference on Innovation Applications of Artificial Intelligence*.

Notes. The paper provides an overview of the design and implementation of a ward based rostering system that uses CLP and constructive heuristics to deal with the wide range of workforce regulations and nursing staff preferences that make up the complex rulebase for the rostering environment.

Church, J. (1973). "SURE STAF: A Computerized Staff Scheduling System for Telephone Business Offices." *Management Science* 20(4), 708–720.

Notes. This paper discuses forecasting demand for call centre operators who have additional duties. In this problem the service representatives (operators) must answer calls and must also complete an amount of paper work each week. The forecasting model, based on standard queueing theory, predicts the number of operators need at each half hour. The service representatives are then allocated by a heuristic algorithm to blocks of time attending the telephones. In unallocated time they attend to their paperwork.

Clement, R. and A. Wren. (1995). "Greedy Genetic Algorithms, Optimizing Mutations and Bus Driver Scheduling." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 213–235. Springer.

Notes. The paper describes the bus driver scheduling problem and provides several special purpose genetic algorithms for solving them. The GAs include several improving strategies such as greedy crossovers and optimised mutations.

Cochran, J., D. Chu, and M. Chu. (1997). "Optimal Staffing for Cyclically Scheduled Processes." *International Journal of Production Research* 35(12), 3393–3403.

Notes. An integrated system is proposed for constructing cyclic rosters. The integrated system consists of collecting data, generating staff requirements for each day of the week using simulation, constructing cyclic rosters using an integer programming formulation, and selecting staff to perform tasks from the existing staff pool. A case study from a semiconductor manufacturing is evaluated with this approach.

Collins, J. and E. Sisley. (1994). "Automated Assignment and Scheduling of Service Personnel." *IEEE EXPERT* 9(2), 33–39.

Notes. This paper discusses the assignment of jobs to field service engineers. The jobs are incrementally added to the schedule as they arrive. This is handled by spawning a local search to incorporate each new job into the current schedule.

Constantino, A.A., C.F.X. de Mendonca Neto, and A.G. Novaes. (2002). "Crew Rostering Problem with Distribution of Workload Based on Preferences." Working Paper.

Notes. This paper describes a heuristic algorithm that builds a cyclic roster that approximates the minimum number of train drivers needed. The heuristic algorithm consists of three phases: establishing a utility function to measure personal preferences, constructing a cyclic master roster by assignment algorithms; and generating personal rosters based on a bottleneck assignment problem.

Corominas, A., A. Lusa, and R. Pastor. (2004). "Planning Annualised Hours with a Finite Set of Weekly Working Hours and Joint Holidays." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 217–233.

Notes. This paper presents an annualised working hours planning problem. The main characteristics are that the holiday weeks, which are established beforehand, are the same for all workers and that the number of weekly working hours, for any worker and for any week, must belong to a finite set. Also, for each worker, the annual number of weeks of each type is fixed. In order to solve the planning problem, three aggregated integer linear programming models are formulated, which incorporate three objectives in a hierarchical manner.

Crainic, T. and J. Rousseau. (1987). "The Column Generation Principle and the Airline Crew Scheduling Problem." *INFOR* 25(2), 136–151.

Notes. The authors present a set covering formulation for airline crew scheduling and a specialised pricing algorithm for generating new pairings. Based on this a column generation algorithm is developed and tested on data from Air Canada.

Curtis, S., B. Smith, and A. Wren. (1999). “Forming Bus Driver Schedules Using Constraint Programming.” In *Proceedings of the 1st International Conference on the Practical Applications of Constraint Technologies and Logic Programming (PACLP’99)*, pp. 239–254. The Practical Application Company.
Notes. This paper describes a constraint programming formulation for the bus driver scheduling problem. A set partitioning formulation is used that has some advantages over the standard zero/one formulation. A search strategy is described which uses the solution of the LP relaxation to direct variable and value selection. This is found to improve the effectiveness of the technique.

Curtis, S., B. Smith, and A. Wren. (2000). “Constructing Driver Schedules Using Iterative Repair.” In *Proceedings of PACLP 2000*, pp. 59–78.
Notes. GENET is a local search technique based on a software simulation of a Neural Network. GENET with suitable modifications and enhancements is used for crew scheduling. The main purpose of this work is to generate a feasible solution of crew scheduling quickly. Several adaptations to GENET have been modelled to try to reduce the number of duties in the solution. Initial numerical results are reported.

Daduna, J. and M. Mojsilovic. (1988). “Computer-Aided Vehicle and Duty Scheduling Using the HOT Program System.” In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 133–146. Springer.
Notes. This paper describes the HOT system that is in use for vehicle scheduling, duty scheduling and duty rostering. The paper describes a set of interactive procedures for carrying out scheduling and rostering.

Dahl, R., J. Greenberg, J. Sanborn, C. Skiskim, M. Ball, and L. Bodin. (1985). “A Relational Database Approach to Vehicle and Crew Scheduling in Urban Mass Transit Systems.” In J. Rousseau (ed.), *Computer Scheduling of Public Transport*, pp. 327–342. North-Holland.
Notes. This paper describes a relational database query approach, implemented in RUCUS II for trip building and run generation.

Danko, J. and V. Gulewicz. (1994). “Insight through Innovation: A Dynamic Approach to Demand Based Toll Plaza Lane Staffing.” In J. Tew, S. Manivanna, D. Sadowski, and A. Seila (eds.), *Proceedings of the 1994 Winter Simulation Conference*, pp. 1116–1123.
Notes. This paper discusses the simulation of a toll both plaza to determine service and staffing levels. Arrival rates and lane choices are modelled based on historical data. Once modelled a simulation package is used to evaluate adjustments to the number of open lanes and duration for which they are open.

Dantzig, G. (1954). “A Comment on Edie’s Traffic Delay at Toll Booths.” *Operations Research* 2, 339–341.
Notes. In this letter Dantzig outlines the use of linear programming for use with scheduling tool-booth operators. This approach has spawned a vast amount of research related to scaling this formulation to larger and more realistic problems.

Darby-Dowman, K. and G. Mitra. (1985). “An Extension of Set Partitioning with Application to Scheduling Problems.” *European Journal of Operational Research* 21(2), 200–205.
Notes. This paper proposes an elastic set partitioning model by allowing both over and under coverage. An application of this model to bus crew scheduling is discussed.

Darby-Dowman, K., J. Jachnik, R. Lewis, and G. Mitra. (1988). “Integrated Decision Support Systems for Urban Transit Scheduling: Discussion of Implementation and Experience.” In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 226–239. Springer.
Notes. The paper provides a brief discussion of the characteristics of vehicle and driver scheduling systems and describes the implementation of two systems.

Darmoni, S., A. Fajner, N. Mahe, A. Leforestier, M. Vondracek, O. Stelian, and M. Baldenweck. (1995). “HOROPLAN: Computer-Assisted Nurse Scheduling Using Constraint-Based Programming.” *Journal of the Society for Health Systems* 5, 41–54.
Notes. This paper describes a standard nurse scheduling problem. The discussion of the implementation is limited. However, the authors discuss some search strategies that match manual scheduling. Other

concerns include fairness of shift allocation, including consideration of previous schedules. Replanning is mentioned as being important, however, there is little discussion of how this is achieved.

Dawid, H., J. Konig, and C. Strauss. (2001). "An Enhanced Rostering Model for Airline Crews." *Computers and Operations Research* 28, 671–688.

Notes. This paper describes a crew rostering problem for airlines where the main objective is to find a feasible solution. The authors allows downgrading (where higher qualified staff perform duties requiring a lower rank) in order to achieve feasibility. An implicit enumeration approach with constraint propagation is used to find solutions. This approach use bounds on the number of staff as given by the number of overlapping pairings to cut the search tree. Numerical results indicate that this method is significantly faster than using a commercial IP solver.

Day, L. (1989). "Automated Staff Scheduling in Long-Term Care Facilities." *Nursing Management* 20(3), 76–78.

Notes. This paper presents a review of existing automated computer staff scheduling systems.

Day, P. and D. Ryan. (1997). "Flight Attendant Rostering for Short-Haul Airline Operations." *Operations Research* 45(5), 649–661.

Notes. The authors describe a system used for several years by Air New Zealand to roster crews over a 14 day period. The method used involves first finding an optimal days off pattern for all staff using a set partitioning formulation, and then assigning pairings. The pairing assignment is done by solving set partitioning problems over a rolling 6 day horizon with limited enumeration of feasible worklines. Finally a re-rostering phase is used to adjust rosters in order to improve equitability among staff. Results for up to 600 duties and 80 staff are reported.

de Silva, A. (2001). "Combining Constraint Programming and Linear Programming on an Example of Bus Driver Scheduling." *Annals of Operations Research* 108, 277–291.

Notes. This paper describes the use of constraint programming to generate duties (columns) in a column generation approach to solving the Crew Scheduling problem. Some complications in solving the LP and IP formulations are discussed.

de Sousa, J. (1991). "A Computer Based Interactive Approach to Crew Scheduling." *European Journal of Operational Research* 55(3), 382–393.

Notes. A human–computer interactive method for transit crew scheduling is presented in this paper. This system is implemented as part of a larger decision support system at the Oporto Urban Transport Authority. Given a set of scheduling rules and pieces of work that need to be performed (as outputs from a bus scheduling model) an iterative process simplifies the process of crew schedule generation. Partially completed manually schedules can be optimized automatically, through a run-cutting heuristic procedure, and then improved upon.

Desaulniers, G., J. Desrosiers, Y. Dumas, S. Marc, B. Rioux, M. Solomon, and F. Soumis. (1997). "Crew Pairing at Air France." *European Journal of the Operational Research Society* 97, 245–259.

Notes. The authors present a branch and price method for crew scheduling at Air France. The master problem is a set partitioning problem with some side constraints and the pricing problem is solved as a constrained shortest path problem. Using this method solutions are obtained for Air France's medium haul crews with gaps of less than 0.5% for problems with up to 1157 flights.

Desaulniers, G., J. Desrosiers, M. Gamache, and F. Soumis. (1998). "Crew Scheduling in Air Transportation." In T. Crainic and G. Laporte (eds.), *Fleet Management and Logistics*, pp. 169–185. Boston: Kluwer.

Notes. This paper starts with the premise that crew scheduling, crew rostering and operational modification of rosters are all essentially the same type of problem mathematically and hence should be solved with the same algorithm. The authors provide a generalised set partitioning formulation and a high level description of a branch and price algorithm. computational results are presented for a variety of problems using the GENCOL software developed by the authors. Unfortunately these results were produced with a range of computers and different versions of GENCOL (2.0–4.0) as well as different LP Optimisers (CPLEX 2.0–3.1, XMP) making comparisons difficult.

Desaulniers, G., J. Desrosiers, A. Lasry, and M. Solomon. (1999). "Crew Pairing for a Regional Carrier." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 19–41. Springer.

Notes. This paper describes the pairing generation problem for crew at a regional airline. Two network models are presented which differ in whether flights rather than duties are presented as arcs or nodes. Either network can be used to generate pairings by solving constrained shortest path problems. Numerical results are also presented of the effects of varying the scheduling constraints that the pairings have to satisfy.

Desrochers, M. and F. Soumis. (1988). "CREW-OPT: Crew Scheduling by Column Generation." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 83–90. Springer.

Notes. The authors describe what is by now a standard algorithm for solving crew scheduling problems using branch and price with a constrained shortest path method for generating columns. They report substantial improvements for two bus driver scheduling problems over those obtained from the commercial HASTUS software.

Desrochers, M. and F. Soumis. (1989). "A Column Generation Approach to the Urban Transit Crew Scheduling Problem." *Transportation Science* 23(1), 1–13.

Notes. This paper presents a column generation approach for solving urban mass transit crew scheduling problems. In this paper the column generation approach decomposes the transit crew scheduling problem into two parts: a set covering problem and a constrained shortest path subproblem for generating new feasible patterns. The set covering model allows for the addition of side constraints relating to the number of straight shifts, trippers and split shifts. A linear relaxation of the set covering problem is embedded in a branch and bound scheme and solved. Given that the set covering problem is often degenerate, a perturbation is used to reduce solution cycling and stalling. The column generation subproblem, used to deliver new columns, is a constrained shortest path problem with resource constraints, defined on an acyclic graph. This is solved using dynamic programming.

Desrochers, M., J. Gilbert, M. Sauve, and F. Soumis. (1992). "Crew-OPT: Subproblem Modelling in a Column Generation Approach to Urban Crew Scheduling." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, pp. 395–406. Springer.

Notes. This paper discusses the pricing problem that arises in column generation methods for bus driver (& crew) scheduling. It shows how this can be modelled as a constraint shortest path problem that is solved using dynamic programming. Some practical tricks for improving the performance of this technique are discussed.

Desrosiers, J. (2001). "Air Canada Reaches 'Altitude'." *OR/MS Today* 28(2).

Notes. This article describes the implementation of the Altitude PBS software for crew rostering at Air Canada in an easily accessible manner suitable for non-technical audiences.

Dias, T., J. Sousa, and J. Cunha. (2002). "Genetic Algorithms for the Bus Driver Scheduling Problem: A Case Study." *Journal of Operational Research Society* 53, 324–335.

Notes. The bus driver scheduling problem is formulated as an extension of the traditional set covering and partitioning formulations, allowing the simultaneous consideration of several complex criteria. A specially designed genetic algorithm is proposed for solving this problem, that can be integrated in a DSS or used as an interactive tool or stand-alone application. It is reported that satisfactory solutions can be produced very quickly.

Dijkstra, M., L. Kroon, J. van Nunen, and M. Salomon. (1991). "A DSS for Capacity Planning of Aircraft Maintenance Personnel." *International Journal of Production Economics* 23(1–3), 69–78.

Notes. The paper describes the problem of planning a multi-skilled workforce of engineers required to carry out aircraft maintenance. The demand for labour is determined by a set of tasks with given skill requirements and fixed start/end times derived from the flight schedule. The authors describe a decision support system that includes a Lagrangean relaxation approach and a constructive heuristic to obtain an approximate solution quickly.

Dillion, J. and S. Kontogiorgis. (1999). “US Airways Optimizes the Scheduling of Reserve Flight Crews.” *Interfaces* 29(5), 123–131.

Notes. Reserve pilots and flight attendants work on call to operate flights that the assigned crew members cannot fly or flights that have not been assigned. The crew rostering problem for reserve pilots and attendants is formulated as an elastic set covering model, with all potential lines of work included. Since 1995, US Airways has used this model as an integrated part of the crew staffing process.

Doerner, K., G. Kotsis, and C. Strauss. (2002). “Rosterbuilder – An Architecture for an Integrated Airline Rostering Framework.” Working Paper.

Notes. This paper presents the specific requirements placed on a rostering framework and derives a generic software architecture for airline crew management. In the proposed architecture, crew pairing, roster, crew operations and crew notifications are the core components accessed by the users of the system. An interface to a crew preference component in the crew rostering process allows crew members to participate in this process.

Dowling, D., M. Krishnamoorthy, H. MacKenzie, and D. Sier. (1997). “Staff Rostering at a Large International Airport.” *Annals of Operations Research* 72, 125–147.

Notes. This paper has a strong application focus. It describes a rostering system implemented for ground staff at a large international airport. A novel feature of this system is the ability of the user to add and modify rostering constraints. The paper includes a high level description of the core simulated annealing algorithm, system overview and describes the outcomes achieved.

Dowsland, K. (1998). “Nurse Scheduling with Tabu Search and Strategic Oscillation.” *European Journal of Operational Research* 106(2–3), 393–407.

Notes. The paper describes a method in which Tabu Search is used to oscillate between finding feasible covers and improving them in terms of nurse preferences. The application is used to develop weekly rosters for nurses in a large general hospital. The method is able to incorporate ranks, skills, preferences and equity distribution of rosters. This paper also considers the use of part time staff to cover demand.

Dowsland, K. and J. Thompson. (2000). “Solving a Nurse Scheduling Problem with Knapsacks, Networks and Tabu Search.” *Journal of the Operational Research Society* 51, 825–833.

Notes. The paper describes the use of a mix of knapsack, network flow and tabu search methods to develop nurse rosters. The system can deal with a wide range of nurse preferences, workplace rules, numbers of nurses needed and different grades of nurses.

Drexl, A. and K. Haase. (1999). “Fast Approximation Methods for Sales Force Deployment.” *Management Science* 45(10), 1307–1323.

Notes. This paper discusses a non-linear integer programming formulation for planning a workforce of field service personnel. The integer programming model incorporates all four aspects of the planning problem: sales force size, personnel location, territory alignment and resource allocation. The non-linear program is solved by approximation, either by transformation to a linear program or via a construct and improve local search.

DuCote, G. and E. Malstrom. (1999). “A Decision of Personnel Scheduling Software for Manufacturing.” *Computers and Industrial Engineering* 37, 473–476.

Notes. This brief paper provides some equations for converting from a bill of materials requirement to a number of employees. Some discussion of costing and scheduling is made, however, few details are provided.

Duder, J. and M. Rosenwein. (2001). “Towards “Zero Abandonments” in Call Center Performance.” *European Journal of Operational Research* 135, 50–56.

Notes. This paper attempts to quantify some of the benefits of operating a call centre at less than 100% utilisation. The discussion especially focuses on reduced abandonment when demand is greater than expected. For some call centres this reduced abandonment can lead to improved profit. Some “rule-of-thumb” analysis is made on how to determine the additional level of staffing justified by the improved service.

Duffuaa, S. and K. Al-Sultan. (1999). "A Stochastic Programming Model for Scheduling Maintenance Personnel." *Applied Mathematical Modeling* 25(5), 385–397.

Notes. A maintenance personnel scheduling problem is formulated as a stochastic program. The demand of personnel for performing tasks with various skills is the sum of known and unknown represented in a probabilistic distribution.

Dupuis, D. (1985). "Automatic Crew Scheduling: New Operating Management and Service Opportunities." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 145–148. North-Holland.

Notes. This paper describes experience and benefits of the HASTUS crew scheduling software system.

Easton, F. and J. Goodale. (2001). "Labor Scheduling with Employee Turnover and Absenteeism." Technical Report, Syracuse University.

Notes. This paper studies the impact of employee turnover and absenteeism on workforce availability and integrates those results into a stochastic set partitioning model. Numerical experiments are carried out to see how much gain can be obtained with different levels of turnovers, absenteeism, variable demands, and profit margins.

Easton, F. and N. Mansour. (1999). "A Distributed Genetic Algorithm for Deterministic and Stochastic Labor Scheduling Problems." *European Journal of Operations Research* 118, 505–523.

Notes. The authors present a distributed genetic algorithm that solves a family of deterministic and stochastic labor scheduling problems with multiple-skilled workforce. In comparison with other existing constructive and metaheuristics, the proposed algorithm is proved to produce better performing solutions than its competitors. The principal limitations of the method appear to be its computational burden and potentially large memory space it requires.

Easton, F. and D. Rossin. (1991a). "Equivalent Alternate Solutions for the Tour Scheduling Problem." *Decision Science* 22, 985–1001.

Notes. Most existing tour scheduling solution procedures usually produce a single solution, though many other solutions with equal or similar costs may exist. Alternate equivalent solutions may increase a manager's ability to achieve secondary staffing and scheduling objectives without increasing costs. A local search method is presented in this paper to find alternate equivalent solutions of tour scheduling.

Easton, F. and D. Rossin. (1991b). "Sufficient Working Subsets for the Tour Scheduling Problem." *Management Science* 37(11), 1441–1451.

Notes. The set covering formulation of the tour scheduling problem is usually of a large scale. This paper presents a column generation approach for generating only a limited number of tours to form a limited version of the set covering formulation. Numerical experiments show that the set covering formulation with sufficient working subsets can generate solutions with minimal effect on solution quality.

Easton, F. and D. Rossin. (1996). "A Stochastic Goal Program for Employee Scheduling." *Decision Sciences* 27(3), 541–568.

Notes. Staffing requirements in planning periods are often established during the demand modelling process. In the traditional set covering formulation for tour scheduling, staffing requirements are deterministic. In reality, staffing requirements are of stochastic nature. This paper proposes a stochastic model for tour scheduling by incorporating stochastic variable demands in the set covering formulation. The merits of the new model are evaluated through numerical experiments.

Easton, F. and D. Rossin. (1997). "Overtime Schedules for Full-Time Service Workers." *Omega* 25(3), 285–299.

Notes. Employing part-time workers is one strategy for improving labor costs and employee utilization in order to handle service demand uncertainty and fluctuations. This paper shows that scheduled overtime provides many of the same operational advantages of part-time scheduling strategies. The experiments are carried out on a set covering model for tour scheduling problems.

Edie, L. (1954). "Traffic Delays at Toll Booths." *Journal Operations Research Society of America* 2(2), 107–138.

Notes. This paper discusses the use of delay and probability theory to calculate the number of toll booths required to provide specific level of service (average waiting time). That is, predicting the level of demand at different times of the day and therefore the amount of staff required.

Eitzen, G. (1999). "Rostering Multi-Skilled Employees Efficiently and Fairly: A Column Generation and Constraint Branching Approach." Technical Report, Working Paper, University of South Australia.

Notes. This paper discusses rostering employees with multiple skills. The problem is modelled with a set covering formulation. Column generation is used to limit the size of the problem. Some description of the branch and bound strategy is given, including the constraint branching strategy used.

Eitzen, G. (2002). "Integer Programming Methods for Solving Multi-Skilled Workforce Optimisation Problems." Ph.D. Thesis, School of Mathematics, University of South Australia.

Notes. This thesis introduces dynamic rostering for developing rosters for a energy company. Dynamic rosters are useful in situations where rosters are required for multi-skilled workers who work in an environment with fluctuating workforce requirements, changes in employee numbers and their work preferences. This thesis develops a wide range of methods such as 'column expansion,' 'reduced column subset' and branch and price, all based on integer programming approaches, for solving these problems.

Eitzen, G., G. Mills, and D. Panton. (2004). "Multi-Skilled Workforce Optimisation." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 359–372.

Notes. The paper describes the problem of rostering staff with non-hierarchical multiple skills under fluctuating demand at a power station. A set covering formulation, using work tours (columns) with a score based on the degree of observation of workplace regulations over the work period, is used to solve the problem. A prime focus is on roster equity between employees. Three column based solution methods: column expansion, column subset and Branch and Price, with constraint branching in the IP phase, were used. Test data sets with up to 100 employees, nine skill levels and three levels of demand were used to generate rosters based on three shifts per day over a 14 day period. The paper discusses how the problem characteristics affect the performance of each of the three solution methods.

Elias, S. (1964). "The Use of Digital Computers in the Economic Scheduling for Both Man and Machine in Public Transportation." *Kansas State University Bulletin*.

Elms, J. (1988). "The Use of Computers in Bus and Crew Scheduling by London Buses and Its Predecessors: A User's View." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 262–271. Springer.

Notes. This paper reviews the use of computerized scheduling at London Buses over a 20-year period.

Emden-Weinert, T. and M. Proksch. (1999). "Best Practice Simulated Annealing for the Airline Crew Scheduling Problem." *Journal of Heuristics* 5(4), 419–436.

Notes. The airline crew scheduling problem is tackled with a simulated annealing (SA) approach in this paper. The neighbourhood moves join or split pairings in a locally optimal manner. Compound moves involving both splits and joins are considered at the end of each temperature run. Results are reported for two data sets with up to 4600 flights. Comparisons are made with constructive and descent heuristics. Not surprisingly the SA performs better in solution quality, but at the cost of significantly more processing time than the simpler heuristics.

Emmons, H. (1985). "Work-Force Scheduling with Cyclic Requirements and Constraints on Days off, Weekends off, and Work Stretch." *IIE Transactions* 17(1), 8–16.

Notes. A cyclic roster is generated for a days-off scheduling problem from a constructive algorithm. The cyclic roster is constructed using the minimum workforce size and must confirm pre-defined off days and off weekends patterns.

Emmons, H. and R. Burns. (1991). "Off-Day Scheduling with Hierarchical Worker Categories." *Operations Research* 39(3), 484–495.

Notes. Heuristic algorithms are designed for solving a days-off scheduling problem with unchanged daily demands and hierarchical workforce categories. Higher ranked workers can always substitute workers with lower ranks.

Emmons, H. and D. Fuh. (1997). "Sizing and Scheduling a Full-Time and Part-Time Workforce with off-Day and off-Weekend Constraints." *Annals of Operations Research* 70, 473–492.

Notes. A days-off scheduling problem with a mixture of full-time and part-time workforce is considered. Exact workforce sizes are calculated under different cost scenarios of part-time workers. Feasible schedules with given workforce sizes are generated using a constructive algorithm to satisfy various constraints such as off days patterns.

Ernst, A., M. Krishnamoorthy, and D. Dowling. (1998). "Train Crew Rostering Using Simulated Annealing." In *Proceedings of ICOTA'98*, Perth.

Notes. This paper describes the application of freight train crew rostering in Australia. Given the number of crew stationed at each depot in a network and given the repeating weekly rail schedules, cyclic crew rosters are developed directly from the train trips. The cost function includes wages, out-of-town expenses and other penalty costs to do with either over-covering or under-covering a trip. A simulated annealing algorithm is developed for the solution of this problem.

Ernst, A., P. Hourigan, M. Krishnamoorthy, G. Mills, H. Nott, and D. Sier. (1999a). "Rostering Ambulance Officers." In *Proceedings of the 15th National Conference of the Australian Society for Operations Research*, Gold Coast, pp. 470–481.

Notes. The paper describes a number of network algorithms used to develop rosters for ambulance officers. The rosters are constructed from specified shift patterns, called stints, using a set of allowed transitions between the stints. The transitions are weighted to indicate preferences for certain stint transitions.

Ernst, A., H. Jiang, M. Krishnamoorthy, H. Nott, and D. Sier. (1999b). "An Optimization Approach to Train Crew Rostering." In *Proceedings of the 15th National Conference of the Australian Society for Operations Research*, Gold Coast, pp. 437–452.

Notes. This paper discusses a formulation for optimising both crew scheduling and crew rostering. The formulation deals with regulations and restrictions to ensure the quality of life for the employees. Additionally, the problem formulation models the unusual sparseness of the Australian rail network. The problem is solved via a massive set partitioning (integer programming) formulation. The dimensions of the integer program are attacked using a combination of cutting planes and column generation. Limited computational results are presented to support the efficacy of this method.

Ernst, A., H. Jiang, M. Krishnamoorthy, H. Nott, and D. Sier. (2001a). "An Integrated Optimization Model for Train Crew Management." *Annals of Operations Research* 108(1/4), 211–224.

Notes. This paper presents an integrated approach to rail crew scheduling and crew rostering. Given a rail network with a number of depots and rail trips that need to be 'covered,' this paper first distinguishes between the planning problem, which is one of deciding the total number of crews and their distribution across the network. Rather than tackling crew scheduling and crew rostering independently and sequentially, this paper proposes an integrated model and generates cyclic rosters in which under-coverage and over-coverage of specific duties is allowed. The model is tested on data sets from long-haul freight train schedules from Australia.

Ernst, A., H. Jiang, M. Krishnamoorthy, H. Nott, and D. Sier. (2001b). "Rail Crew Scheduling and Rostering Optimization Algorithms." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 53–72. Springer.

Notes. This paper describes an integer programming formulation for the 'operational' rail crew scheduling and crew rostering. Given a planning horizon and the train trips that need to be crewed over that planning horizon, the problem is one of generating rosters for all crew in such a way that all trips are covered and all business, operational and crewing rules are satisfied. This paper includes many real-life constraints from an application of rail crew rostering in Australia. An integer programming model is formulated and solved and some computational experiences are described.

Ernst, A., H. Jiang, M. Krishnamoorthy, and D. Sier. (2004). "Staffing Scheduling and Rostering: A Review of Applications, Methods and Models." *European Journal of Operations Research* 153, 3–27.

Notes. This paper provides a review of the rostering literature with almost 200 references. The review covers a wide variety of application areas and common solution techniques. It also provides a classification scheme for describing rostering problems.

Eusebio, J., L. Amado, L. Fragoso, and J. Paixao. (1988). "Development and Implementation of an

Automatic System for Bus and Crew Scheduling at RN-Portugal." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 147–159. Springer.
Notes. This paper provides implementation details of a PC-based automated system for scheduling crews and buses at a bus company in Portugal. The basic set covering model considers the set of all duties over all time intervals. This is simplified in an 'aggregated model' which considers a restricted set of time intervals where a certain number of known duties need to be covered for each interval. This model is solved using a combination of rules-based preprocessing steps, greedy heuristics and an LP-based approach.

Evans, J. (1988). "A Microcomputer-Based Decision Support System for Scheduling Umpires in the American Baseball League." *Interfaces* 18(6), 42–51.
Notes. The paper describes the problem of scheduling baseball umpires for the American Baseball League over one season. This essentially involves find a travelling salesman like tour for each crew of umpires to cover all games, which simultaneously minimises travel cost and maximises equity. The author proposes a very simple heuristic scheme that involves solving a sequence of assignment problems and some manual interaction.

Eveborn, P. and M. Ronnqvist. (2004). "Scheduler – A System for Staff Planning." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 21–45.
Notes. This paper describes a general tour/staff scheduling system called Scheduler that includes a number of important features. The model is based on an elastic set partitioning model that is solved using a branch-and-price algorithm. The system is user-friendly and includes a very general description of legal restrictions, preferences and allowable times. The solution quality is continuously illustrated in a diagram and the process can at any time be stopped and schedules can be analysed against demand. The system is in use at a number of companies.

Faaland, B. and T. Schmitt. (1993). "Cost-Based Scheduling of Workers and Equipment in a Fabrication and Assembly Shop." *Operations Research* 41(2), 253–268.
Notes. This paper primarily discusses the difficulties involved in implementing Materials Requirements Planning. The planning is performed by solving a number of maximum flow problems. This planning identifies bottlenecks in the system which may be to some extent alleviated by hiring, re-deploying, or cross-training staff.

Fahle, T. and S. Bertels. (2002). "A Hybrid Setup for a Hybrid Scenario: Combining Heuristics for the Home Health Care Problem." Working Paper.
Notes. The paper describes the problem of scheduling nurses to visit patients in the home. The requirement is to design rosters that consider both the staff rostering and vehicle routing components while minimising transportation costs and maximising the preferences of the patients and nurses. The paper contains a very good formulation of the problem and an excellent discussion of integrated LP, CP and heuristic solution methods. While the main focus is on solution methods, the paper also outlines a prototype software decision support system, containing these solution methods, for this problem.

Fahle, T., U. Junker, S. Karisch, N. Kohl, M. Sellmann, and B. Vaaben. (2002). "Constraint Programming Based Column Generation for Crew Assignment." *Journal of Heuristics* 8(1), 59–87.
Notes. This paper describes a solution technique for the crew rostering problem based on embedding a constraint programming column generator within a column generation approach. Constraints for generation of columns with negative reduced costs are discussed and their relative efficiency compared. Some discussion of the integration of solvers is made.

Falkner, J. and D. Ryan. (1987). "A Bus Crew Scheduling System Using a Set Partitioning Model." *Asia Pacific Journal of Operational Research* 4, 39–56.
Notes. The paper describes a computerised crew scheduling system based on a set partitioning approach developed for the bus transport authority in Christchurch, New Zealand. The problem size is reduced using heuristic reduction techniques. A set partitioning model is used for developing optimal schedules.

Falkner, J. and D. Ryan. (1988). "Aspects of Bus Crew Scheduling Using a Set Partitioning Model." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and

Mathematical Systems, Vol. 308, pp. 91–103. Springer.
Notes. The paper considers a bus crew scheduling problem in Christchurch, New Zealand. A solution method based on set partitioning has been developed. Methods for overcoming difficulties associated with degeneracy are presented. This includes the use of dual simplex in nodes of the branch and bound tree search.

Falkner, J. and D. Ryan. (1992). "EXPRESS: Set Partitioning for Bus Crew Scheduling in Christchurch." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 359–378. Springer.
Notes. EXPRESS is a bus crew scheduling system based on a set partitioning model. This paper describes the solution method used in EXPRESS. To reduce the size of the set partitioning model, two strategies are used. Firstly, the problem is decomposed into three subproblems according to the starting times of bus trips. Secondly, the method of next available is used to remove some duties that are unlikely to appear in good solutions from the set partitioning model. Finally the resulting integer program is solved using ZIP, an integer linear programming solver.

Feiring, B. (1993). "A Model Generation Approach to the Personnel Assignment Problem." *Journal of the Operational Research Society* 44(5), 503–512.
Notes. The paper discusses a system for evaluating the suitability of individuals for different jobs in a military setting. It compares numerically several error measures. Numerical study of risk analysis models can test the hypotheses of probability of success.

Ferreira, J. and R. Guimaraes. (1995). "A Travelling Salesman Model for the Sequencing of Duties in Bus Crew Rotas." *Journal of the Operational Research Society* 46(4), 415–426.
Notes. The paper describes a system for developing cyclic rosters for bus drivers. The main objective is to minimise the variation of rest periods between duties. The problem is modelled as an asymmetric TSP and solved using a 3-opt based composite heuristic.

Fischetti, M., A. Lodi, S. Martello, and P. Toth. (2001). "A Polyhedral Approach to Simplified Crew Scheduling and Vehicle Scheduling Problems." *Management Science* 47(6), 833–850.
Notes. A special case of the integrated vehicle and crew scheduling problem is considered. The problem is modelled as an integer program rather than the standard set covering formulation. The resulting integer program has a very loose linear programming relaxation, but it can be tightened by means of new families of valid inequalities (cuts). These cuts are embedded into an exact branch and cut algorithm. Numerical experiments on a set of randomly generated test problems and a set of real-world instances show that the new method is competitive on some types of test problems.

Focacci, F., E. Lamma, P. Mello, and M. Milano. (1997). "Constraint Logic Programming for the Crew Rostering Problem." In *Proceedings of PACT'97*, pp. 151–164.
Notes. The paper describes a CLP approach to solving the Crew Scheduling problem. To optimise large problem instances an effective lower bound is used to convert the problem to a constraint satisfaction problem. Some methods for improving the search and for post processing are discussed.

Fores, S. (1996). "Column Generation Approaches to Bus Driver Scheduling." Ph.D. Thesis, University of Leeds.
Notes. This thesis presents a numerical method for solving the bus driver scheduling problem. The problem is formulated as a set covering model from a set of previously generated valid duties. The linear programming relaxation is solved using a column generation scheme in which all columns are stored in memory rather than generated on the fly as in other column generation approaches. The final solution of the bus driver scheduling problem is obtained by solving the integer linear program using the columns that appeared in the optimal solution of the linear programming relaxation. Numerical results show that an average reduction in execution time of 41% using column generation, and the larger data sets yield better schedules in terms of the number of duties and the overall cost.

Fores, S. and L. Proll. (1998). "Driver Scheduling by Integer Linear Programming – the TRACS II Approach." In P. Borne, M. Ksouri, and A.E. Kamel (eds.), *Proceedings CESA'98 Computational Engineering in Systems Applications, Symposium on Industrial and Manufacturing Systems*, Vol. 3, pp. 213–218.

Notes. This paper describes the mathematical models and algorithms embedded in the TRACS II transit vehicle and driver scheduling application. An integer program involves the minimization of a weighted objective function that includes the number of crew used and wage costs. Both set covering and set partitioning constraints are used, given that we can identify situations where overcover can be forbidden. Side constraints are also introduced as necessary. Either a dual steepest edge approach or a column generation method is used to solve the resulting LP relaxation based on the number of shifts that are available to choose from in the model.

Fores, S., L. Proll, and A. Wren. (1998). "A Column Generation Approach to Bus Driver Scheduling." In M. Bell (ed.), *Transportation Networks: Recent Methodological Advances*, pp. 195–208. Pergamon.

Notes. Following the success of column generation techniques in solving a variety of crew scheduling problems (e.g. (Desrochers et al., 1992; Rousseau and Desrosiers, 1995)), the authors attempt in this paper to implement such an approach within the framework of their IMPACS/TRACS II bus driver scheduling software. The proposed column generation technique involves limited enumeration of possible columns which are priced after each LP subproblem is solved. This is compared to the original method where a smaller set of columns is heuristically chosen at the start with no further column generation. Small improvements in solution time and quality are reported for bus driver scheduling problems with up to 500 work pieces.

Fores, S., L. Proll, and A. Wren. (1999). "An Improved ILP System for Driver Scheduling." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 43–62. Springer.

Notes. This paper provides a framework for solving bus crew scheduling problems. Valid shifts are those that satisfy a combination of labour agreements, business rules and employee preferences. Once a set of valid and compact shifts are generated, the general transit crew scheduling problem is one of determining an appropriate set of shifts that minimise costs, or number of crew, or minimises the presence of undesirable shifts, or reduces over/under coverage of pieces of work (or some weighted combination of the above). In the general model, where over or under coverage is allowed, the constraints reflect this. Side constraints may be present too. In this paper, a new framework is presented which solves the IP through a column generation approach.

Fores, S., L. Proll, and A. Wren. (2001). "Experiences with a Flexible Driver Scheduler." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 137–152. Springer.

Notes. The paper describes technical improvements to the optimisation methods in the TRACS II driver scheduling system. The improved system was tested on two large rail problems that had previously required regional decomposition. Better solutions were obtained by dealing with the scheduling problems on a more global level.

Fores, S., L. Proll, and A. Wren. (2002). "TRACS II: A Hybrid IP/Heuristic Driver Scheduling System for Public Transport." *Journal of the Operational Research Society* 53, 1093–1100.

Notes. This paper describes a combined integer linear programming/heuristic approach to the solution of the driver scheduling problem in the crew scheduling system, TRACS II. A column generation scheme is used to solve the linear programming relaxation of the set covering model. A reduction heuristic is proposed to eliminate some duties in order to reduce the size of the set covering model so that it can be solved by performing a limited branch and bound search. Enhancements to the mathematical programming algorithm, together with TRACS II's inherent flexibility, have enabled the solution of increasing large and complex driver scheduling problems.

Forsyth, P. and A. Wren. (1997). "An Ant System for Bus Driver Scheduling." Technical Report, University of Leeds, School of Computer Studies, Research Report No. 97.25.

Notes. This paper explores an ant system heuristic for solving bus driver scheduling problems. The ant trails in this case represent bus driver schedules. Given an initial set of schedules, developed through other heuristics, the ant system develops newer and improved schedules based on the quality of each solution.

Franz, L., H. Baker, G. Leong, and T. Rakes. (1989). "A Mathematical Model for Scheduling and Staffing Multiclinic Health Regions." *European Journal of Operational Research* 41(3), 277–289.
Notes. The paper uses a goal programming approach to the problem of scheduling clinics and then assigning itinerant staff to the clinics in a multi-location health care system. Different types of clinics (family planning, nursing, medical, pharmacy dispensing) are scheduled at the different locations and suitably qualified staff are then assigned to travel between the locations to provide the clinical services. An IP is used to solve the goal programming model.

Franz, L. and J. Miller. (1993). "Scheduling Medical Residents to Rotations – Solving the Large-Scale Multiperiod Staff Assignment Problem." *Operations Research* 41(2), 269–279.
Notes. The paper describes the problem of assigning hospital residents to a series of tasks over a number of time periods. A DSS is used to manage an iterative LP solution and rounding heuristic procedure. Contains an excellent summary of the cultural based difficulties of implementing DSS and computer systems in hospitals.

Freeman, J. (1992). "Planning Police Staffing Levels." *Journal of the Operational Research Society* 43(3), 187–194.
Notes. A simulation model is created for planning staff levels for the UK police service. The primal goals are to evaluate impacts of the following scenarios: the demand; operating policy; and resourcing policy. Quality of solutions for all scenarios are determined by total operating time and other costs, and staff utilization.

Freling, R., P. Wagelmans, and M. Paixao. (1999). "An Overview of Models and Techniques for Integrating Vehicle and Crew Scheduling." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 441–460. Springer.
Notes. This paper considers the problem of integrating vehicle and crew scheduling. Traditional approaches have adopted a vehicle-first–crew-next scheduling method. The paper provides an overview of models and algorithms for the integrated problem.

Freling, R., D. Huisman, and A. Wagelmans. (2001a). "Applying an Integrated Approach to Vehicle and Crew Scheduling in Practice." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 73–90. Springer.
Notes. This paper deals with an integrated approach to the problems of bus scheduling and bus crew scheduling. This integrated approach is originally proposed in (Freling et al., 1999) and is modified in order to incorporate some complicated constraints that arise from a real-life application. Traditionally, these problems have been handled sequentially. In the sequential case, the vehicle scheduling problem is solved using a Lagrangean relaxation approach – the subproblem is a quasi-assignment problem. The crew scheduling part of the sequential approach is achieved by solving a set covering problem. The paper then presents an integer programming formulation of the vehicle and crew scheduling problem, which is solved through a combination of Lagrangean relaxation and column generation.

Freling, R., R. Lentink, and M. Odijk. (2001b). "Scheduling Train Crews: A Case Study for the Dutch Railways." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 153–166. Springer.
Notes. This paper discusses a heuristic approach to the problem of crew scheduling in transit systems. Although the approach is general in nature, the particular application dealt with in this paper is one of scheduling railway guards for Dutch Railways. A column generation approach solves an LP relaxation of the IP formulation while a branch-and-price heuristic yields integer solutions. New columns are generated using a dynamic programming approach.

Freling, R., D. Huisman, and A. Wagelmans. (2003). "Models and Algorithms for Integration of Vehicle and Crew Scheduling." *Journal of Scheduling* 6(1), 63–85.
Notes. This paper studies the problem of integrating vehicle and crew scheduling in a mass transit scheduling context. With a view to assessing the usefulness of this approach, solutions obtained from an integrated approach are compared with those obtained from a sequential vehicle-first–crew-next scheduling approach. Mathematical models are presented for the sequential and the integrated prob-

lems. Lagrangean relaxation and Lagrangean heuristics are developed for the integrated problem. The associated set partitioning type models are solved using column generation approaches.

Freling, R., R.M. Lentink, and A.P.M. Wagelmans. (2004). "A Decision Support System for Crew Planning in Passenger Transportation Using a Flexible Branch-and-Price Algorithm." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 203–222.
Notes. This paper discusses a decision support system for airline and railway crew planning. The system is a state-of-art branch-and-price solver that is used for crew scheduling and crew rostering. Both crew scheduling and crew rostering problems are formulated as set partitioning models. The computational results contain an interesting comparison of results obtained with the approach in which crew scheduling is carried out before crew rostering, and an approach in which these two planning problems are solved in an integrated manner.

Gaballa, A. and W. Peace. (1979). "Telephone Sales Manpower Planning at Qantas." *Interfaces* 9(3), 1–9.
Notes. The telephone sales manpower planning is decomposed into four stages: Forecast of call volumes; Determination of staffing requirements; Shift scheduling; and Roster generation. Integer programming approaches are used for the last two stages while forecasting techniques and queueing theory are employed in the first and the second stages, respectively.

Gaffi, A. and M. Nonato. (1999). "An Integrated Approach to Ex-Urban Crew and Vehicle Scheduling." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 129–154. Springer.
Notes. Rather than scheduling vehicles and crews individually and sequentially, this paper considers the simultaneous solution of these problems particularly for ex-urban mass transit applications. The paper presents a Lagrangean heuristic for the combined problem. The dual heuristic procedure for the set partitioning subproblem uses constrained shortest paths and assignment-based approaches.

Gamache, M. and F. Soumis. (1998). "A Method for Optimally Solving the Rostering Problem." In G. Yu (ed.), *OR in Airline Industry*, pp. 124–157. Boston, MA: Kluwer Academic.
Notes. A set partitioning formulation for the crew rostering problem with employee preferences is presented in this paper together with a standard branch and price approach. The algorithms performance is improved by ensuring that the pricing subproblems generate disjoint pairings in each iteration. The authors discuss in some detail, based on numerical results, the effect of making employee preferences constraints rather than an objective. Some preliminary results are presented, see (Gamache et al., 1999) for more details.

Gamache, M., F. Soumis, D. Villeneuve, J. Desrosiers, and E. Gélinas. (1998). "The Preferential Bidding System at Air Canada." *Transportation Science* 32(3), 246–255.
Notes. This paper discusses the monthly crew rostering problem for pilots at Air Canada. The generation of worklines requires the solution of a set partitioning problem with three side constraints but is complicated by the preferential bidding system. This gives senior staff priority for a variety of preferences that they can express. The algorithm uses a constrained shortest path subproblem for pricing and a custom branch and price method with cut generation at the nodes to obtain integer solutions. Results for up to 100 pilots and 600 pairings are reported.

Gamache, M., F. Soumis, G. Marquis, and J. Desrosiers. (1999). "A Column Generation Approach for Large Scale Aircrew Rostering Problems." *Operations Research* 47(2), 247–263.
Notes. This paper is a further development of (Gamache and Soumis, 1998). It describes the crew rostering problem for cabin personnel on medium haul Air France flights. This problem is solved using the usual set covering formulation with a constrained shortest-path pricing problem involving 6 resources (side constraints). Integer solutions are found through a partial branch and bound tree exploration. Results for problems with up to 380 crew and 1000 pairings are presented, in which normally less than 10,000 columns are generated.

Gans, N., G. Koole, and A. Mandelbaum. (2003). "Telephone Call Centers: Tutorial, Review, and Research Prospects." *Manufacturing & Service Operations Management* 5(2), 79–141.
Notes. This paper provides an excellent and detailed review of the operation of telephone call centres

and the application, and limitations, of Operations Research type modelling to the characterisation of system performance. The authors discuss how call centres work, capacity planning and forecasting, Erlang A, B and C approaches to modelling customer queues, time-varying and uncertain arrival rates, staff scheduling and rostering, hiring and training, skills based routing and networks, data analysis and the specification of operational parameters. The paper concludes with an outline of important problems that have not been addressed and a discussion of promising directions for future call-centre research.

Garnier, G. (1985). "Mercator and HASTUS-Macro Computerization and Changing Working Conditions for RATP Bus Drivers." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 137–144. North-Holland.

Notes. The paper discusses computer systems developed to allow planners to investigate the effects of both long term (one year) workforce regulation scenarios, and short term (days) working condition scenarios in a metropolitan bus service. The paper also discusses a further module for partitioning the problem and generating the data for draft workplace agreements.

Gartner, J. and S. Popkin. (1999). "Influence of Law on Shift Schedule Design: USA and Europe." Technical Report, Vienna University of Technology.

Notes. This paper analyses the constraints on rota design and designs a series of rotas to address this and other scheduling problems, from both an American and a European standpoint.

Gartner, J. and S. Wahl. (1998a). "Design Tools for Shift Schedules: Empowering Assistance for Skilled Designers and Groups." *International Journal Industrial Ergonomics* 21(3–4), 221–232.

Notes. A new approach and a system for computer-supported shift scheduling are presented. The purpose of designing this system is to handle fuzzy definitions of many scheduling requirements and to give schedulers more flexibility of using their experience and knowledge. However, this system does not generate schedules.

Gartner, J. and S. Wahl. (1998b). "The Significance of Rota Representation in the Design of Rotas." *SCAND Journal Work Environment HEA* 24(1997), 96–102.

Notes. The paper uses predefined shift patterns of 10–15 days to construct rosters. The shift patterns are used as an example to illustrate the importance of representation. The rosters are evaluated using a number of criteria including total days off, consecutive days off, consecutive night shifts, and so on. The focus is on evaluating the quality of rosters obtained using different basic shift sequences. A major result is that while certain representations simplify the development of some rosters, they make it very difficult or even impossible to develop others. As a result, it is important to use a number of schedule representations and to maintain information regarding the construction techniques.

Gartner, J., S. Wahl, and K. Horwein. (1998). "A Technique to Take Leave into Account in Shift-Rota Design." *SCAND Journal Work Environment HEA*, 24(Suppl. 3), 103–108.

Notes. The paper describes issues associated with planning rosters so that leave is dealt with in a better way. The roster is adapted in summer to allow for the larger part of the workforce to take their vacation in a common period. Furthermore, maintenance work is used as a buffer to allow better handling of leave.

Gartner, J., N. Musliu, and W. Slany. (2001). "Rota: A Research Project on Algorithms for Workforce Scheduling and Shift Design Optimization." *AI Communications* 14, 83–92.

Notes. This paper presents a framework for solving tour scheduling. This framework consists of four major steps: (1) choosing a set of lengths of work blocks; (2) choosing a particular sequence of work and days-off blocks among those that have optimal weekend characteristics; (3) enumerating possible shift sequences for the chosen work blocks subject to shift change constraints and bounds on sequence of shifts; and (4) assignment of shift sequences to work blocks while fulfilling the staffing requirements. The resulting software is called First Class Scheduler and it has been used in several countries in Europe.

Gartner, J., N. Musliu, and W. Slany. (2002). "First Class Scheduler: A System to Generate Rotating Workforce Schedules." Technical Report, Vienna University of Technology.

Notes. This paper presents numerical results for a scheduling system First Class Scheduler that is described in (Gartner et al., 2001). First Class Scheduler shows much better computational behavior for most previously published benchmarks compared to earlier developed algorithms. Another advantage of this system is the possibility to generate high-quality schedules through the interaction with the human decision-maker. Besides that the generated schedules fulfil all hard constraints, this system also incorporates preferences of the human decision maker regarding soft constraints, that are otherwise more difficult to assess and to model.

Gass, S. (1991). "Military Manpower Planning Models." *Computers and Operations Research* 18(1), 65–73.
Notes. A goal programming model is proposed for military manpower planning. The entire workforce is categorized by grade, skills, and other factors. Personnel can move between categories. The force structure can change through recruitment, promotions, retirement, and attrition. The purpose is to determine the number of personnel and their skills to best meet the future operational requirements of the force.

Gershkoff, I. (1989). "Optimizing Flight Crew Schedules." *Interfaces* 19(4), 29–43.
Notes. This paper provides a high level overview of the crew scheduling practices at American Airlines. It includes a description of the crew scheduling process, costs and workrules that have to be considered, the algorithmic approach used, some of the implementation issues and finally some empirical results on cost savings achieved.

Gierl, L. and B. Pollwein. (1993). "Knowledge-Based Scheduling of Duty Rosters for Physicians." *Medical Informatics* 18(4), 355–366.
Notes. An expert system approach is proposed for generating duty rosters. This approach can handle fairness in every aspect, that is very hard to be captured by mathematical programming methods.

Glen, J. (1975). "A Dynamic Programming Model for Work Scheduling in a Shipyard." *Operational Research Quarterly* 26(4), 787–799.
Notes. This paper discusses the determination of the number of person hours to be applied to each berth per period of a planning horizon for ship building. The sequential decision process to assign hours, within limits for the workforce size, is solved using path restricted dynamic programming. This model can then be used iteratively to explore the optimal workforce size.

Glover, F. and C. McMillan. (1986). "The General Employee Scheduling Problem: An Integration of MS and AI." *Computers and Operations Research* 13(5), 563–573.
Notes. This paper provides an overview of a tabu search approaches to the general employee scheduling problem. The general employee scheduling problem improves the realism of the standard IP set covering formulation by attributing to employees skills and classifications, thus making employee non-interchangeable. Some comment is made on escaping local optima and identification of good local moves.

Glover, F., C. McMillan, and R. Grover. (1985). "A Heuristic Programming Approach to the Employee Scheduling Problem and Some Thoughts on 'Managerial Robots'." *Journal of Operations Management* 4, 113–128.
Notes. The paper describes a range of factors that need to be considered when attempting to develop staff rosters, and how these methods might be implemented in a suitable DSS framework. A simple example of a roster is developed using a problem specific heuristic. The paper reflects its age.

Goodale, J.C. and G.M. Thompson. (2004). "A Comparison of Heuristics for Assigning Individual Employees to Labor Tour Schedules." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 47–63.
Notes. In most approaches for tour scheduling, all workers are assumed to have the same productivity levels and the identical cost. This paper evaluates potential benefits by removing these assumptions. The problem is formulated as a generalized set covering model, but is solved using a simulated annealing method. One of four individual worker assignment heuristics is employed to assign tours to workers. Numerical experiments demonstrate that a simple managerial heuristic of assigning individuals in descending order of their productivity to cost ratio is both fast and effective over a broad range of service environmental scenarios.

Gopalakrishnan, M., S. Gopalakrishnan, and D. Miller. (1993). "A Decision Support System for Scheduling Personnel in a Newspaper Publishing Environment." *Interfaces* 23(4), 104–115.

Notes. This article discusses scheduling employees, especially part time employees, at a newspaper production facility. Predictions are made about the number of employees needed for the given weekly shifts. Then a constructive heuristic assigns employees to shifts, attempting to adhere to employee preferences. This leads to much greater employee utilisation, as manual scheduling tended to result in overstaffing.

Goumopoulos, C., E. Housos, and O. Liljenzin. (1997). "Parallel Crew Scheduling on Workstation Networks Using PVM." In *Lecture Notes in Computer Sciences*, Vol. 1332, pp. 470–477.

Notes. A parallel computational approach is proposed for solving large scale crew scheduling problems. Because the crew pairing generation is decomposable and takes most CPU time for the solution of the crew scheduling problem in the CARMEN system, a significant improvement of the performance is realized by parallelizing the dominant part of the CARMEN system.

Graves, G., R. McBride, I. Gershkoff, D. Anderson, and D. Mahidhara. (1993). "Flight Crew Scheduling." *Management Science* 39(6), 736–745.

Notes. The authors describe a new crew scheduling system for United Airlines. The system uses a partial enumeration method to generating pairings and an LP based algorithm with cutting planes and block echelon enumeration for finding integer solutions. Various modes of operation are described depending on whether a new solution is to be found from scratch or an existing solution is to be improved or adjusted after changes to the flight schedule.

Grayson, R. and S. Yuan. (1997). "PC-Based Worker-Scheduling System for Underground Mines." *Mining Engineering* 49(2), 83–87.

Notes. This report discusses the "mine-management support system." Which, in part, performs job (task) allocation to employees. Limited detail is provided regarding the algorithm which is described as a "goal programming problem solved using the branch-and-bound method."

Green, L., P. Kolesar, and J. Soares. (2001). "Improving the SIPP Approach for Staffing Service Systems that Have Cyclic Demands." *Operations Research* 49(4), 549–565.

Notes. Numerical experimental results are presented to show that the commonly used "stationary independent period by period" (SIPP) approach to setting staffing requirements is inaccurate for parameter values corresponding to many real situations. After exploring several alternatives, two simple modifications of SIPP are proposed and demonstrated to produce reliable staffing requirements for a broad range of practical situations.

Green, L., P. Kolesar, and J. Soares. (2002). "An Improved Heuristic for Staffing Telephone Call Centers with Limited Operating Hours." Technical Report, University of Columbia.

Notes. The stationary independent period by period (SIPP) is a commonly used approach for operator demand modelling in call centers. This research evaluates and improves upon this heuristic for those telephone call centers with limited hours of operation during the workday. The authors show that the SIPP often suggests staffing that is substantially too low to achieve the targeted customer service levels during critical periods. Specific domains for which the SIPP tends to suggest inadequate staffing are identified. Based on an analysis of the factors that influence the magnitude of the lag in infinite server systems that start empty and idle, the authors propose and test two simple "lagged" SIPP modifications that, in most situations, consistently achieve the service target with only modest increases in staffing.

Grossman, T., D. Samuelson, S. Oh, and T. Rohleder. (1999). "Call Centers." Technical Report, Haskayne School of Business, University of Calgary.

Notes. This report provides a review of some of the call centre scheduling literature. References to staffing level prediction and staff scheduling are given without delving into technical detail.

Guerinik, N. and M. van Caneghem. (1995). "Solving Crew Scheduling Problems by Constraint Programming." In *Proceedings of the 1st International Conference on Principles and Practice of Constraint Programming*, Lecture Notes in Computer Science, Vol. XIII, pp. 481–498. Springer-Verlag.

Notes. This paper discusses the use of linear programming and constraint programming for scheduling bus drivers. Constraint programming is used to ensure that schedules conform to the industrial constraints. A linear programming relation of the set partitioning problem is used to direct the enumeration of variables.

Gunes, E. (1999). "Workforce Scheduling." Technical Report, Department of Industrial Engineering, Bilkent University.

Notes. This paper provides a review of 25 papers related to the workforce scheduling problem, that is work force planning through to tour scheduling. Papers are grouped by which aspects of the problem they discuss and solution technique.

Haase, K. (1999). "Advanced Column Generation Techniques with Applications to Marketing, Retail and Logistics Management." Ph.D. Thesis, Habilitation Thesis, University of Kiel.

Notes. This thesis presents three applications in workforce management: Sale force deployment, retail business staff scheduling, and vehicle and crew scheduling. All three problems are formulated as integer programs which are solved using advanced column generation techniques in conjunction with some heuristic algorithms.

Haase, K. and C. Friberg. (1999). "An Exact Algorithm for the Vehicle and Crew Scheduling Problem." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 63–80. Springer.

Notes. This paper presents a mathematical model of the integrated vehicle and crew scheduling problem for single depots with resource constraints on the scheduling graph. The model is general enough to be extended to multiple depots and can incorporate additional constraints. The model is solved using a column generation approach for a set partitioning formulation. The column generation is used for developing lower bounds in a branch and bound algorithm.

Haase, K., G. Desaulniers, and J. Desrosriers. (2001). "Simultaneous Vehicle and Crew Scheduling in Urban Mass Transit Systems." *Transportation Science* 35(3), 286–303.

Notes. An exact approach is presented for solving the integrated vehicle and crew scheduling problem in urban mass transit systems with a single depot. The problem is formulated as a set partitioning model for the driver scheduling with side constraints for the bus itineraries. It is solved using a branch and bound method in conjunction with column generation and cutting plane methods. Given the driver schedule, the solution of a network flow problem provides the bus itineraries. Computational results showed that the proposed method outperformed other existing methods.

Hagberg, B. (1985). "An Assignment Approach to the Rostering Problem." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*. North-Holland.

Notes. The author presents an untried idea for an algorithm to roster taxi cab drivers in Sweden. The algorithm repeatedly solves matching problems to iteratively improve the assignment of duties (shifts) and rest days to groups of drivers.

Halatsis, C., P. Stamatopoulos, I. Karali, T. Bitsikas, G. Fessakis, A. Schizas, S. Sfakianakis and C. Fouskakis. (1996). "Crew Scheduling Based on Constraint Programming: The PARACHUTE Experience." In *Proceedings of the 3rd Hellenic–European Conference on Mathematics and Informatics HERMIS'96*, pp. 424–431.

Notes. This paper provides a description of the crew rostering problem for rostering airline crews. The subdivision of the problem is discussed and limited discussion of parallelism in the solution technique is made. Testing and performance of the system is not discussed.

Hamer, N. and L. Seguin. (1992). "The HASTUS System: New Algorithms and Modules for the 90s." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 17–29. Springer.

Notes. This paper is a non-technical exposition to the features of HASTUS, a widely-used and widely-deployed computerised system for developing crew management systems.

Hancock, W. and T. Chan. (1988). "Productivity and Staffing of Hospital Units with Uncertainty in the Demand for Service." *IIE Transactions* 20(4), 346–353.

Notes. The authors propose six different policies of how to select staffing requirements to meet dynamic daily workloads. Strategies for making policies include overtime, work delay, workforce capabilities and dynamic staffing levels. Efficiency of policies are evaluated using workers' productivity and the total cost.

Hancock, W., P. Flynn, S. DeRosa, P. Walter, and C. Conway. (1984). "A Cost and Staffing Comparison of an RN Staff and Team Nursing." *Nursing Administration Quarterly*, pp. 45–61.

Notes. This paper compares the costs and other impacts under two different staffing scenarios: an all-RN staff and team nursing. Simulation results show that the team nursing approach is more cost effective than the all-RN staff approach, but the former requires more staff than the latter.

Hanssmann, F. and S. Hess. (1960). "A Linear-Programming Approach to Production and Employment Scheduling." *Management Technology* 1, 46–52.

Notes. In a production environment, monthly workforce levels are determined using a linear programming model in order to satisfy customer demands.

Hao, G., K.K. Lai, and M. Tan. (2004). "A Neural Network Application in Personnel Scheduling." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 65–90.

Notes. A neural network model is developed for solving a cyclic rostering problem for an airport ground staff. The problem is formulated as an integer linear program. A procedure is designed to convert this ILP into a neural network model. Numerical comparisons are made against three other metaheuristics: simulated annealing, tabu search and genetic algorithms. It is worth to mention that this work is one of a few neural network models for solving rostering problems.

Hare, D. (2001). "Staff Scheduling with ILOG Solver." Technical Report, Okanagan University College.

Notes. This paper discusses a standard CLP formulation of the nurse scheduling problem with cyclic rosters. A number of additional constraints are described and some alternate search strategies are discussed. There is limited discussion of the performance of the system.

Harris, G. and P. Bohle. (1998). "A Benchmark for Automated Roster Generation Algorithms." *International Journal of Industrial Ergonomics* 21, 243–247.

Notes. The authors set out to provide benchmark problems for rostering. Unfortunately the three tour scheduling problems presented are not useful as they are either completely unrealistic or trivial.

Hartley, T. (1981). "A Glossary of Terms in Bus and Crew Scheduling." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 353–359. Amsterdam: North-Holland.

Notes. This paper provides a comprehensive and useful glossary of terms used in bus and crew scheduling. A common language is always useful in studying the area, particularly when terms have different meanings in different countries.

Henderson, W. and W. Berry. (1976). "Heuristic Methods for Telephone Operator Shift Scheduling: An Experimental Analysis." *Management Science* 22(12), 1372–1380.

Notes. The paper describes a method in which around 40 possible shift types, determined by start time, duration and position of breaks, are used to provide cover for operators based on 15 minute demand intervals. An LP solution is used as the starting point for heuristics to develop the final rosters.

Henderson, W. and W. Berry. (1977). "Determining Optimal Shift Schedules for Telephone Traffic Exchange Operators." *Decision Sciences* 8, 239–255.

Notes. This paper describes a branch and bound algorithm for splitting the demand for staff on a given day into shifts. The branch and bound proceeds by calculating a lower bound on the number of shifts using the LP relaxation. This bound is used to turn the optimisation problem into a series of satisfaction problems by branching on the objective value. Thus the first feasible solution found is an optimal solution. Branching and fathoming rules are described that help detect infeasibility.

Henderson, S. and A. Mason. (1998). "Rostering by Iterating Integer Programming and Simulation." In D. Medeiros and E. Watson (eds.), *Proceedings of the 1998 Winter Simulation Conference*, pp. 677–683.

Notes. This paper describes the idea of using simulation in order to evaluate the quality of service and to feed back the results of the simulation into the IP rostering formulation as cuts (sub-gradients of the non-linear quality of service function). The main problem is that this requires obtaining the gradient of the service levels as a function of the staffing levels at the point defined by the current roster. The authors outline how this could be done using finite differencing but have not computationally tested the idea. The concept of combining simulation and integer programming base rostering methods are further developed in (Atlason et al., 2002).

Henderson, S. and A. Mason. (1999). "Estimating Ambulance Requirements in Auckland New Zealand." In P. Farrington, H. Nembhard, J. Evans, and D. Sturrock (eds.), *Proceedings of the 1999 Winter Simulation Conference*, pp. 1670–1674.

Notes. The paper describes the application of the BartSim simulation package to the Auckland Ambulance service. Issues of travel time, locality, dispatch rule complexity are discussed. The statistics gathered are then used to determine Ambulance (staffing) levels at ambulance stations. Both simulated and historical results are analyzed through graphical methods.

Henderson, S., A. Mason, I. Ziedins, R. Thomson, D. Burgess, and T. Seabrook. (1998). "Heuristics in Rostering for Call Centres." In *Proceedings of the 33rd Conference of the Operational Research Society of New Zealand*.

Notes. This paper discusses the application of steady state queueing models to the prediction of staffing levels required to achieve the desired Grade Of Service. This approach is stated to be an improvement over other models as it better models time dependent interactions between neighbouring time intervals. See also (Henderson et al., 1999).

Henderson, S., A. Mason, I. Ziedins, and R. Thomson. (1999). "A Heuristic for Determining Efficient Staffing Requirements for Call Centres." Technical Report, Department of Engineering Science, University of Auckland.

Notes. This paper provides a more thorough treatment of the author's earlier work (Henderson et al., 1998). The material discussed involves using queueing theory and dynamic programming to determine staffing levels required to achieve the specified Grade Of Service at call centres.

Hershey, J., W. Abernathy, and N. Baloff. (1974). "Comparison of Nurse Allocation Policies: A Monte Carlo Model." *Decision Sciences* 5, 58–72.

Notes. The paper describes the use of Monte Carlo models for evaluating the effectiveness of different fixed and float pool nurse staffing policies.

Hershey, J., W. Pierskalla, and S. Wandel. (1981). "Nurse Staffing Management." In D. Boldy (ed.), *Operations Research Applied to Health Services*, pp. 189–220. New York.

Notes. The paper discusses a wide range of factors associated with managing nurse staffing. The paper considers demand forecasting and workloads based on patient acuity. A model is formulated for nurse scheduling.

Hildyard, P. and H. Wallis. (1981). "Advances in Computer Assisted Runcutting in North America." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 183–192. Amsterdam: North-Holland.

Notes. This paper traces a history of the use of the RUCUS system for scheduling crew in transit operations. Apart from suggesting reasons for the success of the system, the authors also point to areas where it needs improvement and suggest future improvements.

Ho, R., E. Johnson, and T. Shaw. (1998). "Modeling Tools for Airline Crew Scheduling and Fleet Assignment Problems." Technical Report, Georgia Institution of Technology.

Notes. This technical report describes a software tool for solving crew scheduling and fleet assignment problems on a PC. The software is based on the Microsoft Access database product, which is used to implement the user interface, to store the problem data and to link to the CPLEX IP solver for generating solutions. The emphasis of the report is on describing the user interface, data structures and application integration rather than the solution methodology.

Hoffmann, R. (1979). "Expanding Pharmaceutical Services through Efficient Staff Scheduling." *Hospital Pharmacy* 14, 192–198.

Notes. Create a cyclic roster to cover workload adequately using existing employees and free up some employees for business expansions.

Hoffman, K. and M. Padberg. (1993). "Solving Airline Crew Scheduling Problems by Branch-and-Cut." *Management Science* 39(6), 657–682.

Notes. The authors give a detailed description of a branch and cut method for solving the set partitioning problem arising in crew scheduling. The four main elements of this method are (1) several preprocessing techniques to reduce problem size (2) A LP based heuristic for finding good upper bounds (3) generation of cuts, in particular lifted clique and odd-cycle inequalities (4) a branching strategy which is only described superficially in the paper. Numerical results for problems ranging up to 8600 columns with 800 rows and 1 million columns with 145 rows are presented.

Hoffstadt, J. (1981). "Computerized Vehicle and Driver Scheduling for the Hamburger Hochbahn Aktiengsellschaft." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 35–52. Amsterdam: North-Holland.

Notes. The paper describes a system implemented for the Hamburg public transport company, which undertakes timetabling, bus and bus driver scheduling. Mathematical models are introduced for all sub-problems. The crew duty scheduling problem is solved by first run cutting and then solving an assignment/matching problem for morning and evening duties. The paper also attempts duty rostering over a longer planning horizon.

Hoffstadt, J. (1988). "Computer-Aided Scheduling in Urban Mass Transit Companies: Past, Present and Future." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 1–7. Springer.

Notes. This paper provides an early overview of the state-of-play in computer-aided scheduling in urban mass transit operations. It also lists opportunities for computer-aided crew scheduling.

Holloran, T. and J. Byrn. (1986). "United Airlines Station Manpower Planning System." *Interfaces* 16(1), 39–50.

Notes. This paper gives an overview of the system used to roster reservations staff for United Airlines. This task is broken into a number of separate steps including forecasting, shift start time optimisation, tour scheduling and roster assignment. Each optimisation module is based on a mixed integer linear program. The paper includes a nice discussion of the benefits achieved by the system.

Hong, J., M. Chandra, and T. Cavalier. (1989). "The Assignment of Minimum Crews Among Bases in an Airlift Operation." *European Journal of Operational Research* 38, 208–212.

Notes. The problem considered in this paper is one of assigning a minimal number of air crew to a set of military basis such that the total mission time (or equivalently the amount of plane idle time) is within a given upper bound. The authors use queueing theory, with the assumption that there are a large number of planes, to arrive at a non-linear expression for the mean idle time at a base as function for the number of crew assigned to the base. This non-linear program (with just a single constraint on total idle time) is then heuristically optimised by iteratively assigning crews to a base until feasibility is achieved. Results for up to 15 basis are presented.

Hosios, A. and J. Rousseau. (1980). "A Heuristic Scheduling Algorithms." *Journal of the Operational Research Society* 31, 749–753.

Notes. The paper describes a local neighbourhood search method for solving a very loosely constrained generalised staff scheduling problem.

Housos, E. (1997). "Automatic Optimization of Subproblems in Scheduling Airline Crews." *Interfaces* 27(5), 68–77.

Notes. Much of the literature in airline crew scheduling focuses on generating a set of pairings (trips) for a typical day and adjusting the solution for variations in schedule form day to day and week to week. The authors claim to have achieved significantly better results by (heuristically) solving the weekly and even the fully dated problem. In order to make these much larger problems manageable the rely on two tricks: (1) heuristic fixing of flights that must be flown by the same crew based on 'expert rules' mostly based on following the plane rotation (2) splitting the problem geographically and in the time domain to create sub-problems which are optimised while keeping the remainder of the solution fixed. Insufficient details are given to permit any attempt to replicate this work though good results with Lufthansa data reported.

Howard, S. and P. Moser. (1985). "IMPACS: A Hybrid Interactive Approach to Computerized Crew Scheduling." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 211–221. North-Holland.

Notes. This paper describes the heuristic and exact algorithms contained in IMPACS, a computerized system for bus driver run generation and optimization. After developing driver runs through a constructive heuristic, a run-swapping algorithm or a matching algorithm is used to improve the solution quality.

Howick, R. and M. Pidd. (1990). "Sales Force Deployment Models." *European Journal of Operational Research* 48(3), 295–310.

Notes. This paper provides a review of papers related to workforce planning for (field) sales personnel. The main aspects of the review include: sales force size, time-effort allocation and territory alignment. Within these aspects the review is quite thorough, with more than 60 papers reviewed.

Hsu, W. (1984). "Approximation Algorithms for the Assembly Line Crew Scheduling Problem." *Mathematics of Operations Research* 9(3), 376–383.

Notes. This paper discusses approximation algorithms for a parallel minimum make-span problem. As such it pertains more to machine scheduling than people scheduling.

Huarng, F. (1999). "A Primary Shift Rotation Nurse Scheduling Using Zero–One Linear Goal Programming." *Computers in Nursing* 17(3), 135–144.

Notes. The paper describes a goal programming approach to constructing nurse rosters with a primary shift rotation among day, evening and night shifts. Back rotation (evening followed by day, night followed by evening patterns) is forbidden. Days off and preferences are allowed for.

Huarng, F. (2001). "A Hidden Two-Shift Rotation Nurse Scheduling Using Integer Goal Programming." *Pan-Pacific Management Review*.

Notes. The paper describes a goal programming formulation of a nurse rostering problem. A range of workplace rules and nurse preferences are allowed for. The rosters involve shift rotations in which nurses move from working, say, a day/evening shift pattern to an evening/night pattern after some period of time. An example IP solution is given for a problem involving 14 nurses rostered over a 15 day period.

Hung, R. (1991a). "A Cyclical Schedule of 10-Hour, Four-Day Workweeks." *Nursing Management* 22(9), 30–33.

Notes. The paper describes a simple paper based method for constructing rosters of 10 hour shifts. Downward substitution of nurse grades is allowed for.

Hung, R. (1991b). "Single-Shift Workforce Scheduling Under a Compressed Workweek." *Omega* 19(5), 494–497.

Notes. The aim of this paper is to generate optimal cyclic roster with minimum workforce size for two days-off scheduling problems. The methods used are simple constructive heuristics.

Hung, R. (1992). "Improving Productivity and Quality through Workforce Scheduling." *Industrial Management* 34(6), 4–6.

Notes. This paper briefly discuss the following workforce scheduling ideas: rearranged workweek, permanent shift, successive phase delay, shift overlap, and self-scheduling.

Hung, R. (1993). "A 3-Day Workweek Multiple-Shift Scheduling Model." *Journal of the Operational Research Society* 44(2), 141–146.

Notes. The author present a constructive algorithm for finding optimal solution for a tour scheduling problem with given shifts and shift demands. It seeks to minimize the workforce size so that demands are met and workrules relating to off-days, off-weekends, and work stretches are satisfied.

Hung, R. (1994a). "Managing Compressed Workweeks: A Comparison of 4-Day and 3–4 Workweeks." *International Journal of Technology Management* 9(2), 261–266.

Notes. Compare the 4-day workweek and the 3–4 workweek and verify that the 3–4 workweek is a viable alternative compressed workweek.

Hung, R. (1994b). "A Multiple-Shift Workforce Scheduling Model under the 4-Day Workweek with Weekday and Weekend Labor Demands." *Journal of the Operational Research Society* 45(9), 1088–1092.

Notes. This is similar to the work presented in (Hung, 1993) where exactly three working days is allowed for each worker each week.

Hung, R. (1994c). "Multiple-Shift Workforce Scheduling under the 3–4 Workweek with Different Weekday and Weekend Labor Requirements." *Management Science* 40(2), 280–284.

Notes. This work is an extension of (Hung, 1993) where exactly three workings days is allowed for each worker each week.

Hung, R. (1994d). "Single-Shift off-Day Scheduling of a Hierarchical Workforce with Variable Demands." *European Journal of Operational Research* 78(1), 49–57.

Notes. Necessary and sufficient conditions are derived for a hierarchical workforce to be feasible to a days-off scheduling problem. A simple algorithm is provided to generate a feasible solution that is an optimal solution most times. A simple branch and bound based method is used to guarantee an optimal solution.

Hung, R. (1995a). "Compressed Work Schedules in a Police Force: A Survey of Applications." *Optimum* 26(2), 32–36.

Notes. The paper discusses various factors relevant to determining good rosters for police officers.

Hung, R. (1995b). "Hospital Nurse Scheduling." *Journal of Nursing Administration* 25(7/8), 21–23.

Notes. The paper lists 128 other papers on nurse rostering.

Hung, R. (1997a). "An Annotated Bibliography of Compressed Workweeks." *International Journal of Manpower* 17(6–7), 43–54.

Notes. This paper presents an annotated bibliography on compressed workweek patterns. It collects 162 articles.

Hung, R. (1997b). "Scheduling for Continuous Operations: The Baylor Plan." *Journal Materials and Production Technology* 12(1), 37–42.

Notes. This paper espouses the benefits of a roster structure referred to as the Baylor plan. In this approach each weekday is broken into three 8 hour shifts and each weekend day is broken into two 12 hour shifts. The workforce is then divided (by employee preference) into weekday and weekend employees. This is claimed to improve morale and reduce absenteeism.

Hung, R. (1997c). "Shiftwork Scheduling Algorithms with Phase-Delay Feature." *International Journal of Production Research* 35(7), 1961–1968.

Notes. Simple heuristic algorithms are described for two tour scheduling problems with given shifts and shift demands. The algorithms find optimal workforce sizes and optimal schedules to meet demands and to satisfy rules on off days and shift transitions. See also (Hung, 1994c).

Hung, R. (1999a). "A Multiple-Shift Workforce Scheduling Model under Annualized Hours." *Naval Research Logistics* 46, 726–736.

Notes. This work is an extension of (Hung, 1999b). This work allows multiple shifts on each operating day.

Hung, R. (1999b). "Scheduling a Workforce under Annualized Hours." *International Journal of Production Research* 37(11), 2419–2427.

Notes. This paper presents an algorithm for the minimum workforce size for a days-off scheduling in which the number of working days in a week may vary, and demand may change from week to week.

Hung, R. (2002). "Scheduling a Hierarchical Workforce for 7-Days-a-Week Operations under 3-Day, 4-Day, and 5-Day Workweeks." Working Paper.

Notes. The paper describes the problem of assigning workers to shifts where the numbers of workers of different categories needed for each shift are specified and higher category workers can substitute for lower category workers. Workers can work 3, 4 or 5 day weeks. A constructive heuristic for determining a least cost labour mix is described and results are given for an example involving 14 workers in three categories over a five week planning horizon.

Hung, R. and H. Emmons. (1993). "Multiple-Shift Workforce Scheduling under the 3–4 Compressed Workweek with a Hierarchical Workforce." *IIE Transactions* 25(5), 82–89.

Notes. This study is an extension of (Hung, 1993). Here workers have exactly three working days in one week and exactly four working days in the next week. However, shift demands on each day remain unchanged during the week. A simple algorithm is designed to find optimal cyclic roster that satisfies given the scheduling rules.

Ingolfsson, A. and E. Cabral. (2002). "Combining Integer Programming and the Randomization Method to Schedule Employees." Technical Report, University of Alberta.

Notes. This paper describes a method to find low cost employees shift schedules that guarantee that the fraction of customers who wait less than a specified time (the service level) is always at or above a specified minimum. An integrated model is proposed to combine demand modelling and shift scheduling. The method iterates between a schedule evaluator and a schedule generator. An iteration begins with the schedule evaluator using the randomization method to calculate transient service levels and identify infeasible intervals when the service level is lower than desired. The schedule generator solves a series of integer programs to produce schedules. One constraint is added to the integer program for every infeasible interval, in an attempt to eliminate infeasibility without eliminating the optimal solution. Numerical results are carried out for 16 test problems to identify factors that make this approach more likely to outperform previous approaches.

Ingolfsson, A., E. Akmetshina, S. Budge, Y. Li, and X. Wu. (2002a). "A Survey and Experimental Comparison of Service Level Approximation Methods for non-Stationary M/M/s Queueing Systems." Technical Report, University of Alberta.

Notes. This paper compares the performance of six methods in computing or approximating service levels for non-stationary M/M/s queueing systems: an exact method, a randomization method, a closure approximation, a direct infinite server approximation, a modified offered load infinite server approximation, and an effective arrival rate approximation. All six methods are used to solve the same set of 128 test problems. Numerical experiments may offer a guide for the user to select the best method for demand modelling.

Ingolfsson, A., M. Haque, and A. Umnikov. (2002b). "Accounting for Time-Varying Queueing Effects in Workforce Scheduling." *European Journal of Operational Research* 139, 585–597.

Notes. The commonly used approach for solving tour scheduling problems is to first estimate staffing requirements and then to generate tours to meet staffing requirements and objectives and constraints. This paper presents an integrated model for solving the whole problem in one go. The main idea is iteratively to vary staffing requirements and then evaluate service levels and scheduling costs. The queueing model is used for calculating service levels and a genetic algorithm is proposed for generating tours. Comparison with the commonly used approach indicates that the new method can estimate service levels more accurately and that it can sometimes generate schedules that have both lower cost and higher service level. One disadvantage of this new method is its computational burden.

Iskander, W. and J. Chou. (1985). "Manpower Scheduling for Unbalanced Production Lines." In *1985 Annual International Industrial Engineering Conference*, pp. 546–552.

Notes. This paper discusses the determination of the number of workers to attend each station in a production line. The workers must possess appropriate skills to attend certain stations. The workers need not be fully utilised and output rates are non-deterministic. An approximation algorithm is presented which selects workers for the stations. Validation of the algorithm is done via simulation.

Isken, M. (1995). "Personnel Scheduling Models for Hospital Ancillary Units." Ph.D. Thesis, Industrial and Operations Engineering, The University of Michigan.

Notes. The thesis looks at scheduling hospital ancillary staff in different hospital units. The work covers a very wide range of the factors that need to be considered when rostering staff in the (interactive) units of a hospital. A number of different MIP and stochastic programming models for scheduling staff and capacity planning are given together with various linear relaxation and branch and bound methods for solving the models. Results are given for a number of well-structured test examples.

Isken, M. (2004). "An Implicit Tour Scheduling Model with Applications in Healthcare." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 91–109.

Notes. An implicit and compact integer linear programming formulation is proposed for the tour scheduling problem. The model includes both controllable, overlapping start time bands and full and part-time tour types. However, rest and meal breaks are not considered in this model. It has been in use as a tactical scheduling analysis tool for more than a decade in a hospital. This model complements the

one developed in (Brusco and Jacobs, 2000).
Isken, M. and W. Hancock. (1991). "A Heuristic Approach to Nurse Scheduling in Hospital Units with non-Stationary, Urgent Demand, and a Fixed Staff Size." *Journal of the Society for Health Systems* 2(2), pp. 24–41.
Notes. The paper describes a model for rostering nurses in units in which demand is very dependent on the time of day and of an urgent nature. SA is used to solve a set covering model arising from the highly variable demand in a post anaesthesia care unit (operating theatre recovery room).
Isken, M. and W. Hancock. (1998). "Tactical Staff Scheduling Analysis for Hospital Ancillary Units." *Journal of the Society for Health Systems* 5, 11–23.
Notes. An implicit tour scheduling mixed-integer programming model is presented which has been used to address various tactical scheduling problems in hospital ancillary units. A software based decision support framework for using the model is also described.
Jachnik, J. (1981). "Attendance and Rostering System." In *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 337–343. Amsterdam: North-Holland.
Notes. The paper describes the development of a computerised cyclic rostering system for a bus company in Rome. The algorithm looks at all the duties that need to be performed over a weeks' duration and takes into account planned leave to arrive at least-cost rosters through the application of a constructive heuristic. The solution is then improved through swaps.
Jackson, W. and W. Havens. (1997). "Staff Scheduling: A Simple Approach that Worked." Technical Report, Simon Fraser University.
Notes. This report discusses scheduling security officers. In this problem there is one hard constraint (no double booking) and two soft constraints. The objective reduces relatively easily into a single cost. The authors did not have success with complicated techniques such as modelling as resource allocation problem, constraint programming, or meta-heuristics. The authors found the best tradeoff of solution quality and execution time came from greedy, randomised local search.
Jacobs, L. and S. Bechtold. (1993). "Labor Utilization Effects of Labor Scheduling Flexibility Alternatives in a Tour Scheduling Environment." *Decision Sciences* 24(1), 148–166.
Notes. A factorial experimental design and an implicit modelling methodology are employed for investigating how a number of factors could impact on labor utilization within a tour scheduling environment. The factors investigated include break placement, starting-time selections, shift lengths, off days patterns, shapes and key statistical measures of demand curves. Several conclusions are arrived from numerical experiments. For example, flexibility on break placement and shift length choices result in substantial improvement in labor utilization.
Jacobs, L. and M. Brusco. (1996). "Overlapping Start-Time Bands in Implicit Tour Scheduling." *Management Science* 42(9), 1247–1259.
Notes. A compact implicit integer programming model is presented for a tour scheduling problem that has overlapping starting-time bands. It is used for scheduling toll collectors. The results indicate that starting-time bands can provide an important improvement in scheduling efficiency when compared with to the exclusive use of schedules that require workers to begin work on the same hour of the day on each day of their tour.
Jarrah, A. and J. Diamond. (1997). "The Problem of Generating Crew Bidlines." *Interfaces* 27(4), 49–64.
Notes. In this paper the authors provide an overview of the practical considerations in providing a crew rostering system and their software system that addresses these needs. The system described allows for a degree of manual input so that the human schedulers can include secondary quality criteria rather than purely minimising costs. However in order to make the rostering task manageable bid lines are generated by heuristically solving a set partitioning IP, with limited enumeration of columns. Numerical results are presented for monthly rostering problems with up to 1700 trips for both domestic and international operations.
Jarrah, A., J. Bard, and A. de Silva. (1994). "Solving Large-Scale Tour Scheduling Problems." *Management Science* 40(9), 1124–1144.

Notes. This paper presents a new methodology for solutions of a tour scheduling problem that arises in general mail facilities. Tour scheduling is modelled as an integer program with implicit modelling techniques and is solved using a decomposition approach. However, the solutions obtained from the model do not give final tours. It is necessary to do postprocessing for allocating breaks in shifts and for constructing tours from shifts.

Jaumard, B., F. Semet, and T. Vovor. (1998). "A Generalized Linear Programming Model for Nurse Scheduling." *European Journal of Operational Research* 107(1), 1–18.

Notes. A nurse scheduling problem is modelled as a column generation integer program. In the master problem, each column is a feasible schedule of the six-week for a nurse. The subproblem of generating feasible schedules is resource constrained shortest paths. Resources considered include workload, off weekends, rotations, consecutive assignments, shift ratios, and holidays among others. The column generation model is solved using a specially designed branch and price approach.

Jelinek, R. and J. Kavois. (1992). "Nurse Staffing and Scheduling: Past Solutions and Future Directions." *Journal of the Society for Health Systems* 3, 75–82.

Notes. The paper discusses historical approaches to workload measurement, nurse and personnel scheduling. It also considers possible future nurse scheduling systems.

Jelinek, R., T. Zinn, and J. Brya. (1973). "Tell the Computer how Sick the Patients Are and It Will Tell How Many Nurses They Need." *The Modern Hospital*, pp. 81–88.

Notes. This paper describes a computer system that has four components: Prediction of workload and staff requirements; Planning personnel scheduling; Operational personnel scheduling; and Performance analysis.

Jennings, O., A. Mandelbaum, W. Massey, and W. Whitt. (1996). "Server Staffing to Meet Time-Varying Demand." *Management Science* 42, 1383–1394.

Notes. The paper evaluates the number of servers needed to provide satisfactory service, defined as a target average waiting time, for fluctuating arrival rates. The system uses a G/G/s queueing model with time varying arrivals.

Johns, S. (1995). "Heuristics to Schedule Service Engineers within Time Windows." *Journal of the Operational Research Society* 46(3), 339–346.

Notes. The paper describes a set of heuristics for assigning service engineers to emergency jobs arising at different locations. The problem is set up as a variant of TSP with time windows.

Johnson, E., G. Nemhauser, and M. Savelsbergh. (1997). "Progress in Linear Programming-Based Algorithms for Integer Programming: An Exposition." *INFORMS Journal on Computing* 12(1), 2–23.

Notes. The authors provide a good overview of techniques that can be used to solve large combinatorial optimisation problems such as those that arise in rostering and crew scheduling using Integer Programming base approaches. The article covers a range of topics including preprocessing, branch and price, branch and cut, row and column management, etc. The application of these techniques to crew scheduling and rostering is discussed briefly.

Jones, R. (1989). "Development of an Automated Airline Crew Bid Generation System." *Interface* 19(4), 44–51.

Notes. The author describes the implementation of a crew rostering system for American Airlines. The system uses a two phase method which first generates a set of feasible or nearly feasible monthly rosters from the given pairings and then improves these monthly rosters using a steepest descent local search. The article discusses in some detail the need to work closely with the users of the system (human crew schedulers) in order to achieve a successful implementation. Improvements in both ease of use and quality of solutions were reportedly achieved by the new crew rostering software.

Jorvang, C. (1992). "ARHUS Public Transport's Innovative Rostering Technique." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 31–45. Springer.

Notes. This paper describes a business process re-engineering study undertaken for Arhus Public Transport in Denmark, which led to the introduction of new computerised planning systems for bus and crew scheduling.

Junker, U., S. Karisch, N. Kohl, B. Vaaben, T. Fahle, and M. Sellmann. (1999). "A Framework for Constraint Programming Based Column Generation." In *Proceedings of the 5th International Conference on the Principles and Practice of Constraint Programming*, Lecture Notes on Computer Science Series, Vol. 1713, pp. 261–274. Springer.

Notes. This paper discusses a framework for combining column generation and constraint programming. In this framework the column generation subproblem is a general constraint satisfaction problem, rather than a constrained shortest path problem. This allows complex or non-linear constraints to be added to problems, such as airline crew rostering, while still solving large problem instances. Additionally, propagation algorithms for the path constraint are given to improve performance of the constrained shortest path problem.

Kakas, A. and A. Michael. (1998). "An Abductive-Based Scheduler for Air-Crew Assignment." Technical Report, Department of Computer Science, University of Cyprus.

Notes. This technical report discusses the application of Abductive Logic Programming to the crew rostering problem. This report is almost entirely superseded by its publication (Kakas and Michael, 1999).

Kakas, A. and A. Michael. (1999). "Air-Crew Scheduling through Abduction." In *Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, pp. 600–611.

Notes. This paper discusses the application of Abductive Logic Programming to the crew rostering problem. Abductive Logic Programming refines the declarative programming of Logic and Constraint Logic Programming with additional inference techniques. This allows high level modelling of the problem. Limited details are provided regarding the efficiency (relative to other techniques) and implementation.

Kataoka, K. and K. Komaya. (1998). "Crew Operation Scheduling Based on Simulated Evolution Technique." In *Proceedings of the International Conference on Computer-Aided Design, Manufacture and Operation in the Railway and other Advanced Mass Transit Systems*, pp. 277–285.

Notes. The paper discusses simulated evolution as a possible method for developing schedules for train drivers. The simulated evolution technique is similar to GA. It simulates competition to survive between races (partial solutions) to find a better solution from a set of partial solutions.

Keith, E. (1979). "Operator Scheduling." *AIIE Transactions* 11(1), 37–41.

Notes. This is one of early papers that introduce under and over coverage in the set partitioning model for shift scheduling.

Kendall, G., E. Soubeiga, and P. Cowling. (2002). "Hyperheuristics: A Robust Optimisation Method for Real-World Scheduling." Working Paper.

Notes. The concept of hyperheuristic is a high-level heuristic which adaptively chooses between several low-level knowledge-poor heuristics. In this paper, a hyperheuristic approach is used for solving 52 instances of an NP-hard nurse rostering problem occurring at a major UK hospital. Compared with tabu search and genetic algorithms, which have previously been used to solve the same problem, the hyperheuristic proves to be as robust as the former and more reliable than the latter in terms of solution feasibility.

Khan, Z. (1991). "Note on a Network Model for Nursing Staff Scheduling Problems." *Information and Decision Technologies* 17(1), 63–69.

Notes. The paper presents network and LP formulations of a problem to minimise the number of employees needed to staff emergency, neonatal intensive care, and orthopaedic wards.

Khan, M. and B. Callahan. (1993). "Planning Laboratory Staffing with a Queueing Model." *European Journal of Operational Research* 67, 321–331.

Notes. Queueing theory is employed to determine optimal staffing levels in a laboratory. Unlike many other applications, the objective considered in this paper is to maximize revenue rather than the cost of labour and service standards.

Khoong, C. and H. Lau. (1992). "ROMAN: An Integrated Approach to Manpower Planning and Scheduling." In O. Balei, R. Sharda, and S. Zenios (eds.), *Computer Science and Operations Research: New Developments in Their Interfaces*, pp. 383–396. New York: Pergamon.

Notes. This paper describes the design and implementation of a generic toolkit ROMAN for tour scheduling. ROMAN has the following components: specifications, shift scheduling, a special tour scheduling, and roster assignment. The specification module defines rules for shift types and days off types. The shift scheduling module determines shift types for each day. The tour scheduling module generates tours using shifts constructed in the shift scheduling module. The roster assignment module assigns tours to workers and also modifies tours if necessary.

Kilby, P. (2001). "The Augmented Regret Heuristic for Staff Scheduling." In *Proceedings of the 16th Australian Society of Operations Research*.

Notes. The paper discusses an extension of the regret method. The augmented regret heuristic looks ahead to include (discounted) future options. The method is applied to a problem of assigning 30 staff to 200 jobs over a period of 14 days subject to a series of hard and soft constraints defining workplace regulations.

Klabjan, D. and K. Schwan. (2001). "Airline Crew Pairing Generation in Parallel." In *Proceedings of the 10th SIAM Conference on Parallel Processing for Scientific Computing*.

Notes. This paper focuses on the task of generating crew pairings that arises as part of crew scheduling. In particular, all feasible constrained paths in the duty timeline network are to be enumerated. The authors present a parallel implementation that dynamically distributes the load of this enumeration task across multiple processors. Extensive numerical results are presented using up to 160 processors for three data sets with up to 200 flights showing the effectiveness of the load balancing scheme.

Klabjan, D., E. Johnson, and G. Nemhauser. (2001a). "Solving Large Airline Crew Scheduling Problems: Random Pairing Generation and Strong Branching." *Computational Optimization and Applications* 20(1), 73–91.

Notes. The authors describe a method for solving very large airline crew scheduling problems using an integer programming based heuristic approach for solving the set covering formulation. The method has a number of elements that are used to achieve a high quality solution: duties and a large number of pairings are generated heuristically using a randomised greedy heuristic. After a number of iterations of pairing generation and solving the LP relaxation to obtain reduced costs, the problem is simplified by heuristically eliminating columns. Integer solutions are then found by a variation of the follow on branching rule that branches on the amount of time between a flight and the next in a pairing (i.e., whether this is less than or greater than some duration). The authors also use a variation of the strong branching rule for selecting variables to branch on. Computational results are provided based on a cluster machine with 160 processors, though not all of these are used in all steps. Results for both daily and weekly crew scheduling problems are given with up to up to 450 and 650 flights.

Klabjan, D., A. Schaefer, E. Johnson, A. Kleywegt, and G. Nemhauser. (2001b). "Robust Airline Crew Scheduling." In *Proceedings of TRISTAN IV*, pp. 275–280.

Notes. Existing approaches to airline crew scheduling do not consider delays and disruptions. Delays and disruptions may increase the operating costs of crew pairing dramatically. Therefore it is important to create crew schedules that may not be optimal, but are very robust to efficiently and economically to cope with delays and disruptions. This paper discusses two approaches for this purpose. In the first approach, the planned pairing cost is replaced by the expected pairing cost in the crew scheduling models such as the set covering formulation. The second approach addresses robustness by considering swaps of crew members in operations.

Klabjan, D., E. Johnson, and G. Nemhauser. (2002a). "Airline Crew Scheduling with Regularity." *Transportation Science* 35(4), 359–374.

Notes. This paper addresses the desire to produce regular crew schedules in the weekly crew scheduling problem for airlines. In particular, most flights repeat on all or most days of the week. For these flights it is desirable to generate the same pairings on each day as far as possible. The authors present two formulations: an exact formulation based on pairing variables which gets too large to be amenable to direct solution. The second formulation is a multi-commodity approximation involving variables for the connections between flights. This is too weak by itself. However, by combining these two methods, the authors manage to get good solutions using an integer programming based heuristic. Results for data sets with up to 500 flights are presented as solved on cluster machines with 48 and 160 processors.

Klabjan, D., E. Johnson, G. Nemhauser, E. Gelman, and S. Ramaswamy. (2002b). "Airline Crew Scheduling with Time Windows and Plane Count Constraints." *Transportation Science* 36(3). Forthcoming.

Notes. In this paper the authors propose a way of reducing the operating cost of an airline by solving the crew scheduling problem before the aircraft routing. In order to do this additional plane count constraints need to be added to the formulation which ensure that a feasible routing can be found when the crew schedule forces turns (i.e., for short crew connections the plane turn must be the same as the pairings follow on flight). In addition, the authors allow the flight times to be varied within given time windows in order to obtain additional flexibility in the crew scheduling. The paper describes how the pairing generation, by depths first search of the duty time graph, can be extended to cope with time windows. Some numerical results for up to 450 flights are presented that show that significant savings can be achieved by these extensions to the standard crew scheduling method.

Koelling, C. and J. Bailey. (1984). "A Multiple Criteria Decision Aid for Personnel Scheduling." *IIE Transactions* 16(4), 299–307.

Notes. This paper presents a multiple criteria set partitioning model for a shift scheduling problem. It contains three modules: Staffing requirements generator; Schedule generator; Schedule evaluation model. Queueing theory is used in the staffing requirements generator. A set partitioning model with multiple objectives is used for finding optimal schedule under various scenarios. Simulation techniques are employed for evaluating schedules and therefore allow the scheduler to accept or refuse or revise schedules.

Kohl, N. and S. Karisch. (2004). "Airline Crew Rostering: Problem Types, Modeling, and Optimization." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 223–257.

Notes. A comprehensive description of real world airline crew rostering problems is given. Both simple and extended mathematical programming models are developed for dealing with various objectives and constraints. The solution methodology built in the Carmen Crew Rostering system is presented. The paper also reports practical experience of using the Carmen system in eight major airlines in Europe and North America and several railways.

Kolesar, P., K. Rider, T. Craybill, and W. Walker. (1975). "A Queueing-Linear Programming Approach to Scheduling Police Patrol Cars." *Operations Research* 23(6), 1045–1062.

Notes. This paper discusses the prediction of staffing levels, for police patrol cars, to meet service requirements and shift scheduling to meet the staffing levels thus determined. The prediction of staffing levels is achieved via queueing theory with some approximations to eliminate the non-stationary aspects of the problem. An integer programming formulation then allocates a number of cars to each possible start time and within that allocation lunch break times.

König, J. and C. Strauss. (2000). "Rostering-Integrated Services and Crew Efficiency." *Information Technology & Tourism* 3(1), 27–39.

Notes. In this paper the authors argue for the use of richer (airline) crew rostering models in which staff attributes are considered in order to increase the level of service offered by an airline without necessarily increasing costs. Two types of modification to the standard set partitioning model are proposed. The first is to add a demand for desirable skills and penalise undercoverage. For example, this can be done to encourage rosters where flights to and from Japan have a minimum number of Japanese speakers among the cabin crew. The model distinguishes between code share flights, small outward bases and home based assignments. The second type of change to the formulation is to combine the rostering problem for all ranks, with higher ranked crew able to fill more junior positions. The authors argue that this not only leads to higher quality service but also gives the airline greater flexibility and hence potentially cheaper rosters. However, it also makes the problems much larger so that solving instances for large fleets may be intractable. The heuristic method proposed for creating solutions involves implicit enumeration of possible rosters with constraint propagation and backtracking, though the authors stop at the first feasible solution found.

Koop, G. (1986). "Cyclic Scheduling of Offworkends." *Operations Research Letters* 4(6), 259–263.
Notes. Some necessary and sufficient conditions are provided for ensuring that off days fall into weekends must exceed the given level in a cyclic roster.

Koop, G. (1988). "Multiple Shift Workforce Lower Bounds." *Management Science* 34(10), 1221–1230.
Notes. This paper concerns with lower bounds of minimum workforce size for a special tour scheduling problem in which shifts are given and demand is given for each shift in all days in a week. It is required to construct cyclic rosters and rosters are constructed to meet demands and to satisfy the given shift transition rules for all feasible tours. A network flow model is used for finding minimum workforce size.

Kostreva, M. and P. Genevier. (1989). "Nurse Preference vs. Circadian Rhythms in Scheduling." *Nursing Management* 20, 50–62.
Notes. This study compares a mathematical programming approach with a circadian rhythm method. The results shows that the former provides satisfactory schedules and saves cost while the latter generates schedules with significantly lower circadian violations.

Kostreva, M. and K. Jennings. (1991). "Nurse Scheduling on a Microcomputer." *Computers and Operations Research* 18(8), 731–739.
Notes. The paper describes a system for nurse rostering that allows a high degree of interaction to cater for nurse preferences. Benders decomposition is used to solve an IP with two stages: generating a set of all feasible schedules and optimally assigning a feasible subset of these to the nurses.

Koutsopoulos, H. (1990). "Scheduling of Extraboard Operators in Transit Systems." *Transportation Science* 24(2), 87–104.
Notes. The paper discusses the problems of workforce planning for mass transit and bus companies. An integer programming (IP) formulation is presented to determine the number of permanent and casual staff required together with the distribution of rest days over a typical week. A second simple IP formulation is presented to determine the number of permanent and casual staff required on each 15 minute interval of the day together with the amount of overtime to be worked in order to cover expected absenteeism. The first IP is solved using a rounding method, the second as a dynamic program. Results are reported for the Massachusetts Bay Transport Authority involving around 20–30 staff.

Koutsopoulos, H. and N. Wilson. (1987). "Operator Workforce Planning in the Transit Industry." *Transportation Research* 21A, 127–138.
Notes. This paper presents strategic, tactical and operational views of mass transit operator workforce planning. These planning problems deal with the issue of strategic hiring and staffing levels, vacation scheduling to maintain workforce size throughout the year and work day and work time allocation throughout a week/day. Models are presented for each of these problems. A specific case study is presented, which involves the Massachusetts Bay Transportation Authority (MBTA).

Kragelund, L. and B. Mayoh. (1999). "Nurse Scheduling Generalised." Technical Report, Prolog Development Center A/S.
Notes. The paper attempts to develop methods for formal representations of classes of employee scheduling problems. The main focus is on proposing a formal basis for defining generalised staff scheduling problems. Two examples of nurse scheduling using SA as the solution method are given.

Krajewski, L., L. Ritzman, and P. Mckenzie. (1980). "Shift Scheduling in Banking Operations: A Case Application." *Interfaces* 10(2), 1–8.
Notes. This paper describes the problem of planning the shifts of bank employees to process cheques. Historical data on the arrival of cheques, from the last year, is used to forecast expected arrival rates. These forecasts are used to determine number, starting time, and duration of shifts so that the cheques can be processed before close-out time. A linear programming formulation is used to find the optimal arrangement of shifts. Rounding is used to convert to an integer solution that conforms to resource constraints.

Kress, M. and B. Golany. (1994). "Optimizing the Assignment of Aircrews to Aircraft in an Airlift Operation." *European Journal of Operational Research* 77, 475–485.
Notes. This paper discusses the problem of planning crews for a military airlift operation. This involves

determining the minimum number of crews, the basis for each of these crews and any flight delays that are necessary to allow a cyclic operation of a given set of flights. The authors provide a simple network flow formulation that allows optimal solutions to be found efficiently.

Krishnamoorthy, M. and A. Ernst. (1999). "Algorithms for the Shift Minimisation Personnel Task Scheduling Problem." Technical Report, CSIRO.
Notes. This paper describes the problem of assigning tasks with fixed start and end times to a given set of shifts that also have fixed start and end times. The aim is to assign all tasks while minimising the number of shifts used (see also (Kroon et al., 1997)). The paper introduces a local search heuristic and two exact methods based on integer programming and column generation. Numerical results are presented for up to 60 staff and 300 tasks.

Kroon, L. and M. Fischetti. (2001). "Crew Scheduling for Netherlands Railways Destination: Customer." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 181–202. Springer.
Notes. A set covering model is described for scheduling train drivers for the Dutch railway. The model is solved by a column generation method, Lagrangean relaxation and some constructive heuristics. Instances with over 2500 trips have been solved by this method, which is also able to cope with some complex scheduling and operational rules. It also successfully dealt with instances with more than 9000 trips.

Kroon, L., M. Salomon, and L. VanWassenhove. (1997). "Exact and Approximation Algorithms for the Tactical Fixed Interval Scheduling Problem." *Operations Research* 45(4), 624–638.
Notes. Consider the problem of performing a set of tasks with fixed start and end times, and with various skill requirements using a multi-skilled workforce. This paper describes a network flow based Lagrangean relaxation method and a greedy heuristic to obtain solutions that minimise the size (cost) of the workforce required. While this problem was derived from an aircraft maintenance application, only random data sets are tested in the paper.

Kumar, A. (1989). "Discrete Simulation Application – Scheduling Staff for the Emergency Room." In *Winter Simulation Conference Proceedings – WSC'89*, pp. 1112–1120.
Notes. A simulation model is developed to determine optimal staffing requirements in emergency rooms in hospitals. Several criteria are used to evaluate quality of staffing levels.

Kumar, S. and S. Arora. (1999). "Efficient Workforce Scheduling for a Serial Processing Environment: A Case Study at Minneapolis Star Tribune." *Omega* 27(1), 115–127.
Notes. This paper discusses the prediction of newspaper size (number of pages). The newspaper size has direct impact on the amount of machinery, and therefore staff, required. Attributes relating to the day of week and position in terms of holidays are used for prediction. Mixture modelling is then used to perform classification/prediction of the newspaper size. This prediction can then be used to determine staffing levels.

Kusumoto, S. (1996). "Nurse Scheduling System Using ILOG Solver." In *Proceedings of the 2nd ILOG Solver and Scheduler User Conference*. Paris: ILOG.
Notes. This paper describes a basic nurse scheduling problem and provides minimal discussion of the solution technique. Some issues relating to interface and database access are discussed.

Kwan, A., R. Kwan, M. Parker, and A. Wren. (1996a). "Producing Train Driver Shifts by Computer." In J. Allan, C. Brebbia, R. Hill, G. Sciutto, and S. Sone (eds.), *Computers in Railways – V*, Vol. 1, pp. 421–435.
Notes. This paper describes the development of a software tool for developing rail driver shifts. The tool is applied to develop schedules for various companies in the UK, each of which has slightly different rostering strategies.

Kwan, A., R. Kwan, M. Parker, and A. Wren. (1996b). "Scheduling Train Drivers and Investigating Alternative Scenarios by Computer." Technical Report, University of Leeds, School of Computer Studies, Research Report 96.27.
Notes. The paper describes the different aspects of train driver scheduling that were used to develop the TRACS II driver scheduling system. The characteristics of six different rail services, as they relate to

implementing TRACS, are also discussed.

Kwan, A., R. Kwan, M. Parker, and A. Wren. (1999a). "Producing Train Driver Schedules under Differing Operating Strategies." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 129–154. Springer.

Notes. The paper describes an approach for developing train driver schedules. The paper also describes a few case studies of successful applications of this approach to a few instances in the U.K. The software system has to cope with factors such as massive problem size, deadheading, multiple leg shifts, route knowledge, meal breaks and several other issues to come up with schedules that are applicable across multiple depots. First a set of legal shifts is constructed. This set covers all train trips. Next the minimum set of shifts is selected using an integer programming approach.

Kwan, A., R. Kwan, and A. Wren. (1999b). "Driver Scheduling Using Genetic Algorithms with Embedded Combinatorial Traits." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 81–102. Springer.

Notes. TRACS II is a crew scheduling software package developed for train companies. Approximate optimal solutions of crew scheduling are obtained by solving a set covering model. However, TRACS II cannot always guarantee a feasible schedule. This paper proposes a hybrid approach for generating a feasible schedule in the way that a genetic algorithm is applied to solutions generated by TRACS II.

Kwan, R. and A. Wren. (1996). "Hybrid Genetic Algorithms for bus Driver Scheduling." In L. Bianco and P. Toth (eds.), *Advanced Methods in Transportation Analysis*, pp. 609–619. Springer.

Notes. A hybrid approach combining a genetic algorithm, a rule based driver duty estimator and integer linear programming is described for bus driver scheduling. The genetic algorithm is used to create a set of good duties based on which an integer linear program is formulated. Approximate optimal schedules are generated by solving the resulted integer linear program.

Kwan, R., A. Wren, and B. Smith. (1988). "An Expert System for Bus Crew Scheduling." Technical Report, University of Leeds, School of Computer Studies, Report 88.14.

Notes. This report introduces the idea of using an expert system to produce a manageable set of duties for a crew rostering system.

Kwan, R., A. Wren, and L. Zhao. (1992). "Driver Scheduling Using Intelligent Estimation Techniques with Heuristic Searches." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 379–394. Springer.

Notes. The paper describes a knowledge-based system for developing schedules for bus crew which takes into account practical constraints from the operational environment. Such a system would be able to incorporate the expert knowledge of the scheduler as well as the labour rules. These rules differ from organisation to organisation and are best described using an AI method.

Kwan, R., A. Wren, L. Zhao, R. Clement, and M. Rahin. (1993). "Applications of Information Technology for Bus and Driver Scheduling." In *Proceedings of SERC Conference on Informing Technologies for Construction, Civil Engineering and Transport*.

Notes. The paper describes an interactive system for scheduling bus routes and discusses the use of GA methods for solving the driver scheduling problems associated with the bus schedules. The GA results are compared with those obtained from IP methods for different problem sizes.

Kwan, R., A. Wren, and A. Kwan. (2000). "Hybrid Genetic Algorithms for Scheduling Bus and Train Drivers." In *Proceedings of Congress on Evolutionary Computing CEC'2000*, pp. 285–292. IEEE Press.

Notes. This paper considers the problem of short-haul driver scheduling for bus and rail crew. After describing early work in the area, the paper then documents different mathematical modelling enhancements and also provides new heuristic approaches. The main thrust of this paper is a hybrid GA/LP approach. Simple heuristics are first used to develop a master set of all potential shifts. An LP relaxation of a set covering problem yields a lower bound on the optimal set of shifts that are required. A GA then starts with the relaxed solution to provide good solutions to the crew scheduling problem.

Kwan, R., A. Kwan, and A. Wren. (2001). "Evolutionary Driver Scheduling with Relief Chains." *Evolutionary Computation* 9, 445–460.

Notes. The paper describes the use of a GA with combinatorial traits (GACT) for scheduling bus drivers. During a shift drivers work 'spells' possibly on different vehicles. Duties are specified in terms of vehicle work. Vehicles must be driven so as to cover the bus schedules. Every piece of vehicle work is assigned to a shift, and shifts must comply with workplace rules. The total number of shifts and the total cost are minimised.

Kwok, L., S. Hung, and C.-C. Pun. (1995). "Knowledge-Based Cabin Crew Pattern Generator." *Knowledge-Based Systems* 8(1), 55–63.
Notes. This paper describes an expert systems approach for pairing generation based on the operations of Cathay Pacific. The description of the approach is relatively general and focuses on explaining how expert systems work in the context of this application. No attempt is made to compare this with more established crew scheduling techniques.

Lagerholm, M., C. Peterson, and B. Söderberg. (1997a). "Airline Crew Scheduling with Potts Neurons." *Neural Computation* 9(7), 1589–1599.
Notes. This paper develops a mean field Potts approach in the context of Neural Networks for airline crew scheduling. One technique used is the problem size reduction achieved by airport fragmentation and flight clustering, narrowing down the solution space by removing much of the sub-optimal part. Then a mean field annealing approach based on Potts neurons is applied, where a novel key ingredient is the use of a propagator formalism for handling topology, leg-counting, etc.

Lagerholm, M., C. Peterson, and B. Söderberg. (1997b). "Statistical Properties of Unrestricted Crew Scheduling Problems." Technical Report, LU.
Notes. This paper discusses the statistical properties the problem of pairing arrivals and departures at a single airport. This problem is one component of the crew scheduling problem. The statistical properties can be used to gain insight into the large problem.

Lagerholm, M., C. Peterson, and B. Söderberg. (2000). "Airline Crew Scheduling Using Potts Mean Field Techniques." *European Journal of Operational Research* 120(1), 81–96.
Notes. This paper is a continuation of (Lagerholm et al., 1997a). The method developed in (Lagerholm et al., 1997a) is explored on a set of synthetic problems, which are generated to resemble two real-world problems representing long and medium distance services. The algorithm performs well with respect to solution quality, with a computational requirement that at worst is in $O(N)$, where N is the number of flights.

Lamont, J. (1988). "The Transition to Computerized Bus and Crew Scheduling at the Montreal Urban Community Transit Company." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 272–278. Springer.
Notes. This paper describes the computerized scheduling business process at the Montreal Urban Community Transport Company (MUCTC), which uses the HASTUS system for scheduling buses and crew. This paper does not deal with the particular algorithms or mathematical models included in the system but rather describes the processes, the issues associated with installing and using a computerized system in what is effectively a manual scheduling environment.

Landis, M. (1981). "A Perspective on Automated Bus Operator Scheduling: Five Years Experience in Portland, Oregon." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 61–67. Amsterdam: North-Holland.
Notes. This paper describes experience with the RUCUS software system at Tri-Met Transit District, Portland, OR.

Laporte, G. (1999). "The Art and Science of Designing Rotating Schedules." *Journal of the Operational Research Society* 50, 1011–1017.
Notes. This paper concerns the construction of fixed shift cyclic rosters. Typical constraints as they occur in emergency services are discussed and how these need to be relaxed in order to obtain feasible solutions. An example of employees at Quebec Ministry of Transportation is discussed in some detail.

Laporte, G., Y. Nobert, and J. Biron. (1980). "Rotating Schedules." *European Journal of Operational Research* 4(1), 24–30.

Notes. To create cyclic rosters the author first creates work segments consisting of several day/evening/night shifts followed by some days off. Segments vary in length and may start on different days of the week. An IP is then used to select a set of work segments that cover all shifts. These are then spliced together using a complete enumeration approach.

Lasry, A., D. McInnis, F. Soumis, J. Desrosiers, and M. Solomon. (2000). "Air Transat Uses ALTITUDE to Manage Its Aircraft Routing, Crew Pairing, and Work Assignment." *Interfaces* 30(2), 41–53.

Notes. This article reports a successful application of an airline crew management system ALTITUDE. Aircraft routing, crew scheduling and crew rostering can be modelled as large scale set partitioning problems that are solved using a column generation approach.

Lau, H. (1994). "Manpower Scheduling with Shift Change Constraints." In *Proceedings of the 5th Annual International Symposium on Algorithms and Computation*, Beijing, China, Lecture Notes in Computer Science, Vol. 834, pp. 616–624.

Notes. This paper presents some results on a shift assignment problem. The problem is NP-hard in general, but some special cases can be solved in polynomial time. Further work can be found in (Lau, 1996a, 1996b). In particular, given a set of shift types, this paper considers the changing shift assignment problem which takes into account permissible changes of shifts from one day to the next. Several variants of this problem are presented: (1) with monotonic shift change matrix and demand satisfaction being exact, (2) with fixed-length work stretches, (3) with fixed off days.

Lau, H. (1996a). "Combinatorial Approaches for Hard Problems in Manpower Scheduling." *Journal of the Operational Research Society of Japan* 39(1), 88–98.

Notes. The work carried out is an extension to that in (Lau, 1996b). The special tour scheduling problem is reformulated as a fixed cost network flow problem for which known computational techniques have been developed in the literature. It is also shown that the discussed problem can be solved in polynomial time with special shift transition rules.

Lau, H. (1996b). "On the Complexity of Manpower Shift Scheduling." *Computers and Operations Research* 23(1), 93–102.

Notes. This paper considers a special tour scheduling problem in which off days for each worker are given and consecutive shifts in two consecutive working days follow some given rules. The aim is to assign shifts to workers such that variable demands are met and shift transition rules are satisfied. It is proved that in the cyclic case, the problem is NP-hard in general, but can be solved in polynomial time if the transition rules are of special forms. The same result hold for the cyclic case.

Lau, H. and S. Lau. (1997). "Efficient Multi-Skill Crew Rostering via Constrained Sets." In *Proceedings of the 2nd ILOG Solver and Scheduler Users Conference*. Paris: ILOG.

Notes. This paper discusses the application of CLP set constraints to scheduling the multi-skilled staff in a movie studio. The set constraint representation is claimed to provide substantial benefits over the finite domain representation. However, empirical analysis is not provided.

Lauer, J., L. Jacobs, M. Brusco, and S. Bechtold. (1994). "An Interactive, Optimization-Based Decision Support System for Scheduling Part-Time Computer Lab Attendants." *Omega* 22(6), 613–626.

Notes. This study presents an interactive decision support system for a tour scheduling problem arising from a computer lab. The system can be highly responsive to various management objectives and allows managerial interactions by overriding existing schedules.

Lavoie, S., M. Minoux, and E. Odier. (1988). "A New Approach for Crew Pairing Problems by Column Generation with an Application to Air Transportation." *European Journal of Operational Research* 35(1), 45–58.

Notes. This paper provides a column generation approach for a set covering formulation of the crew scheduling problem. Unlike many other variants of this problem, the restrictions on pairings are simple enough that the pricing problem can be (re)formulated as an unconstrained shortest path problem. Computational results are reported for problems with up to 329 flights which, with one exception, give integer solutions for the LP relaxation.

Layfield, C., B. Smith, and A. Wren. (1999). "Bus Relief Opportunity Selection Using Constraint Program-

ming." In *Proceedings of the 1st International Conference on the Practical Applications of Constraint Technologies and Logic Programming (PACLP'99)*, pp. 537–552. The Practical Application Company.
Notes. This paper describes the application of constraint programming to perform pre-processing for the crew scheduling problem. Relief opportunities are selected or eliminated by forming "meal-break chains." The reduction in relief opportunities makes the crew scheduling problem more tractable. This is essentially the same work presented in (Smith et al., 1998).

Lazaro, J. and P. Aristondo. (1995). "Using Solver for Nurse Scheduling." In *Proceedings of the 1st ILOG Solver and Scheduler Users Conference*. Paris: ILOG.
Notes. The paper provides a limited description of how ILOG solver might be used to solve a simple nurse rostering problem.

Lee, C. and G. Vairaktarakis. (1997). "Workforce Planning in Mixed Model Assembly Systems." *Operations Research* 45(4), 553–567.
Notes. This paper discusses the determination of staffing levels in mixed model assembly lines. The manufacturing jobs are to be sequenced in such a way as to minimize staffing levels across a number of stations. A matching algorithm is presented for the two-station case and heuristics for the general case.

Leprince, M. and W. Mertens. (1985). "Vehicle and Crew Scheduling at the Societe des Transports Intercommunaux de Bruxelles; or Data Processing as an Aid to Operational Planning an Urban Passenger Transport System." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 149–178. North-Holland.
Notes. The paper describes briefly the steps for developing timetabling and crew scheduling solutions for an urban transport systems. The steps discussed are: determining the required car journeys, drawing the car-run graphs, computerised control and updating of the car-run graphs, establishing the timetable documents, breaking down vehicle work into staff duties, and duty rosters.

Lesaint, D., N. Azarmi, R. Laithwaite, and P. Walker. (1998). "Engineering Dynamic Scheduler for Work Manager." *BT Technology Journal* 16(3), 16–29.
Notes. Dynamically scheduling/replanning the workforce of technicians for British Telecom is a complex task. This paper describes a system which uses several algorithms for subdivisions of the complete problem. The methods used include CLP for tightly constraint task allocation, SA for better optimisation of loosely constrained tasks, and CLP for checking rule conformance. A thorough written description of the problem is given.

Lesaint, D., C. Voudouris, and N. Azarmi. (2000). "Dynamic Workforce Scheduling for British Telecommunications plc." *Interfaces* 30(1), 45–56.
Notes. This paper provides a lighter introduction to the material presented in (Lesaint et al., 1998). It describes the problem of assigning tasks to British Telecom technicians. It also includes some discussion of a combined CLP and SA solution techniques.

Lesaint, D., C. Voudouris, N. Azarmi, and B. Laithwaite. (1997). "Dynamic Workforce Management." In *Proceedings of the 1997 IEE Colloquium on AI for Network Management Systems, IEE Stevenage, UK, England*, pp. 1/1–1/5.
Notes. This paper touches on the features of a system for task assignment to technicians at a large telecommunications companies. Details of the problem and solution techniques are provided in (Lesaint et al., 1998).

Lessard, R., J. Rousseau, and D. Dupuis. (1981). "Hastus I: A Mathematical Programming Approach to the Bus Driver Scheduling Problem." In A. Wren (ed.), *Computer Scheduling of Public Transport*, pp. 255–267. Amsterdam: North-Holland.
Notes. This paper presents the integer programming formulations and solution strategies that are included in the HASTUS system, a software application for solving bus and crew scheduling problems in three stages. The IP formulations can become large and intractable even for small operations. Hence, the paper introduces an LP relaxation of the problem which also includes a discretization of the time intervals. A combination of smart heuristics and an algorithm based on solving a matching problem are used to solve the relaxation.

Levine, D. (1996). "Application of a Hybrid Genetic Algorithm to Airline Crew Scheduling." *Computers and Operations Research* 23(6), 547–558.
Notes. The paper provides a detailed discussion of using a hybrid GA and local search algorithm to solve the set partitioning problems that arise in air crew scheduling. The algorithm was tested using problems from the Hoffman–Padberg test set. Results are compared with those from the more traditional OR methods developed for these problems.

Lewis, M. (1992). "Experience of Using the Same Computerized Scheduling System under Three Different Operating Conditions." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 59–74. Springer.
Notes. This paper reports the experience of using a crew scheduling system BUSMAN in three companies with different operating conditions.

Li, Y. (1985). "The Application of the Microcomputer in Bus and Crew Scheduling in Shanghai." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 179–198. Elsevier Science.
Notes. The paper describes the development of bus scheduling and crew scheduling systems for the Shanghai Public Transportation System.

Li, J. and R. Kwan. (2000a). "A Fuzzy Simulated Evolution Algorithm for the Driver Scheduling Problem." Technical Report, University of Leeds.
Notes. In this paper the crew scheduling problem is modelled as a standard set covering problem. The duties are generated by an evolutionary algorithm which makes use of a constructive heuristic for initialisation and mutation (repair).

Li, J. and R. Kwan. (2000b). "A Genetic Algorithm with Fuzzy Comprehensive Evaluation for Driver Scheduling." Technical Report, University of Leeds.
Notes. In this paper the crew scheduling problem is modelled as a standard set covering problem. The pairings are generated by a greedy constructive heuristic. The behaviour of the heuristic is controlled by fuzzy weights in the objective function. A GA is used to conduct a problem space search to find appropriate weights.

Li, N. and L. Li. (2000). "Modeling Staffing Flexibility: A Case of China." *European Journal of Operational Research* 124, 255–266.
Notes. This paper presents a multiple objective integer programming formulation for a multiple-skilled workforce planning problem in a health case system. The demand for each category of tasks is the sum of known appointments and random walk-in customers. Each task is performed primarily by one class of workers, but can be performed by other classes of workers with lower productivity. The aim of this study is to determine appropriate workforce mixture that captures the balance of costs and benefits of staff flexibility. A case study is analyzed for a AIDs preventive clinic.

Li, C., E. Robinson, and V. Mabert. (1991). "An Evaluation of Tour Scheduling Heuristics with Differences in Employee Productivity and Cost." *Decision Sciences* 22, 700–718.
Notes. The paper describes the use of a range of heuristics to develop rosters for bank clerical workers, of different skill levels, engaged in processing cheques for commercial customers. The nature of these problems requires more general formulations of the standard tour scheduling models (as at 1991).

Liang, T. and B. Buclatin. (1988). "Improving the Utilization of Training Resources through Optimal Assignment in the U.S. Navy." *European Journal of Operational Research* 33, 183–190.
Notes. Navy personnel are assigned to perform tasks. Each task requires a specific skill. A person is eligible for performing a task but without proper skills will gain skills through training. A network model is developed for optimally allocating personnel to training courses so that the total benefit of the assignments is maximized. This model can be used either as an operational or a planning tool.

Liang, T. and T. Thompson. (1987). "A Large-Scale Personnel Assignment Model for the Navy." *Decision Sciences* 18(2), 235–250.
Notes. An integrated network flow model is presented that solves a personnel allocation and assignment problem for the navy. The purpose of this application is to ensure that qualified personnel are assigned to various activities and that the minimum manning levels for all classes of officers are met, while

attempting to achieve multiple objectives. The model can be used to evaluate different policies.

Lin, C. (1999). "The Development of a Workforce Management System for a Hotline Service." *Computers and Industrial Engineering* 37, 465–468.

Notes. This paper touches lightly on a process for scheduling staff at a call centre. It discusses forecasting of call rates, converting expected call rates into demand for shifts, and then a construction heuristic for scheduling the staff to meet this demand.

Lin, C., K. Lai, and S. Hung. (2000). "Development of a Workforce Management System for a Customer Hotline Service." *Computers and Operations Research* 27, 987–1004.

Notes. This paper discusses the scheduling of call centre employees. Scheduling is performed in several distinct phases. Queueing simulation and linear regression are used for forecasting staffing levels. Staffing levels are transformed into shift demand by mixed integer programming. Then a special purpose heuristic forms tours of duty to meet the demand.

Linder, R. (1969). "The Development of Manpower and Facilities Planning Methods for Airline Telephone Reservation Offices." *Operational Research Quarterly* 20(1), 3–21.

Notes. The author provides a reappraisal of service standards in terms of their effects on the customers and on the direct cost of operations in the context of an airline telephone reservation office. These service standards are used as inputs to obtain the number of telephone lines and hourly staff requirements using a combination of simulation and queueing theory.

Littler, R. and D. Whitaker. (1997). "Estimating Staffing Requirements at an Airport Terminal." *Journal of the Operational Research Society* 48(2), 124–131.

Notes. The paper describes the use of simulation models, based on service times for immigration processing, to determine immigration staffing levels for different flight schedules.

Loucks, J. and F. Jacobs. (1991). "Tour Scheduling and Task Assignment of a Heterogeneous Work Force: A Heuristic Approach." *Decision Sciences* 22(4), 719–739.

Notes. The paper provides a goal programming approach to rostering general staff who are limited in their times of availability. The model deals with a range of work practice constraints. The objectives are to minimise over staffing and to assign hours of work as closely as possible to those requested by the employees. The model is tested using a series of examples for restaurant staffing.

Lourenco, H., J. Paixao, and R. Portugal. (2001a). "Metaheuristics for the Bus-Driver Scheduling Problem." Technical Report, Department of Economics and Management, Universitat Pompeu Fabra, Barcelona, Spain.

Notes. The paper develops meta-heuristic algorithms such as tabu search, genetic algorithms and GRASP for solving bus crew scheduling in order to consider different objectives such as the total scheduling cost and the total number of duties. These methods have been incorporated in the Decision Support System for Transportation Planning GIST.

Lourenco, H., J. Paixao, and R. Portugal. (2001b). "Multiobjective Metaheuristics for the Bus-Driver Scheduling Problem." *Transportation Science* 35(3), 331–341.

Notes. The paper develops meta-heuristic algorithms such as tabu search, genetic algorithms and GRASP for solving bus crew scheduling in order to consider different objectives such as the total scheduling cost and the total number of duties. These methods have been incorporated in the Decision Support System for Transportation Planning GIST. The GIST system is being used by six public transportation companies in Portugal.

Lourenco, H., J. Paixao, and R. Portugal. (2002). "The Crew-Scheduling Module in the GIST System." Technical Report, Department of Economics and Management, Universitat Pompeu Fabra.

Notes. The crew scheduling module is one of most relevant modules in the GIST Planning Transportation Systems. This module is based on the application of meta-heuristics, in particular GRASP, tabu search and genetic algorithms to solve the bus-driver scheduling problem. The meta-heuristic have been successfully incorporated in the GIST Planning Transportation Systems and are actually used by several public transportation companies representing more than half of the bus and coach transportation market in Portugal.

Love, R. and J. Hoey. (1990). "Management Science Improves Fast Food Operations." *Interfaces* 20(2), 21–29.

Notes. An integer programming model is used for solving a manpower scheduling problem in a fast-food restaurant. Because of time availability of employees and skill requirements, the resulting integer program is too large to be solved quickly. Therefore the integer program is decomposed into two network flow subproblems.

Lowerre, J. (1977). "Work Stretch Properties for Scheduling of Continuous Operations under Alternative Labor Policies." *Management Science* 23(9), 963–971.

Notes. Under each of nine policies on days off patterns, cyclic rosters for days-off scheduling are constructed with minimum workforce using heuristic algorithms.

Lucic, P. and D. Teodorovic. (1999). "Simulated Annealing for the Multi-Objective Aircrew Rostering Problem." *Transportation Research, Part A: Policy and Practice* 33(1), 19–45.

Notes. The paper evaluates SA as a technique for scheduling tours of duty for pilots. The problem is modelled as a multi-objective rostering problem with a wide range of roster constraints. The paper provides a good discussion of particular SA solution evaluation criteria useful for this class of problems.

Luedtke, L. (1985). "RUCUS II: "A Review of System Capabilities." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 61–116. North-Holland.

Notes. The paper describes the capabilities of the RUCUS II vehicle and driver scheduling system. The system is installed (1985) in a number of US transit operations. Detailed examples are given of the use and operation of the system.

Lukman, D., J. May, L. Shuman, and H. Wolfe. (1991). "Knowledge-Based Schedule Formulation and Maintenance under Uncertainty." *Journal of the Society for Health Systems* 2, 42–64.

Notes. This paper describes a rule based approach to scheduling nurses. The nurses are first scheduling at unit level by application of a set of rules, including preferences and pre-allocations. Then the unit level rosters are merged using rules to resolve conflicts. The system is also used to repair rosters due to unplanned events.

Mabert, V. (1979). "A Case Study of Encoder Shift Scheduling under Uncertainty." *Management Science* 25(7), 623–631.

Notes. The traditional set covering model is replaced by a stochastic program for a shift scheduling problem in order to capture uncertainty of forecast errors on variable staffing requirements. A series of simulation tests are conducted to evaluate the new model's performance under different operating costs, forecast errors and other factors.

Mabert, V. and A. Raedels. (1977). "The Detail Scheduling of a Part-Time Work Force: A Case Study of Teller Staffing." *Decision Sciences* 8, 109–120.

Notes. A days off scheduling problem for tellers at a bank is presented in this paper. The aim is to generate a work schedule that minimises the number of part time staff required. While the initial IP formulation is easily solvable using todays computers and commercial IP solvers, the authors had to resort to heuristics in order to obtain solutions in the 1970s.

Mabert, V. and C. Watts. (1982). "A Simulation Analysis of Tour-Shift Construction Procedures." *Management Science* 28(5), 520–532.

Notes. A tour scheduling problem is formulated as a set covering model. In implementations, only a limited number of tours are selected in the formulation. This paper proposes six different ways of selecting tours and investigates how these different ways impact on costs, employee productivity and other matters.

Maier-Rothe, C. and H. Wolfe. (1973). "Cyclical Scheduling and Allocation of Nursing Staff." *Socio-Economic Planning Sciences* 7, 471–487.

Notes. The paper describes the development of cyclic nurse rosters to meet the needs of different wards in a hospital. The fluctuations in patient care requirements are met from a 'float pool' of nurses. The extra nurses needed are determined from daily assessment of patients' needs and the qualifications/skills of the nurses already assigned to duty on the cyclic roster.

Makri, A. and D. Klabjan. (2001). "Efficient Column Generation Techniques for Airline Crew Scheduling." Technical Report, University of Illinois at Urbana-Champaign.

Notes. Solving the linear programming relaxation of the set partitioning/covering model for the airline crew scheduling problem is computationally challenging. Within a column generation scheme, this challenge is mostly due to the difficulty of solving the pricing subproblem which is traditionally modeled as a resource constrained shortest path. The subproblem is used to price out new pairings or columns. This paper develops both an approximate and an exact approach for pruning pairings. The approximate approach is to reduce computational efforts while the exact approach is to guarantee optimality. Based on their numerical results, the authors recommend that the benefits of using pruning rules are substantial, and that therefore the pruning rules should be considered by any robust and flexible airline crew scheduling solver.

Manington, B. and A. Wren. (1975). "A General Computer Method for Bus Crew Scheduling." In *International Workshop on Urban Passenger Vehicle and Crew Scheduling*, pp. 1–49.

Notes. This paper describes a historical perspective of bus and crew scheduling research undertaken at the University of Leeds in the years from 1967 to 1975.

Marsten, R. and F. Shepardson. (1981). "Exact Solution of Crew Scheduling Problems Using the Set Partitioning Model: Recent Successful Applications." *Networks* 11, 165–177.

Notes. The author reviews several applications of crew scheduling methods based on a set partitioning formulations. The examples covered are Flying Tiger Line, Pacific Southwest Airways, Continental Airlines and Helsinki City Transport.

Marsten, R., M. Muller, and C. Killion. (1979). "Crew Planning at Flying Tiger: A Successful Application of Integer Programming." *Management Science* 25(12), 1175–1183.

Notes. The authors describe the crew scheduling and rostering problem arising at Flying Tiger, an air cargo carrier. Both the scheduling and the rostering problem are modelled as a standard set partitioning problem that is solved with a standard LP/IP solver. Most of the material in this paper is reproduced in (Marsten and Shepardson, 1981).

Martello, S. and P. Toth. (1986). "A Heuristic Approach to the Bus Driver Scheduling Problem." *European Journal of Operational Research* 24(1), 106–117.

Notes. A fairly complicated heuristic algorithm is proposed for solving a bus driver scheduling problem of which mathematical programming formulations are generally too complex to be exactly solved. This method is particularly suitable for the cases where heavy constraints on meal breaks are present. Computational results are reported for real-world applications.

Mason, A. (1999). "Branch and Cut and Integer Programming for Cyclic Rostering." In *Proceedings of the 1999 Nordic MPS Conference*, Phoenix, AZ.

Notes. This paper considers creation of cyclic rosters for tour scheduling. A somewhat different set partitioning model is used for modelling the problem. A new branch and cut scheme is developed in which a 3-way branching approach replaces the usual binary branching strategy. Computational results are provided for a range of test problems.

Mason, A. (2001). "Elastic Constraint Branching, the Wedelin–Carmen Lagrangean Heuristic and Integer Programming for Personnel Scheduling." *Annals of Operations Research* 108, 239–276.

Notes. In this paper the author provides a further development of the Lagrangean relaxation heuristic developed by Wedelin (Wedelin, 1995) as applied to tour scheduling problems. In particular, the paper shows the relationship between this paper and branching methods for integer programming. Results for a variety of real world data sets are presented and show that in some cases this method compares favourably to the standard solution technique using a commercial IP solver. Some insights into which types of problems the Lagrangean heuristic finds hard to solve is also given.

Mason, A. and D. Nielsen. (1999a). "PETRA: A Programmable Optimization Engine and Toolbox for Personnel Rostering Applications." Technical Report, Department of Engineering Science, University of Auckland.

Notes. This presentation provides an overview of the approach used by the PETRA system. It describes set partitioning formulations for several different application areas and discusses some of the issues related to using an Integer Programming/Column Generation formulation. A more formal treatment is provided by technical report of the same name (Mason and Nielsen, 1999b).

Mason, A. and D. Nielsen. (1999b). "PETRA: A Programmable Optimization Engine and Toolbox for Personnel Rostering Applications." Technical Report, Department of Engineering Science, University of Auckland.

Notes. This report describes the approach used by the PETRA system. It details set partitioning formulations for several different application areas and discusses some of the issues related to using an Integer Programming formulation. Additionally, some discussion is made regarding scalability of the problem. Two approaches are used: decomposition into sub-problems and column generation.

Mason, A. and M. Smith. (1998). "A Nested Column Generator for Solving Rostering Problems with Integer Programming." In L. Caccetta, K. Teo, P. Siew, Y. Leung, L. Jennings, and V. Rehbock (eds.), *International Conference on Optimization: Techniques and Applications*.

Notes. A set covering model is used for finding solutions of a tour scheduling problem in which the number of workers is given. A nested column generation approach is employed for solving the set covering model. Efficient network flow models are designed to quickly price out new columns/tours.

Mason, A., D. Ryan, and D. Panton. (1998). "Integrated Simulation, Heuristic and Optimisation Approaches to Staff Scheduling." *Operations Research* 46(2), 161–175.

Notes. An integrated approach is developed for generating cyclic rosters for customs staff at the Auckland International Airport. A new simulation and heuristic descent methods are used for calculating near-optimal staffing requirements for all planning periods. The set covering model is used for solving shift scheduling problems one for each day. Cyclic rosters are created based on the solutions obtained in the shift scheduling problems from the techniques in (Panton, 1991). The application of this integrated approach has resulted in significantly lower staffing requirements, while at the same time creating both high-quality rosters and ensuring the service provided to passengers are satisfactory.

Mateus, G. and J. Casimiro. (2002). "Models and Algorithms for the Crew Scheduling Problem." Working Paper.

Notes. This paper presents a Lagrangean relaxation based method for solving the crew scheduling problem that is formulated as a set covering model. Numerical results are reported for a set of problems from OR-library. It also describes the algorithm developed in (Caprara et al., 1998b) for crew rostering. Numerical results show that there is still a lot of room for further improvement.

Mazzolla, D. and R. Oppenheimer. (1973). "Matrix Schedules for Nurses." *Industrial Engineering* 5(3), 36–37.

Notes. The paper describes a 10 week cyclic roster for operating theatres.

McGinnis, L., W. Culver, and R. Deane. (1978). "One- and Two-Phase Heuristics for Workforce Scheduling." *Computers and Industrial Engineering* 2(1), 7–15.

Notes. The paper describes the construction of rosters for 200 staff with 8 hour shifts over a one week planning period. Demand is specified in one hour intervals. A two-phase heuristic is used to first determine shift patterns and then assign staff to shifts to determine individual weekly schedules. A one-phase heuristic combining both stages is also considered.

McHugh, M. (1989). "Computer Simulation as a Method for Selecting Nurse Staffing Levels in Hospitals." In *Proceedings of the 1989 Winter Simulation Conference*, pp. 1121–1129.

Notes. A computer simulation method is used for selecting appropriate nurse staffing levels. The best staffing level is determined by direct cost, overstaffing rates and understaffing rates.

Megeath, J. (1978). "Successful Hospital Personnel Scheduling." *Interfaces* 8(2), 55–60.

Notes. The paper describes a simple paper based method for developing cyclic nurse rosters for three levels of qualified nurses over a six week period.

Mehrotra, V. (1997). "Ringing up Big Business." *OR/MS Today* 24(4).

Notes. This paper provides a non-technical introduction to the issues involved in call centre scheduling. It discusses forecasting staffing levels and touches on shift scheduling. Also, some directions for future research are provided including increasing the realism of the modelling and better exploiting the value of the data that is being recorded.

Mehrotra, A., K. Murthy, and M. Trick. (2000). "Optimal Shift Scheduling: A Branch-and-Price Approach." *Naval Research Logistics* 47, 185–200.

Notes. The traditional set partitioning formulation is used for finding solutions to shift scheduling with multiple breaks and break time windows. A branch and price method is developed for solving the proposed model. Three specialized branching strategies are devised. They are work period based branching, break period based branching, and duty period based branching. The computational study demonstrates that the proposed formulation and method are computationally superior on a large number of problems and are very competitive with alternative methods on all shift scheduling problems described in the literature.

Meilton, M. (2001). "Selecting and Implementing a Computer Aided Scheduling System for a Large Bus Company." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 203–214. Springer.

Notes. This paper explains the process undertaken by a company to select a computer aided scheduling software application. The paper provides a useful characterisation of the steps that are vital in undertaking a software implementation. It is necessary to understand scheduling functional requirements clearly.

Meisels, A., E. Gudes, and G. Solotorevsky. (1997). "Combining Rules and Constraints for Employee Timetabling." *International Journal of Intelligent Systems* 12, 419–439.

Notes. This paper discusses a nurse scheduling problem. The representation is fairly standard, however, the authors allow the user to define additional constraints. These constraints and directions for the search strategy are defined in an expert system framework. The expert system is then used to guide the construction heuristic and to repair dead ends in the search.

Meisels, A. and E. Kaplansky. (2001). "Iterative Restart Techniques for Solving Employee Timetabling Problems." Technical Report, Ben-Gurion University.

Notes. This paper discusses the application of randomised restarting to the standard CSP search strategy for a Nurse scheduling problem. Previous work by these authors reported that standard complete search strategies had limited ability to solve hard problems. Randomised restarting with an increasing backtrack limit, however, provides marked improvement for these problems.

Meisels, A. and N. Lusternik. (1997). "Experiments on Networks of Employee Timetabling Problems." In *Practice and Theory of Automated Timetabling II*, Lecture Notes in Computer Science, Vol. 1408, pp. 130–141. Springer.

Notes. This paper discusses the use of constraint techniques and GAs on nurse scheduling problems. The performance of these techniques for randomly generated problem instances is discussed. A discussion of the hardness of the problem in relation to list and graph colouring is made.

Meisels, A. and A. Schaerf. (2003). "Modelling and Solving Employee Timetabling Problems." *Annals of Mathematics and Artificial Intelligence* 39(1–2), 41–59.

Notes. This paper discusses the application of a hill climbing algorithm to the nurse scheduling problem previously explored by these authors (Meisels et al., 1997; Meisels and Lusternik, 1997). They discuss the choice moves and computation resources spent selecting move parameters. Results are presented for a number of problem instances. Some comparisons are made against CLP and hybrid systems, however, the most favourable results come from hill climbing.

Mellouli, T. (2001). "A Network Flow Approach to Crew Scheduling Based on an Analogy to a Vehicle Maintenance Routing Problem." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 91–120. Springer.

Notes. This paper develops a network flow model for the crew scheduling problem for airline and rail applications based on a state-expanded aggregated time-space network. This model, which was used in a German intercity rail application, for solving maintenance routing problems, is extended and ported to solve airline crew scheduling problems.

Meyer, J. and R. Markowitz. (1997). "A Database Program for the Management of Staff Scheduling a Radiology Department." *Amer. J. Roentgenol.* 169(6), 1489–1492.

Notes. The paper describes the use of a simple database system for balancing the patient load and assigning duties to staff in a radiology department.

Meyer auf'm Hofe, H. (2000). "Solving Rostering Tasks as Constraint Optimization." In *PATAT-2000: Practical Applications and Theory of Automated Time Tabling*, pp. 280–297.

Notes. This paper discusses the application of hierarchical constraints to a generalised nurse scheduling problem. Having found an initial assignment an iterative improvement algorithm is used to improve solution quality. Identification of bad regions and complex moves (including optimisation of regions) are used to direct the search quickly to better solutions.

Meyer auf'm Hofe, H. (2001). "Nurse Rostering as Constraint Satisfaction with Fuzzy Constraints and Inferred Control Strategies." In E. Freuder and R. Wallace (eds.), *Constraint Programming and Large Scale Optimisation Problems*, DIMACS Series, Vol. 57, pp. 67–99. American Mathematical Society.

Notes. This paper builds on previous work (Meyer auf'm Hofe, 2000) with a generalised nurse scheduling problem. Included in this paper is a discussion the application of fuzzy constraints and the impact on solution technique. A construction heuristic generates an initial solution and then an iterative improvement algorithm is used to improve the satisfaction of constraints. The moves of the improvement algorithm are guided by the constraints.

Millar, H. and M. Kiragu. (1998). "Cyclic and non-Cyclic Scheduling of 12 h Shift Nurses by Network Programming." *European Journal of Operational Research* 104(3), 582–592.

Notes. The paper develops a method based on stints, fixed patterns of shifts, with allowed transitions between the stints. Work schedules are developed for both cyclic and acyclic rosters by formulating the problem as a network of stints. The objective is to minimise the cost of the roster. The problem is solved as a shortest path problem with side constraints.

Miller, J. and L. Franz. (1996). "A Binary-Rounding Heuristic for Multi-Period Variable-Task-Duration Assignment Problems." *Computers and Operations Research* 23(8), 819–828.

Notes. A multiple-period assignment problem is formulated as a generalized assignment problem with side constraint. Each task may require a different number of employees to perform it at each time period. A binary-rounding heuristic is developed for finding an approximation solution to the problem.

Miller, H., F. Pierce, W. Pierskalla, and G. Rath. (1979). "Nurse Utilization Algorithm." In G. Chacko (ed.), *Health Handbook*, pp. 675–690. New York: North-Holland.

Notes. The paper describes a mathematical programming approach to the problem of generating nurse rosters. The basic approach is to try and minimise the violation of staffing levels and nurse preferences expressed as penalties. The paper discusses the steps involved in implementing such a system in a hospital and the processes involved in gathering staff preference data.

Miller, H., W. Pierskalla, and G. Rath. (1976). "Nurse Scheduling Using Mathematical Programming." *Operations Research* 24(5), 857–870.

Notes. The paper describes a descent method for determining nurse schedules by balancing the trade off between staff coverage and the schedule preferences of the nurses.

Mills, R. and D. Panton. (1992). "Scheduling of Casino Security Officers." *Omega International Journal of Management Science* 20(2), 183–191.

Notes. This paper discusses the scheduling of permanent and casual security personnel in the context of a cyclic roster. First an integer programming model is used to determine the number of personnel required and placement of their shifts throughout a typical week (days off scheduling). A special purpose algorithm is then used to construct lines of work throughout the roster cycle which satisfy these personnel requirements.

Mingozzi, A., M. Boschetti, S. Ricciarde, and L. Biancolli. (2000). "A Set Partitioning Approach to the Crew Scheduling Problem." *Operations Research* 47(6), 873–888.

Notes. The authors present a generic method for solving crew scheduling problems formulated as set partitioning problems. They use a variety of heuristic methods to get successively better approximations to the dual solution. This additive bounding method allows heuristic and optimal solutions to the crew scheduling problem to be found faster than with standard LP based methods.

Mitchell, R. (1985). "Results and Experiences of Calibrating HASTUS-Macro for Work Rule Cost at the Southern California Rapid Transit District." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 119–136. North-Holland.

Notes. This paper describes operational experience with the implementation of HASTUS-MACRO in the Southern California Rapid Transit District.

Mitra, G. and K. Darby-Dowman. (1985). "CRU-SCHED: A Computer-Based Bus Crew Scheduling System Using Integer Programming." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 223–232. North-Holland.

Notes. This paper describes a crew scheduling system, CRU-SCHED. A design objective of the CRU-SCHED system was to provide the schedules with a means of obtaining good crew schedules rapidly. Furthermore, the system is designed to be easy to use and to allow schedulers with little computer experience to specify characteristics they wish to see in the computer produced crew schedules. The mathematical model built in the system is the generalized set partitioning. The system has been used in Ireland.

Mitra, G. and A. Welsh. (1981). "A Computer-Based Crew Scheduling System Using a Mathematical Programming Approach." In *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 281–296. Amsterdam: North-Holland.

Notes. This paper presents a computerised system for bus crew scheduling problems that is based on integer programming formulations and their LP relaxation. Solutions to the problems are made possible through exploring alternative ways of enabling optimal solutions of the LPs to be found.

Monfroglio, A. (1996). "Hybrid Genetic Algorithms for a Rostering Problem." *Software Practices Expert* 26(7), 851–862.

Notes. The paper describes a hybrid greedy algorithm – GA for rostering train drivers over an approximate 120 day (summer) period.

Monroe, G. (1970). "Scheduling Manpower for Service Operations." *Industrial Engineering* 2(8), 10–17.

Notes. A constructive heuristic is designed for finding a cyclic roster for a tour scheduling problem with simple off days pattern.

Moondra, S. (1976). "An Linear Programming Model for Work Force Scheduling for Banks." *Journal of Bank Research* 6, 299–301.

Notes. This paper presents a simple linear program to determine the number of full time and part time staff that should be employed by a bank and the shifts that they should work in order to handle a typical daily workload.

Morgado, E. and J. Martins. (1992). "Scheduling and Managing Crew in the Portuguese Railways." *Expert Systems with Applications* 5, 301–321.

Notes. This paper provides a description of a computerised (rail) crew scheduling and duty assignment system for Portuguese Railways. The computerised system has modules for crew scheduling and crew assignment as well as a module for crew management and tracking. These modules employ a mix of manual methods and simple heuristics to provide a decision support framework for roster officers.

Morgado, E. and J. Martins. (1993). "An AI-Based Approach to Crew Scheduling." In *Proceedings of the Ninth Conference on Artificial Intelligence for Applications*, pp. 71–77. Los Alamitos, CA: IEEE Computer Society Press.

Notes. This paper describes the application of an A^* state-space search algorithm to the crew rostering problem. The problem of generating pairings and assignments is simplified by pre-processing the problem and domain reduction. The scheduling phase then uses domain knowledge implemented in the successor function to guide the search toward better solutions. This search may be controlled by the user by manual intervention. Repair of the schedule is mentioned in passing.

Morris, J. and M. Showalter. (1983). "Simple Approaches to Shift, Days-off and Tour Scheduling Problems." *Management Science* 29(8), 942–950.

Notes. Days off, shift and tour scheduling problems are all formulated as set covering models. Both days-off and shift scheduling problems are solved using a cutting plane procedure, while the tour scheduling problem is solved by a heuristic algorithm that first generates a fractional solution to its linear programming relaxation and then constructs an integer solution from round-down heuristics.

Morrish, A. and A. O'Conner. (1970). "Cyclical Scheduling." *Hospitals* 14, 66–71.

Notes. The paper describes a simple computer program for constructing 12 week cyclic rosters.

Mott, P. and H. Fritsche. (1988). "INTERPLAN: An Interactive Program System for Crew Scheduling and Rostering of Public Transport." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 200–211. Springer.

Notes. INTERPLAN is an interactive program system with multiple graphical support functions for crew scheduling and crew rostering of public transport. For crew scheduling, it provides a heuristic algorithm that cuts blocks and generates duties simultaneously, and a matching based algorithm to determine optimal duties. For crew rostering, the Hungarian Algorithm is used to generate the optimal roster that maximizes the rest time between consecutive duties and balances workload between drivers.

Mould, G. (1996). "Case Study of Manpower Planning for Clerical Operations." *Journal of the Operational Research Society* 47(3), 358–368.

Notes. The paper describes a spreadsheet model for determining the numbers of clerical workers of different skill levels needed to process claims in an insurance company. The model was set up as a DSS that allowed managers to investigate the effects of different employment scenarios on dealing with a demand for increased claims processing.

Moz, M. and M.V. Pato. (2004). "Solving the Problem of Rerostering Nurse Schedules with Hard Constraints: New Multicommodity Flow Models." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 179–197.

Notes. This paper considers rerostering nurse schedules when some nurses are unable to take some shifts in the existing schedules. Two new multicommodity flow formulations are developed for rerostering. Both models have taken hard constraints into account, but soft constraints have not been incorporated. Some computational experiments are carried out to test the efficiency of both formulations. It turns out that the compact formulation proves to be more efficient than the other disaggregated one, both in terms of computing time and in solution quality.

Musa, A. and U. Saxena. (1984). "Scheduling Nurses Using Goal-Programming Techniques." *IIE Transactions* 16(3), 216–221.

Notes. The paper describes a 0–1 integer goal programming approach to rostering 11 nurses to the day shift in a ward over a two-week period. The demand for nurses of differing qualification levels is given.

Musliu, N., J. Gartner, and W. Slany. (2000). "Efficient Generation of Rotating Workforce Schedules." Technical Report, Vienna University of Technology.

Notes. A framework of generating cyclic rosters is presented in (Gartner et al., 2001). This paper describes four major steps in this system in details. The constraint satisfaction and problem-oriented intelligent backtracking algorithms in each of the four steps finds good solutions for real-world problems in acceptable time.

Nachreiner, F., L. Qin, H. Grzech-Sukalo, and I. Hedden. (1991). "Computer-Aided Design of Shift Schedules." In *Ergonomics Proceedings of the 10th International Symposium on Night and Shiftwork*, Vol. 36, pp. 77–83. Bristol: Taylor & Francis.

Notes. This paper reports a list of rules to be considered in constructing both shifts and tours in tour scheduling with regular and irregular demand patterns.

Narasimhan, R. (1996). "An Algorithm for Single Shift Scheduling of Hierarchical Workforce." *European Journal of Operational Research* 96(1), 113–121.

Notes. This paper studies a days-off scheduling with a hierarchical workforce. A constructive heuristic algorithm is presented for finding the optimal solution.

Nicoletti, B. (1975). "Automatic Crew Rostering." *Transportation Science* 9(1), 33–42.

Notes. A constructive heuristic for building up an airline crew roster is presented in this paper. The algorithm solves essentially an assignment problem for each day to assign duties to staff taking into account the restrictions imposed by duties assigned previously. Results for a problem with 103 crew are given in the paper.

Nobert, Y. and J. Roy. (1998). “Freight Handling Personnel Scheduling at Air Cargo Terminals.” *Transportation Science* 32(3), 295–301.
Notes. Personnel scheduling at air cargo terminals consists of two stages: converting forecasted dynamic workload into staff requirements and creating optimal schedules to meet staff requirements. Employees at air cargo terminals handle freight within terminals. An integer program is used to model this two-stage problem, and is solved in two stages. Firstly, approximate staff requirements are obtained by solving the linear programming relaxation, and optimal schedules are obtained by solving a shift scheduling problem which is a typical set covering model.

Nooriafshar, M. (1995). “A Heuristic Approach to Improving the Design of Nurse Training Schedules.” *European Journal of Operational Research* 81(1), 50–61.
Notes. The paper describes a simulation package designed to allocate trainee nurses to wards so as to meet the requirements of training programs while observing staff requirements at the ward level.

Norby, R., L. Freund, and B. Wagner. (1977). “A Nurse Staffing System Based on Assignment Difficulty.” *Journal of Nursing Administration* 7(9), 2–24.
Notes. The paper considers a wide range of patient care, budgetary, equipment and nurse/patient ratio requirements that need to be considered when attempting to develop nurse rosters to provide the level of care needed in a ward.

Okada, M. (1992). “An Approach to the Generalized Nurse Scheduling Problem – Generation of a Declarative Program to Represent Institution-Specific Knowledge.” *Computers and Biomedical Research* 25(5), 417–434.
Notes. Presents a prolog based AI interactive system that has interview and scheduling modes. In the interview mode, the user enters the rules relating to the nurse schedules, and then a declarative program that represents the institution specific rules is generated. In the scheduling mode, the system allows the user to construct schedules that obey the rules by combining the generated declarative program with the institution-independent scheduling engine.

Okada, M. and M. Okada. (1988). “Prolog-Based System for Nursing Staff Scheduling Implemented on a Personal Computer.” *Computers and Biomedical Research* 21(1), 53–63.
Notes. The paper describes a prolog based system that was used to mimic the methods used in the manual construction of nurse rosters. The system can be used to apply the manual process and then construct rosters for a period of some months.

Okada, M., H. Mitsue, Y. Chizuko, and M. Okada. (1991). “A Software System to Support Generation of a Nurse Scheduling Program.” In *Proceedings of the Symposium on Industrial Applications of PROLOG*, pp. 15–22.
Notes. The paper describes a grammar for translating nurse preferences, determined by interview, into constraints for a rostering system.

Onodera, K. (1989). “Cockpit Crew Scheduling and Supporting System Using AI Techniques.” *NEC Research and Development* 92, 151–156.
Notes. A scheduling expert system is designed for constructing monthly rosters for cockpit crew. Such an expert system ensures high flexibility for changes in regulations and labor agreements.

Owens, B. (2001). “Personnel Scheduling Using Constraint Logic Programming.” Master’s Thesis, Computer Science and Software Engineering, Monash University, Australia.
Notes. This honours thesis discusses the application of constraint programming to flexible tour scheduling problems with complex constraints. A detailed discussion of constraint programming representation and labelling strategies is given. A comparison is made between the results for the constraint programming approach and a benchmark local search algorithm on test sets from several application domains.

Owens, B., A. Ernst, M. Garcia de la Banda, and K. Marriott. (2001). “Personnel Scheduling Using Hybrid CLP and Meta-Heuristic Approaches.” Technical Report, CSIRO Mathematical and Information Sciences.

Notes. This paper discusses the combination of constraint programming and local search for flexible tour scheduling problems with complex constraints. The constraint programming representation and labelling strategies are discussed. The most positive results are gained by a construct-improve approach using constraint programming for construction and local search for improvement.

Ozkarahan, I. (1989). "A Flexible Nurse Scheduling Support System." In *Computer Methods and Programs in Biomedicine, Symposium on Computer Applications in Medical Care*, Vol. 30, pp. 145–153.

Notes. The paper describes a potential DSS for managing a goal programming approach to the development of nurse rosters.

Ozkarahan, I. (1991a). "A Disaggregation Model of a Flexible Nurse Scheduling Support System." *Socio-Economic Planning Sciences* 25(1), 9–26.

Notes. This paper describes the form of a possible DSS using parameters to control and integrate various modules that could be used to develop nurse rosters. These include time of day, day of week and shift assignment modules. It provides mathematical programming (LP, IP and Goal Programming) formulations of these modules. Further, it discusses possible applications of the assignment module for assigning nurses within wards, across wards and substitution (higher qualified staff can do the work of lower qualified staff.

Ozkarahan, I. (1991b). "An Integrated Nurse Scheduling Model." *Journal of the Society for Health Systems* 3(2), 79–101.

Notes. The paper discusses the development of time of day and day of week subproblems for nurse rostering. A set covering IP and heuristics are used to solve the combined subproblems using a mix of 8, 10 and 12 hour shifts over a period of 7 days, based on demand specified in one hour intervals.

Ozkarahan, I. and Bailey, J. (1988). "Goal Programming Model Subsystem of a Flexible Nurse Scheduling Support System." *IIE Transactions* 20(3), 306–316.

Notes. The paper uses a goal programming approach to develop nurse rosters given shift based demand for nurses of different grades together with nurse preferences. A DSS is used to formulate the GP. Solutions from the GP module are used for shift assignments to individuals.

Paias, A. and J. Paixao. (1993). "State Space Relaxation for Set Covering Problems Related to Bus Driver Scheduling." *European Journal of Operational Research* 71(2), 303–316.

Notes. This paper describes a relaxation method for handling the large state space that is associated with a dynamic programming re-formulation of a set covering formulation for the bus crew scheduling problem. Instead of driving the state space relaxation procedure to optimality the paper uses it as a procedure for yielding lower bounds. The relaxed solution also provides a basis for a heuristic procedure that produces good upper bounds.

Paixao, J. and M. Pato. (1989). "A Structural Lagrangean Relaxation for Two Duty Period Bus Driver Scheduling Problem." *European Journal of Operations Research* 39, 213–222.

Notes. This paper considers the two-duty period bus driver scheduling problem as a particular case of the generalised set covering problem. The paper develops a structural Lagrangean relaxation approach, combined with greedy heuristics, for solving this problem. The structural Lagrangean relaxation is derived by adding some redundant constraints to the original problem and by relaxing the original constraints. The resulting problem has a network flow structure, which is exploited in the solution algorithm.

Paixao, J., M. Branco, E. Captivo, and M. Pato. (1986). "Bus and Crew Scheduling on a Microcomputer." In J. Coelho and L. Tavares (eds.), *OR Models on Microcomputers*, pp. 79–95. Elsevier.

Notes. This paper lists some early experience with a microcomputer-based approach to bus crew scheduling. The paper first presents a mathematical model and an assignment-based algorithm for the bus scheduling problem. The driver scheduling problem is then presented as a set covering problem. Given that the model was solved on a microcomputer for a real-life instance – in this case a large urban mass transit operation in Portugal – the original problem had to be modified. The restricted problem is solved using a linear programming approach coupled with a greedy heuristic.

Panton, D. (1991). "On the Creation of Multiple Shift Continuous Operation Cyclic Rosters under General Workforce Conditions." *Asia–Pacific Journal of Operational Research* 8(2), 189–201.

Notes. A tour scheduling problem with shifts and shift demands are given is considered. Shift demands are repeated weekly. It is required to generate a cyclic roster with a given workforce. This paper first describes the use of a modular approach for the creation of a days-off schedule, and then assigning shifts to days worked using either integer programming or network models. The proposed method is applied for generating a cyclic roster for casino security officers.

Panton, D. and G. Eitzen. (1997). "Dynamic Rosters: Addressing Fatigue and Recovery Issues in the Workforce." *The Journal of Occupational Health and Safety* 13(5), 487–492.

Notes. This paper compares the ramifications for fatigue and equity when using acyclic rosters versus cyclic rosters. As part of the discussion constraints are given for a particular energy supplier which ensure equity and avoid fatigue for their acyclic rosters.

Panton, D. and D. Ryan. (1999). "Column Generation Models for Optimal Workforce Allocation with Multiple Breaks." Technical Report, The University of South Australia.

Notes. A shift scheduling problem with multiple breaks and break windows is formulated as a set covering model. Two approaches are presented for solving this problem. In the first approach, shifts are determined using the set covering model assuming that no breaks exist and then all possible break combinations are enumerated for those generated shifts. In the second approach, column generation is used to handle the large size of the set covering model.

Parker, M. and B. Smith. (1981). "Two Approaches to Computer Crew Scheduling." In *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 193–221. Amsterdam: North-Holland.

Notes. This paper provides descriptions of two methods for solving bus crew scheduling problems. The first is a traditional approach that is based on a constructive heuristic approach. The second is a linear programming-based approach.

Parker, M. and A. Wren. (1976). "Computer Models for Scheduling Buses and Their Crews." In *Australian Road Research Forum*, pp. 1–34.

Notes. The paper describes how crew scheduling is solved via a two-stage approach: generation of valid duties and partial duties, and the refining stage in which either the number of duties is reduced or the amount of unassigned tasks is decreased. The work had been used in a large number of bus undertakings in UK.

Parker, M. and A. Wren. (1983). "Costs of Different Bus Crew Scheduling Constraints and Levels of Service." In *Proceedings of the Fifteenth Annual Seminar on Public Transport Operations Research*.

Notes. The paper presents the results of research undertaken to determine the effects on costs both of different levels of peak and off-peak bus operation, and of different crew scheduling constraints. The work used existing bus and crew scheduling computer programs to develop speedily a wide range of schedules.

Parker, M., A. Wren, and R. Kwan. (1995). "Modelling the Scheduling of Train Drivers." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 359–370. Springer.

Notes. The paper describes how the IMPACS system that was developed for scheduling bus crew was adapted to solve rail crew problems. The system needed to be slightly modified to take into account the particular needs of British Rail, the end user in this case study. The client's requirements were to carry out a wide-ranging series of experiments with a view to estimating the impact of these scenarios on operating costs. The IMPACS system solves crew scheduling problems by modelling it as a set covering problem and solving these using a combination of heuristics and linear programming.

Patrikalakis, I. and D. Xerocostas. (1992). "A New Decomposition Scheme of the Urban Public Transport Scheduling Problem." In M. Desrochers and J. Rousseau (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 386, pp. 407–425. Springer.

Notes. In this paper, the authors present a method for solving the bus crew scheduling problem. The work is motivated by problem instances and data from the Athens Area Urban Transport Organization. The crew scheduling subproblem is decomposed into morning and afternoon duties, which are formulated and solved. This approach integrates the solution to a crew scheduling problem and a vehicle scheduling problem. The crew scheduling subproblem is solved as a set partitioning problem while the vehicle scheduling problem is solved as a network flow problem with side constraints.

Pavlopoulou, C., A. Gionis, P. Stamatopoulos, and C. Halatsis. (1996). "Crew Pairing Optimization Based on CLP." Technical Report, University of Athens.

Notes. This paper discusses a pure CLP approach to the crew rostering problem. The problem is modelled as a set partitioning problem with a number of additional constraints. A limited analysis of performance concludes that while CLP models the problem well, efficiency is a problem for large instances.

Pedrosa, D. and M. Constantino. (2001). "Days-off Scheduling in Public Transport Companies." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 215–232. Springer.

Notes. A set covering model is presented for days-off scheduling for workers in transportation systems. The entire workforce is divided into several groups and a cyclic roster is used for all members in each group. A column generation scheme is used for solving the linear programming relaxation of the set covering model using the shortest path problem in a special network to solve the pricing subproblem. A constructive heuristic is employed for assigning schedules to workers.

Piccione, C., A. Cherici, M. Bielli, and A. La Bella. (1981). "Practical Aspects in Automatic Crew Scheduling." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 223–235. Amsterdam: North-Holland.

Notes. This paper describes a system that has been implemented for a public transport system in the metropolitan area of Melbourne. The system attempts bus line design, vehicle scheduling, crew scheduling, crew rostering as well as crew attendance. This paper addresses the crew scheduling aspects of the system. Crew scheduling is attempted by solving a set partitioning problem. The problem is solved by undertaking problem-specific modifications to a well-known approach for solving set partitioning problems.

Poliac, M., E. Lee, J. Slagle, and M. Wick. (1987). "A Crew Scheduling Problem." In *IEEE First International Conference on Neural Networks*, pp. 779–786.

Notes. This paper describes a shift scheduling problem for fast food outlets and similar operations. The problem includes variable demand for labour, multiple tasks, and different staff skill levels. The authors describe a neural network for generating a set of shifts. Unfortunately the paper contains neither results nor even enough detail on the setting of parameters to allow the reader to implement the suggested method.

Popova, E. and D. Morton. (1998). "Adaptive Stochastic Manpower Scheduling." In D.J. Medeiros, E.F. Watson, J.S. Carson, and M.S. Manivannan (eds.), *Proceedings of the 1998 Winter Simulation Conference*, Vol. 1, pp. 661–668.

Notes. Workforce planning is studied in a manufacturing environment where production rates and machine availability are dynamic and random. A stochastic programming model is formulated for determining the staffing levels for each shift on each day on each machine. The production rates and machine availability are simulated using a time-dynamic Bayesian model.

Quinn, P., B. Andrews, and H. Parsons. (1991). "Allocating Telecommunications Resources at L.L. Bean." *Interfaces* 21(1), 75–91.

Notes. This paper describes the improvements in profit gained at a call centre by increasing resource allocation to improve service. While other work by the authors has focused on the queueing theory, this paper concentrates on the economic benefits.

Raggl, A. and W. Slany. (1998). "A Reusable Iterative Optimization Software Library to Solve Combinatorial Problems with Approximate Reasoning." *International Journal of Approximate Reasoning* 19(1–2), 161–191.

Notes. This paper describes a generalised shift scheduling system derived from a steel mill scheduling system. Fuzzy logic is used to represent soft constraints and a limited set of hard constraints are built in. The system assumes that an initial solution which is feasible with respect to the hard constraints will be provided. A repair method (hill climbing) is used to iteratively improve the solution. Iterative deepening is used to search for an arbitrarily large sequence of simple moves that will result in a move from one feasible solution to another feasible and improved solution.

Ramli, R., A. Khader, and A. Mustafa. (2002). "Nurse Scheduling Models: Recent Solutions and Future Directions." Working Paper.

Notes. The article is a literature review of some more recent work in the area of nurse rostering. The authors discuss the objectives and constraints typical of nurse rostering, and provide a summary of different solution techniques grouped into exact, search, constructive heuristic, and hybrid categories.

Randhawa, S. and D. Sitompul. (1993). "A Heuristic-Based Computerized Nurse Scheduling System." *Computers and Operations Research* 20(8), 837–844.

Notes. The paper uses a DSS to generate one and two week day and shift work patterns. These patterns are evaluated in terms of hospital work regulations and nurse preferences. Schedules are developed for 4, 8 or 12 weeks using selected patterns. Penalty costs are used to observe constraints.

Reeves, G. and R. Reid. (1999). "A Military Reserve Manpower Planning Model." *Computers & Operations Research* 26, 1231–1242.

Notes. This paper describes the development of a multiple-objective mathematical programming model for manpower planning in a military reserve unit over a 12 month planning horizon. Given resource limitations and the conflicting objectives, the model allocates personnel in an efficient way by moving them across grade and skill classes in order to meet fluctuate activity demands over the planning horizon.

Rekik, M., J.-F. Cordeau, and F. Soumis. (2004). "Using Benders Decomposition to Implicitly Model Tour Scheduling." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 111–133.

Notes. The authors present a comprehensive and general model for the continuous tour scheduling problem. This model implicitly supports most forms of flexibility such as different days-on patterns, different shift starting times and lengths, break placement flexibility, and so on. The proposed model is compact and is based on the use of forward and backward constraints to match break, shift and tour variables. It is proved that the compact model is equivalent to a large-scale model based on a transportation problem for shift scheduling. This implicit compact formulation is extended for solving the tour scheduling problem.

Rising, E., R. Baron, and B. Averill. (1973). "A Systems Analysis of a University-Health-Service Outpatient Clinic." *Operations Research* 21(5), 1030–1047.

Notes. The paper uses Monte Carlo simulation methods to evaluate policies of arrival smoothing, and appropriate scheduling of appointments in an outpatient clinic. The associated scheduling of ancillary units such as X-ray and medical records is also considered.

Ritzman, L., L. Krajewski, and M. Showalter. (1976). "The Disaggregation of Aggregate Manpower Plans." *Management Science* 22(11), 1204–1214.

Notes. This paper discusses disaggregating (large scale) manpower requirements into operational plans. A randomised greedy constructive heuristic is described which assigns tours (enumerated before hand) to groups of employees. The construction terminates when the collection of tours produces at least the required amount of output. Several parameters are used to control the randomised behaviour of the constructive heuristic. Statistical analysis is used to determine preferential values for their problem instance.

Roberts, S. and L. Escudero. (1983a). "Minimum Problem-Size Formulation for the Scheduling of Plant Maintenance Personnel." *Journal of Optimization Theory and Applications* 39(3), 345–362.

Notes. This paper discusses scheduling the times of a set of maintenance jobs in a manufacturing plant (from which a trivial assignment of jobs to employees can be done). The specifics of the problem are presented elsewhere. The paper focuses on a sequence of integer programming formulations which lead to a model with a much lower number of variables.

Roberts, S. and L. Escudero. (1983b). "Scheduling of Plant Maintenance Personnel." *Journal of Optimization Theory and Applications* 39(3), 323–343.

Notes. Given a set of tasks and a group of people with various skills, it is required to assign people to tasks so that workers' idle time is minimized. An integer linear programming formulation is used for solving this problem.

Rogers, N., T. Roberts, and D. Dawson. (1997). "Improving Shiftwork Management." *The Journal of Occupational Health and Safety* 13(5), 429–437.
Notes. The paper provides a review of some health and safety and psychological factors associated with shiftwork. It also discusses the nature of the jobs usually carried out by shiftwork.

Rosenbloom, E. and N. Goertzen. (1987). "Cyclic Nurse Scheduling." *European Journal of Operational Research* 31(1), 19–23.
Notes. The paper uses an IP to minimise the number of surplus nurses while covering demand using specified cyclic rosters.

Rothstein, M. (1972). "Scheduling Manpower by Mathematical Programming." *Industrial Engineering*, pp. 29–33.
Notes. A simple days off scheduling is formulated as a set partitioning model.

Rothstein, M. (1973). "Hospital Manpower Shift Scheduling by Mathematical Programming." *Health Services Research* 8, 60–66.
Notes. The paper describes a formulation of an LP designed to schedule housekeeping (cleaners, cafeteria and rubbish removal) staff in a hospital. The objective is to cover a pre-determined demand subject to specified days-off patterns.

Rousseau, J. and J. Blais. (1985). "HASTUS: An Interactive System for Buses and Crew Scheduling." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 45–60. North-Holland.
Notes. This paper describes the sophisticated man-machine interface designed for HASTUS, a scheduling system. HASTUS has three major subsystems: HASTUS-Bus, for vehicle scheduling, HASTUS-Macro, for manpower and service planning and for preprocessing of vehicle data as a first step in manpower scheduling, and HASTUS-Micro, for the generation of actual operator assignments. This paper presents detailed interactive features, input data and output data for all three subsystems.

Rousseau, J. and J. Desrosiers. (1995). "Results Obtained with Crew-Opt, a Column Generation Method for Transit Crew Scheduling." In *Lecture Notes in Economics and Mathematical Systems*, Vol. 430, pp. 349–358. Berlin: Springer.
Notes. This paper describes the solution procedure in Crew-Opt an algorithm embedded within the HASTUS computerised system for mass transit scheduling. The LP relaxation of a set covering (partitioning) model is solved and a column generation approach is used to identify a solution. The column generation method is also included at every node of the branch and bound tree search. Feasible duties are then linked together using a shortest path algorithm. The paper then presents details of an actual implementation at client-sites in Toulouse, Barcelona, Vienna and the East Japan Railway network.

Rousseau, J., R. Lessard, and J. Blais. (1985). "Enhancements to the HASTUS Crew Scheduling Algorithm." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 295–310. North-Holland.
Notes. The paper provides an update on modifications and enhancements of the HASTUS system for bus driver scheduling and rostering. The main development is in the matching algorithm for putting together pieces of work.

Rubin, J. (1973). "A Technique for the Solution of Massive Set Covering Problem, with Application to Airline Crew Scheduling." *Transportation Science* 7(1), 34–48.
Notes. This paper presents a formulation for airline crew scheduling with base-constraints specifying the number of flight crews available at each base. The method for solving these problems commences from a known legal solution and applies heuristics for covering all flight legs while minimising cost.

Rushmeier, R., K. Hoffman, and M. Padberg. (1995). "Recent Advances in Exact Optimization of Airline Scheduling Problems." Technical Report, Department of Operations Research and Operations Engineering, George Mason University.
Notes. This is a review paper that covers fleet assignment and crew scheduling. The fleet assignment problem presented includes aggregate crew constraints. The types of constraints typically encountered in the crew scheduling problem are described and the standard set partitioning formulation is presented. The paper provides a good overview of different column generation strategies for reducing problem size

without discussing the details of any pricing algorithm. The issue of dead heading is also dealt with. Finally, methods for solving the set partitioning sub-problems are reviewed. The authors discuss some future directions for research including greater integration of crew scheduling with other operational problems such as fleet assignment.

Ryan, D. (1992). "The Solution of Massive Generalized Set Partitioning Problems in Aircrew Rostering." *Journal of the Operational Research Society* 43(5), 459–467.
Notes. The author describes the crew rostering problem and how to overcome some of the difficulties in solving these. The approach described involves complete enumeration of the feasible lines of work, solving the LP (possibly with perturbation to reduce redundancy) and a constraint branching scheme. Results for up to 200 trips and 150,000 columns are presented.

Ryan, D. (2000). "New Zealand: Optimization Earns Its Wings: The Development of Crew Scheduling Systems for Air New Zealand." *OR/MS Today* 27(2), 26–30.
Notes. This article gives an overview of the work done by the author (and others) over a period of 16 years with Air New Zealand. It describes some of the problems relating to crew rostering and planning that have been tackled as well as implementation and integration issues that were important to achieve a successful outcome.

Ryan, D. and J. Falkner. (1988). "On the Integer Properties of Scheduling Set Partitioning Models." *European Journal of Operational Research* 35(3), 442–456.
Notes. The authors consider the general set partitioning problem and theory relating to integrality of the LP relaxation. From this they derive conditions on the structure of columns that ensure that the LP relaxations are integral or nearly integral. In particular, in the context of crew scheduling they show that this can be achieved by following each flight or task by the next available flight. This is the basis for the "follow-on" rule that has been widely used for branching in the literature since this paper has been published. Computational results for problems with up to 185 flights illustrate the effectiveness of this idea.

Ryan, D. and B. Foster. (1981). "An Integer Programming Approach to Scheduling." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 269–280. Amsterdam: North-Holland.
Notes. Many crew scheduling problems are formulated and solved as set partitioning problems. Even for small instances, these problems tend to be very large and difficult to solve. This paper investigates the imposition of additional structure on the formulation, thereby over-constraining the integer program, which leads to obtaining integer solutions from the LP relaxation.

Ryan, T., B. Barker, and F. Marciante. (1975). "A System for Determining Appropriate Nurse Staffing." *Journal of Nurse Administration* 5(5), 30–38.
Notes. The paper discusses methods for translating patient acuity measures into the amount of nursing time for different nurse skill levels.

Samuelson, D. (1999). "Predicative Dialing for Outbound Telephone Call Centers." *Interfaces* 29(5), 66–81.
Notes. This paper discusses the pacing of calls for outbound call centres. That is given the number of operators available and expected call durations determine the rate at which the automated dialling machinery should be dialling out to generate new calls. Queueing theory is used to make these predictions and some discussion of the difficulties of developing a real-time application for this is made.

Sanders, P., T. Takkula, and D. Wedelin. (1999). "High Performance Integer Optimization for Crew Scheduling." In *7th International Conference on High performance Computing and Networking Europe*, pp. 3–12.
Notes. This paper discusses implementation details for the Wedlin algorithm for set partitioning problems introduced in (Wedelin, 1995). The changes are designed to make the algorithm more friendly for modern computer architectures (less cache misses) and to introduce parallelization.

Sarin, S. and S. Aggarwal. (2001). "Modeling and Algorithmic Development of a Staff Scheduling Problem." *European Journal of Operational Research* 128, 558–569.
Notes. Workers are required to load and unload trucks. Each truck arrives at different time within the given shift and needs the time to be loaded or unloaded. The aim is to determine the minimum number

of workers to load and unload trucks in each shift. It is modelled as a set partitioning problem and is solved using a column generation method. Numerical results are presented and compared with heuristic methods.

Sarker, B. (1986). "Optimum Manpower Models for a Production System with Varying Production Rates." *European Journal of Operational Research* 24(3), 447–454.
Notes. Optimum models are proposed for estimations of workforce on the assembly line in this paper. The estimation for varying production rates on the same production line is done with reference to the present production rate and to the maximum installed capacity.

Schaefer, A., E. Johnson, A. Kleywegt, and G. Nemhauser. (2001). "Airline Crew Scheduling under Uncertainty." Technical Report TLI-01-01, The Logistics Institute, Georgia Institute of Technology.
Notes. This paper presents a method for estimating the real costs of operating a set of airline crew schedules which differ from the planned costs due to disruptions. To make the problem tractable the authors assume that disruptions are always handled by delaying flights. Two methods for estimating operational costs are presented which are both based on simulation. Computational results are presented showing improvements in cost and percentage of flights on time.

Schaerf, A. and A. Meisels. (1999). "Solving Employee Timetabling Problems by Generalized Local Search." In *the 6th Congress of the Italian Association for Artificial Intelligence AI*AI 99: Advances in Artificial Intelligence*, Bologna, Italy, Lecture Notes of Artificial Intelligence, Vol. 1792, pp. 380–390.
Notes. The paper describes a number of local search methods for assigning employees to tasks in a set of shifts. Each task occupies a complete shift. Constraints on possible shift patterns are discussed briefly.

Schindler, S. and T. Semmel. (1993). "Station Staffing at Pan American World Airways." *Interfaces* 23, 91–98.
Notes. This paper describes the peculiarities of the Pan Am shift scheduling problem for airport staff, particularly relating to the use of part time staff. The part time shifts may not be adjacent (as this would effectively replace a full time staff) and the number of shift start times is limited. These restrictions are handled by adding some side constraints to the standard set covering formulation for covering the demand given in 15 minute intervals. Shift breaks are determined in a second phase, as the integrated model becomes too large for effective solution.

Schneeweiß, C., S. Loinjak, and G. Muller. (1996). "Determining the Distribution of Yearly Working Time by Shift Plan Optimization." *OR Spektrum* 18, 15–27.
Notes. The authors consider a problem in which a yearly roster needs to be developed for a manufacturing operation. This roster is to be built up from a given set of cyclic roster patterns which can be applied across any number of weeks. The aim is to minimize the amount of overtime and other shift costs given a yearly pattern of labour demand and some restrictions on the use of the patterns. The authors provide a mixed integer linear programming model and develop a problem specific branch and bound algorithm using the LP lower bounds. The detailed discussion of results based on a problem with 15 different roster patterns shows the effect of changing some of the problem data. Note that its paper is written in German except for the abstract.

Schulmerich, S. (1986). "Converting Patient Classification Data into Staffing Requirements for the Emergency Department." *Journal of Emergency Nursing* 12(5), 286–290.
Notes. The objective of this paper is to calculate daily as well as yearly staff requirements from patient classification data.

Scott, S. (1998). "Learning Behaviour in a Case-Based Workforce Scheduler." In *Proceedings of the 17th UK Planning and Scheduling Special Interest Group*.
Notes. This paper discusses the use of case based reasoning for nurse scheduling. A selection of cases (rosters or roster fragments) are generated. The scheduling algorithm produces a new roster by piecing together existing cases. Repairs are made to improve the solution. If deemed appropriate, the final solution is recorded as a new case. The procedure may be iterated to produce alternative, improved solutions or to increase the number of cases.

Scott, S. and R. Simpson. (1998). "Case-Bases Incorporating Scheduling Constraint Dimensions: Ex-

periences in Nurse Rostering." In B. Smyth and P. Cunningham (eds.), *Lecture Notes in Artificial Intelligence*, Vol. 1488. Springer.
Notes. The paper describes a system in which case bases of good patterns of early, late or off shifts are used to limit the search space when building cyclic rosters.

Segal, M. (1974). "The Operator-Scheduling Problem: A Network-Flow Approach." *Operations Research* 22(4), 808–823.
Notes. This paper considers the problem of rostering telephone operators to shifts in such a way that all calls that arrive (for each half hour block in a day) are answered within a prescribed service standard. The paper formulates the daily tour scheduling problem as a network flow model. The out-of-kilter algorithm along with two network flow modelling embellishments provide optimal solutions.

Seitman, D. (1994). "In-House Medical Personnel Scheduler – A Computerized on-Call Scheduling Program." *Internat. J. Clin. Monit. Com.* 11(1), 7–10.
Notes. The paper describes a simple tool for scheduling anaesthesia unit staff to be on call. Leave, simple restrictions on the duty patterns and eligibility to take calls are used to guide a simple search to allocate the most appropriate person to calls as they arrive.

Sellmann, M., K. Zervoudakis, P. Stamatopoulos, and T. Fahle. (2000). "Integrating Direct CP Search and CP-based Column Generation for the Airline Crew Assignment Problem." In *Proceedings of the 2nd International Workshop on the Integration of AI and OR Techniques in Constraint Programming for Combinatorial Optimization Problems*.
Notes. This paper briefly discusses the combination of constraint programming and column generation for crew rostering problems. Limited discussions of the technique and results are included.

Shen, Y. and R. Kwan. (2000). "Tabu Search for Time Windowed Public Transport Driver Scheduling." Technical Report, No. 14, University of Leeds.
Notes. This paper develops a tabu search approach for bus driver scheduling problems with relief opportunity time windows. Previous approaches to bus driver scheduling only include specific time points as relief opportunities. The tabu search heuristic attempts to provide feasible driver duties in such a way that, firstly, the number of duties are minimised and secondly, the total wage cost is minimised.

Shen, Y. and R. Kwan. (2001). "Tabu Search for Driver Scheduling." In S. Voss and J. Daduna (eds.), *Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 505, pp. 121–136. Springer.
Notes. This paper presents a tabu search approach for bus and rail driver scheduling. The paper demonstrates that, although the quality of solutions obtained by the tabu search method is marginally poorer than those that can be obtained from other methods based on integer programming, the heuristic has potential to be further refined. Moreover, it is able to handle soft rules that would otherwise not be possible. Furthermore, the tabu search heuristic, which incorporates an efficient memory structure and a multi-neighbourhood framework, is competitive in terms of computational time.

Shepardson, F. (1985). "Modelling the Bus Crew Scheduling Problem." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 247–261. North-Holland.
Notes. This paper provides a theoretical review of models and algorithms that could be used for crew scheduling, particularly run-cutting, in the context of computerized applications. The drawbacks and advantages of using set covering models and Lagrangean approaches are discussed.

Shepardson, F. and R. Marsten. (1980). "A Lagrangian Relaxation Algorithm for the Two Duty Period Scheduling Problem." *Management Science* 26, 274–281.
Notes. A two duty period shift scheduling problem is formulated as a set partitioning problem with a side constraint. Using the Lagrangean relaxation approach by dualizing the side constraint, the model is transformed into a classical shift scheduling problem that can be solved as a minimal cost network flow problem. A special branching and bound strategy is employed in the computational implementation.

Sherali, H. and M. Rios. (1984). "An Air Force Crew Allocation and Scheduling Problem." *Journal of the Operational Research Society* 35(2), 91–103.
Notes. The authors represent a problem in which both flight times and crew assignments need to be

simultaneously determined for a set of air force missions. In this problem the routes are pre-determined. Each crew needs to rest after each individual flight while the plane continues to complete its mission (round trip) back to the home base. The aim is to maximise plane utilisation (minimise idle time) subject to simple constraints on minimum rest period for crews between flights. The authors provide two related constructive heuristics that iteratively try to re-assign the starting positions of the crew and the missions to planes before determining flight times in chronological order. The heuristics appear to perform well on problems with up to 50 crew, 20 planes and a 90 day planning horizon.

Siferd, S. and W. Benton. (1992). "Workforce Staffing and Scheduling: Hospital Nursing Specific Models." *European Journal of Operational Research* 60(3), 233–246.

Notes. The paper provides a detailed review of the factors influencing the design of nurse rosters. The general characteristics of hospital units (wards) are considered together with the role of OR methodologies in a hospital context.

Siferd, S. and W. Benton. (1994). "A Decision Modes for Shift Scheduling of Nurses." *European Journal of Operational Research* 74(3), 519–527.

Notes. The paper considers methods for determining the numbers of nurses needed in a shift based on patient acuity, patient admissions and discharges around the shift.

Silvestro, R. and C. Silvestro. (2000). "An Evaluation of Nurse Rostering Practices in the National Health Service." *Journal of Advanced Nursing* 32, 525–535.

Notes. The paper reviews different rostering methods: departmental rostering, self rostering and team rostering in terms of their effectiveness and popularity in hospitals.

Sinuany-Stern, Z. and Y. Teomi. (1986). "Multi-Objective Scheduling Plans for Security Guards." *Journal of the Operational Research Society* 37(1), 67–77.

Notes. This paper discusses assigning duties, including training, to security guards in Israel. A multi-objective integer programming formulation is given to describe the problem. A goal-programming algorithm is given which can perform the optimisation. A heuristic algorithm is also given, it is this algorithm which is used in the implementation.

Sitompul, D. and S. Radhawa. (1990). "Nurse Scheduling: A State-of-the-Art Review." *Journal of the Society for Health Systems* 2, 62–72.

Notes. The paper provides a review of some methods for generating cyclic and acyclic nurse rosters, and discusses the relative merits of the methods. The author proposes some form of DSS to allow less restricted rosters to be developed and allow flexible, easy to use systems for developing nurse rosters. The DSS provides assistance to set up the problem and then runs various heuristics or exact algorithms.

Sklar, M., R. Armstrong, and S. Samn. (1990). "Heuristics for Scheduling Aircraft and Crew during Airlift Operations." *Transportation Science* 24(1), 63–76.

Notes. The problem considered in this paper involves assigning crew and flight times to given missions (sequence of flights) such that the number of crew is minimised. This problem is very similar to (Sherali and Rios, 1984) but with a different objective and no freedom in aircraft assignment. The problem is formulated as an MILP. By fixing the flight times, the crew problem can be solved as a simple assignment problem. Similarly for fixed crew assignment optimal flight times can be determined by solving a transshipment problem (or the authors' specialised algorithm). The combined problem is solved by iteratively fixing flight times to optimise crew assignments and vice versa. Results are reported for problems requiring 50 crews and 18 aircraft.

Smith, L. (1976). "The Application of an Interactive Algorithm to Develop Cyclical Rotational Schedules for Nursing Personnel." *INFOR Journal* 14(1), 53–70.

Notes. The paper describes an iterative process for constructing cyclic or non-cyclic rosters to cover a pre-calculated demand. The rosters allow for days off and balanced day, evening and night shifts.

Smith, L. and A. Wiggins. (1977). "Computer-Based Nurse Scheduling System." *Computers and Operations Research* 4(3), 195–212.

Notes. The paper describes a computer system for generating cyclic rosters. Complicated nurse preferences and special requests are entered from data sheets. The algorithm balances staff requirements over different units and then generates rosters by a list processing method. The solution rosters can be manually adjusted.

Smith, B. and A. Wren. (1984). "Computer Scheduling Using the BUSMAN Programs." In *Proceedings of the Sixteenth Annual Seminar on Public Transport Operations Research*.

Notes. The BUSMAN suite of applications deals with route planning, bus scheduling, bus crew scheduling and crew rostering. This paper deals with enhancements to the crew scheduling and crew rostering aspects of the application.

Smith, B. and A. Wren. (1988). "A Bus Crew Scheduling System Using a Set Covering Formulation." *Transportation Research, Part A: General* 22A(2), 97–108.

Notes. This paper presents a method for bus crew scheduling that is based on a set covering formulation of the problem. The problem is one of assigning all runs within bus blocks to crew duties in such a way that the number of duties is minimized and all blocks are covered at minimum overall cost while satisfying all the crew allocation constraints. A set covering formulation is solved by relaxing it as a linear program at the root node. A few constructive heuristics keep the problem down to a manageable size and specialized branch-and-bound method is employed to find an integer optimal solution which also takes into account all the side constraints.

Smith, L., D. Bird, and A. Wiggins. (1979a). "A Computerized System to Schedule Nurses that Recognizes Staff Preferences." *Hospital and Health Services Administration* 24(4), 19–35.

Notes. A computer system is developed for generating monthly shift schedules. A particular feature of this system is that personal preferences such as the vacations, holidays, and special requests are recognized in the scheduling process.

Smith, B., C. Layfield, and A. Wren. (1998). "A Constraint Programming Pre-Processor for a Bus Driver Scheduling System." In *Proceedings of the DIMACS Workshop on Constraint Programming and Large Scale Discrete Optimization*.

Notes. This paper discusses the use of constraint programming to prune the number of relief points for scheduling bus drivers and train crews. The number of relief points, points where crew may be changed, have a substantial impact on the efficiency of the integer programming formulation used to solve the crew rostering problem. Positive results are presented describing gains in efficiency with little reduction in solution quality.

Smith, L., A. Wiggins, and D. Bird. (1979b). "Post-Implementation Experience with Computer Assisted Nurse Scheduling in a Large Hospital." *Information Systems and Operational Research* 17, 309–321.

Notes. The paper describes the long term outcomes of installing a computerised rostering system at a large hospital. The paper provides a very good overview of the factors affecting the acceptance and continued use of a rostering system over a period of three years. Various technical and behavioural factors that may determine the long term success of such a system are discussed.

Sodhi, M.S. (2003). "A Flexible, Fast, and Optimal Modeling Approach Applied to Crew Rostering at London Underground." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 259–281.

Notes. The paper describes a method for rostering crew as an application for London Underground. The authors decompose the overall problem of generating the required cyclic rosters into two stages: generating shift patterns for the entire roster and then assigning specific duties to the resulting patterns. The first stage is solved by forming a directed graph with nodes representing allowed weekly (and multi-week) patterns of early shifts, late shift, night shifts, and rest days, and with arcs representing allowed week-to-week transitions between these patterns. This graph captures the hard constraints in the system. An MILP model is then used to find an optimal cyclic path to cover all the weeks of the roster. The objective, which includes soft constraints, seeks to maximize crew satisfaction by balancing the provision of regular weekends, pairs of rest days, and long weekends. The MILP model provides solutions within minutes for problems with up to 150 drivers within 98 an assignment problem with side constraints also specified as a MILP model and this also solves quickly in seconds within 98 provide the proof of optimality of their method and claim that their method is quite flexible in that it relies on commercial MILP solvers rather than specialized code with the modeling emphasis being mainly in the one-time effort of creating the graph.

Söhngen, L. (1988). “Planning Shift Work and Duty Roster for Personnel with Variable Workload.” In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 119–132. Springer.

Notes. This paper describes processes of generating staff requirements, shift scheduling and roster constructions.

Spyropoulos, C. (2000). “AI Planning and Scheduling in the Medical Hospital Environment.” *Artificial Intelligence in Medicine* 20(2), 101–111.

Notes. This paper provides a review of the research into using AI methods (agent based, machine learning, search) in planning within a hospital environment. It touches on nurse scheduling as well as scheduling of hospital resources.

Stern, H. and M. Hersh. (1980). “Scheduling Aircraft Cleaning Crews.” *Transportation Science* 14(3), 277–291.

Notes. The problem presented consists of assigning workers to cleaning duty for different aircraft as well as a one hour meal break given fixed shift times and cleaning requirements expressed in person-hours per aircraft. All times are discretised in hours and the cleaning duties for each aircraft as well as the meal times have a time window within which they have to be performed. The authors present a neat IP formulation that determines the minimum number of staff required for each shift and their work duties. They then illustrate a number of shortcomings of the solutions of the basic formulation (such as cleaning duties for a single aircraft being split between shifts, as well as frequent stopping and starting on a cleaning job). A significantly more complex formulation is provided that addresses these issues as well as a simple decomposition approach to make the problem tractable to IP solvers available in the late 1970s.

Stojković, M. and F. Soumis. (2001a). “The Operational Flight and Multi-Crew Scheduling Problem.” Technical Report, Les Cahiers du GERAD, École des Hautes Études Commerciales, Montréal, Canada.

Notes. The authors extend their work on operational pilot scheduling (Stojković and Soumis, 2001b) to crew scheduling. The main feature of these problems is that both crew schedules and flight times (within bounds) can be modified to generate an operational schedule. Furthermore, crews need not stay together as they move from one flight to another. Extensive numerical results of the specialised branch and price method described in the paper shows that this method produces better solution than considering crews and flight times in isolation. However, the computational times to obtain optimal solutions are quite large (hours) for the larger problems tested (up to 190 flights) particular as the number of crews considered increases beyond two or three.

Stojković, M. and F. Soumis. (2001b). “An Optimization Model for the Simultaneous Operational Flight and Pilot Scheduling Problem.” *Management Science* 47(9), 1290–1305.

Notes. A model is proposed for solving the pilot scheduling problem on the day of operations while simultaneously considering the option of delaying flights. A branch and price algorithm is described which uses constraint branching and subproblems consisting of shortest-paths with time windows. Extensive numerical results are presented for three data sets with up to 190 flights, 60 pilots and 80 planes demonstrating the effectiveness of the model.

Stojković, M., F. Soumis, and J. Desrosiers. (1998). “The Operational Airline Crew Scheduling Problem.” *Transportation Science* 32(3), 232–245.

Notes. This paper describes in some detail the types of constraints and objectives that arise in creating operational airline crew rosters. The aim is to follow as closely as possible the planned roster while accommodating the disruptions and changes to schedule. A column generation based method is described and used to provide some preliminary results.

Sze, D. (1984). “A Queueing Model for Telephone Operator Staffing.” *Operations Research* 32, 229–249.

Notes. A queueing model approach for calculating staffing requirements in call centres is presented. This model captures the following features: general service times, abandonments, reattempts, nonstationarity, and priority schemes. The Bell System has used the model to reduce the cost of meeting its service criteria for planning purposes.

Tajima, A. and S. Misono. (1997). "Airline Crew-Scheduling Problem with Many Irregular Flights." In *Lecture Notes in Computer Science*, Vol. 1350, pp. 2–11.

Notes. The authors describe the complication to the standard crew scheduling problem created by the presence of many irregular flights on top of the daily repeating flight schedule. They deal with this by first solving a set partitioning problem for the regular and irregular flights separately. The pairings from the solution to the second problem are divided into chunks of work which can then be inserted into pairing of daily flights (possibly pushing out some flights that need to be inserted elsewhere). By repeatedly inserting such segments of flights in a heuristic manner until all flights have been allocated, an efficient solution can be found. Results are reported for up to data sets with about 6000 regular flights (200 per day) and 3000 irregular flights.

Taylor, P. and S. Huxley. (1989). "A Break from Tradition for the San Francisco Police: Patrol Officer Scheduling Using an Optimization-Based Decision Support System." *Interfaces* 19(1), 4–24.

Notes. This paper discusses planning and scheduling police officers. Planning begins with forecasting officer requirements based on incident data. This forecast produces a demand for officers for each hour of the week. An integer programming formulation is then used to schedule officers based on the demand. The scheduling algorithm uses a special purpose heuristic to avoid branch and bound search. This tool has also been applied to more strategic planning. Scenarios evaluated include the change from five 8 hour shifts to four 10 hours shifts and switching from allocating two officers per patrol car to a mixture of two and one officer per patrol car.

Teodorovic, D. (1998). "A Fuzzy Set Theory Approach to the Aircrew Rostering." *Fuzzy Sets and Systems* 95(3), 261–271.

Notes. This paper discusses the application of fuzzy set theory to airline crew rostering. The set membership values are used to consolidate two fairness objectives into one, an assignment problem is then solved to assign crew members to pairings for the current day.

Tharmmaphornphilas, W. and B.A. Norman. (2004). "A Quantitative Method for Determining Proper Job Rotation Intervals." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering.

Notes. The paper discusses the problem of rotating workers between jobs so as to increase work variety, and minimise the performance of repetitive tasks, exposure to noise, and so on. Rotating the workers requires a balance between observing OSHA regulations relating to exposure to industrial hazards and workplace requirements such as setup times as workers move between jobs. Job Severity Indices (or other stress measures) are calculated for different jobs performed over different time intervals and an IP is used to determine rotation patterns that minimise the maximum JSI. Additionally, different IPs are solved using different rotation intervals to demonstrate how choosing different intervals (1 hour, 2 hour, etc.) affects the workers.

Thompson, G. (1993). "Accounting for the Multi-Period Impact of Service when Determining Employee Requirements for Labor Scheduling." *Journal of Operations Management* 11(3), 269–287.

Notes. A new method is introduced for translating customer demand for service into staff requirements. Impacts of service across consecutive planning periods are taken into account by revising customer arrival rates. A queueing model is applied on the revised arrival rates for calculating staff requirements. Simulation experiments show that the new method can improve service productivity.

Thompson, G. (1995a). "Improved Implicit Optimal Modelling of the Shift Scheduling Problem." *Management Science* 41(5), 595–607.

Notes. An implicit modelling technique is presented for solving the shift scheduling problem that may require extensive flexibility of allowing alternate shift starting/finishing times, shift lengths, break/rest placement and overtime. The proposed integer programming model is an generalization of that in (Moondra, 1976; Bechtold and Jacobs, 1990).

Thompson, G. (1995b). "Labor Scheduling Using NPV Estimates of the Marginal Benefit of Additional Labor Capacity." *Journal of Operations Management* 13, 67–86.

Notes. Limitations of the set covering model and its extensions for both shift and tour scheduling problems are identified in this paper. A new formulation is designed to overcome the identified limitations by incorporating measurements of incremental profits if additional staffing requirements are added to planning periods. Simulation experiments demonstrate that the new formulation is superior to the set covering model.

Thompson, G. (1996a). "Controlling Action Times in Daily Workforce Schedules." *Cornell Hotel and Restaurant Administration Quarterly* 40(3), 82–96.

Notes. At shift starting, finishing and break times, the schedule status changes. Frequency of schedule status changes has impacts on the managerial burden and flexibility of having real-time control of the planned schedule. This paper examines how much flexibility can be achieved on schedule status changes without increasing staffing costs. Preemptive-programming formulations are used for this investigation.

Thompson, G. (1996b). "A Simulated-Annealing Heuristic for Shift Scheduling Using Non-Continuously Available Employees." *Computers and Operations Research* 23(3), 275–288.

Notes. The paper discusses a model for scheduling shifts using employees that are available for only individually specified times. The paper provides a very good discussion of the implementation of a SA heuristic for this class of problems.

Thompson, G. (1997a). "Assigning Telephone Operators to Shifts at New Brunswick Telephone Company." *Interfaces* 27(4), 1–11.

Notes. This paper describes the problem of assigning shifts to call centre operators to meet their preferences. Having already determined the necessary shifts to meet forecast demand these shifts must be allocated to individual employees. By reflecting employee preferences this can greatly improve staff satisfaction. A goal programming formulation is given in which the seniority of the employee determines their priority in the objective function. Rather than employ branch-and-bound search a randomised construction heuristic generates assignments combined with a simple repair heuristic which improves solution quality/feasibility. This process is iterated until a time limit is reached.

Thompson, G. (1997b). "Labor Staffing and Scheduling Models for Controlling Service Levels." *Naval Research Logistics* 44(8), 719–740.

Notes. Two new models are presented for shift and tour scheduling problems. The interesting part of this paper is to take service levels into account when generating optimal shifts or tours. This is done by allowing staff requirements to be variables. This work can be viewed as an integrated model of considering demand modelling and shift/tour scheduling simultaneously.

Thompson, G. (1998a). "Labor Scheduling: Forecasting Demand." *Cornell Hotel and Restaurant Administration Quarterly* 39(5), 22–31.

Notes. The paper discusses the steps needed to forecast demand. The process is broken down into eight steps: determining the nature of the work, identifying the labour drivers, determine whether these drivers are time invariant, determine time interval for tracking time-variant drivers, forecast the time-variant drivers, smooth driver variability, check the accuracy of forecasts, and define the time periods for the actual work.

Thompson, G. (1998b). "Labor Scheduling: Knowing How Many on-Duty Employees to Schedule." *Cornell Hotel and Restaurant Administration Quarterly* 39(6), 26–37.

Notes. The paper considers the factors to be taken into account when determining the number of staff needed to provide a service at levels that meet specified productivity, service quality and economic standards.

Thompson, G. (1999a). "Labor Scheduling: Controlling Workforce Schedules in Real Time." *Cornell Hotel and Restaurant Administration Quarterly* 40(3), 85–96.

Notes. In contrast to most work done in scheduling and rostering, this work discusses the real-time control of the schedule, in which the managers assesses whether the schedule is ensuring that customers are actually serviced as planned. Some actions that managers can take are suggested when demand does not match the planned schedule.

Thompson, G. (1999b). "Labor Scheduling: Developing a Workforce Schedule." *Cornell Hotel and Restaurant Administration Quarterly* 40(1), 86–96.

Notes. This paper explains the considerations for creating the schedule that account for employees' availability and preferences while also meeting the organization's specific service and economic objectives.

Thompson, G. (2002). "Reflections on Workforce Scheduling." Working Paper.

Notes. This paper contains a "personal reflection on the state of the art in workforce scheduling" by the author. While initially appearing a little simple, the points made in the paper are in fact very pertinent, particularly with respect to the different expectations of journal editors and managers with staff to roster.

Thornton, J. and A. Sattar. (1996). "An Integer Programming-Based Nurse Rostering System." In *Concurrency and Parallelism, Programming, Networking, and Security*, Lecture Notes in Computer Science, Vol. 1179, pp. 357–358. Springer.

Notes. The paper provides a very brief outline of an IP formulation of a very generally defined rostering problem.

Tibrewala, R., D. Philippe, and J. Browne. (1972). "Optimal Scheduling of Two Consecutive Idle Periods." *Management Science* 19(1), 71–75.

Notes. A simple algorithm is designed for finding the minimum workforce size and an optimal schedule for a days-off scheduling problem in which each worker has exactly one consecutive two-days off each week.

Tien, J. and A. Kamiyama. (1982). "On Manpower Scheduling Algorithms." *SIAM Review* 24(3), 275–287.

Notes. The general manpower scheduling problem is decomposed into five stages. A systematic review of available manpower scheduling models and algorithms is provided from the five-stage framework.

Tingley, G. (1979). "Still Another Solution Method for the Monthly Aircrew Assignment Problem." In *1979 AGIFORS Symposium Proceedings*, Vol. 19, pp. 143–203.

Notes. This paper provides details of a method to roster crew at Swiss Air which was never implemented. The algorithm, based on solving sequential assignment and network flow problems to assign pairings to pilots, has been superseded by advances in computing and OR algorithms.

Topaloglu, S. and I. Ozkarahan. (1998). "A Research on Optimization Based Modeling for Tour Scheduling Problems with Flexible Break Assignments." In *the Proceedings of the 7th Annual Industrial Engineering Research'98 Conference*, Banff, Alberta, Canada.

Notes. Alternative implicit models are provided for both shift and tour scheduling problems. The extension for tour scheduling is based on (Bailey and Field, 1985; Bechtold and Jacobs, 1990). An alternative to the implicit model of (Aykin, 1996) is proposed for shift scheduling.

Topaloglu, S. and I. Ozkarahan. (2000). "A Goal Programming Approach for Large-Scale Tour Scheduling Problems with Flexible Break Assignments." In *the Proceedings of the 31st Annual Meeting of the Decision Sciences Institute*, Orlando, FL.

Notes. A goal programming approach is presented for tour scheduling. It has the following three stages: formulate the goal programming models for both days-off and shift scheduling problems; perform integration of these goal programming models; develop heuristic to assign start times and break periods to the days of optimum work patterns.

Topaloglu, S. and I. Ozkarahan. (2004). "An Implicit Goal Programming Model for the Tour Scheduling Problem Considering the Employee Work Preferences." *Annals of Operations Research* 128, Special Issue on Staff Scheduling and Rostering, 135–158.

Notes. This paper presents a goal programming model for the tour scheduling problem that implicitly represents scheduling flexibility and also incorporates information about the preferred working patterns of employees. After solving the proposed model, a work schedule will be generated for each employee without requiring a further step for the assignment of shifts, break times, and work days to employees. The model is capable of handling multiple scheduling objectives, and it can produce optimal solutions rapidly in very short computing times.

Tosini, E. and C. Vercellis. (1988). "An Interactive System for Extra-Urban Vehicle and Crew Scheduling Problems." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in

Economics and Mathematical Systems, Vol. 308, pp. 41–53. Springer.
Notes. This paper presents a heuristic algorithm for solving crew scheduling problems in mass transit applications. The interactive, two-stage solution process, which has been applied to mass transit organizations in Italy, is formulated as an integer program. First, a set of feasible duties is generated. Then a randomised heuristic procedure assigns trips to duties by repeatedly solving M-best bipartite b-matching problems.

Townsend, W. (1988). "An Approach to Bus-Crew Roster Design in London Regional Transport." *Journal of the Operational Research Society* 39(6), 543–550.
Notes. The paper provides a description of the crew rostering problem at London Regional Transport. This model is used after crew scheduling has been attempted and completed, and involves the issue of stringing together a series of weekday and weekend crew duties in such a way that duties are covered and there is an equitable work-spread amongst the workforce.

Trivedi, V. and D. Warner. (1976). "A Branch and Bound Algorithm for Optimum Allocation of Float Nurses." *Management Science* 16(10), 972–981.
Notes. The paper describes the use of an IP model for allocating nurses from a float pool to cover fluctuations in demand arising from variations in patient care needs across shifts.

Tsang, E. and C. Voudouris. (1997). "Fast Local Search and Guided Local Search and Their Application to British Telecom's Workforce Scheduling Problem." *Operations Research Letters* 20(3), 119–127.
Notes. The paper describes a system using fast guided local search algorithms to schedule British Telecom engineers to a set of jobs. The jobs are specified by location, duration and type (morning or afternoon). Results are presented for a problem with 118 engineers and 250 jobs where each job can be served by, on average, 28 engineers.

Tykulsker, R., K. O'Neil, A. Ceder, and Y. Sheffi. (1985). "A Commuter Railway Crew Assignment/Work Rules Model." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 233–246. Elsevier Science.
Notes. This paper constructs rail crew schedules and rosters. An enumeration approach, controlled by user-parameters, is used to construct and cost a set of feasible crew duties. This set is reduced with the help of heuristic procedures. A set covering problem is used to select for the best from the remaining set of possible crew duties. This program was developed for and implemented at New Jersey Transit Corporation.

Vairaktarakis, G., X. Cai, and C. Lee. (2002). "Workforce Planning in Synchronous Production Systems." *European Journal of Operational Research* 136(3), 551–572.
Notes. This paper discusses assignment of workforce to stations in an assembly line. The models determine the number of staff to be assigned to stations in order to minimise cost and meet pacing requirements.

Valls, V., A. Perez, and S. Quintanilla. (1996). "A Graph Colouring Model for Assigning a Heterogeneous Workforce to a Given Schedule." *European Journal of Operational Research* 90(2), 285–302.
Notes. This paper considers assigning a multiple-skilled workforce to various activities characterized by skills required and starting and finishing times. A branch and bound method based on a colouring model is used for determination of the minimum number of workers required to perform all given activities.

Valouxis, C. and E. Housos. (2000). "Hybrid Optimization Techniques for the Workshift and Rest Assignment of Nursing Personnel." *Artificial Intelligence in Medicine* 20(2), 155–175.
Notes. The paper describes a hybrid system in which an approximate IP is used to generate feasible rosters and these solutions are improved using tabu search, local search and 2-opt heuristics. Rosters are constructed from sets of allowed day, evening, night shift patterns separated by days off. The objective minimises the number of work shifts for all nurses over the planning horizon. Examples are given of solutions for rostering 16 nurses over a 28 day planning horizon.

Valouxis, C. and E. Housos. (2002). "Combined Bus and Driver Scheduling." *Computers and Operations Research* 29(3), 243–259.
Notes. In this paper, the authors present and solve a combined bus and crew scheduling model. This is

necessitated by the fact that in the application of interest (in Greece) it is for crew to be attached to the same bus. An IP model is presented for the combined problem. A quick search constructive heuristic is first developed for the problem. This commences with the partitions of the trips into 'levels.' These levels are then used to develop a matching-based assignment algorithm of trips to shifts. The solutions are improved using a 2-opt and 3-opt heuristic. The paper also describes a column generation approach in which the LP relaxation of the IP model is solved with a column creation scheme and the quick search heuristic to obtain integer solutions.

Vance, P., C. Barnhart, E. Johnson, and G. Nemhauser. (1997). "Airline Crew Scheduling: A New Formulation and Decomposition Algorithm." *Operations Research* 45(2), 188–200.
Notes. This paper describes a variation to the standard branch and price approach for crew scheduling. In this method flights are first grouped into duties (shifts) using a set partitioning formulation and then duties are formed into pairings. To speed up the solution of pairing problem a key set approach is used in which the problem is formulated in terms of deviation from an initial (key) set of pairings. Results for domestic problems with up to 174 flights are reported.

Vandenberg, Y. and D. Panton. (1994). "Personnel Shift Assignment: Existence Conditions and Network Models." *Networks* 24(7), 385–394.
Notes. This paper considers existence conditions and network based techniques for the assignment of shifts to cyclic rosters in which the day-on and day-off patterns have already been constructed. Conditions under which both acyclic and cyclic lines of work can be obtained are both examined. The results of extensive experiments which apply the network based algorithms for implementing the assignments are discussed.

VanGilder, K. and J. Usher. (1996). "Using Factory Flow to Predict Material Handling Manpower Requirements for a Future Increase in Production." In *International Industrial Engineering Proceedings of the 1996 47th International Industrial Engineering Conference and Exposition*, pp. 121–130.
Notes. Four alternative operation policies are evaluated in order to minimize material handling manpower at a company that supplies large stampings for the automotive industry.

VanOudheusden, D. and W. Wen-Jenq. (1982). "Telephone Operator Scheduling with a Fixed Number of Operators." *European Journal of Operational Research* 11, 55–59.
Notes. This paper focuses on the problem of dividing the demand of call centre operators into demand for shifts given a limited number of operators. Several integer programming formulations are reviewed and comparisons between them are drawn in terms of number and kind of variables and in terms of execution time. The paper discusses solving one of the models using rounding and permutations of the objective function rather than using a branch and bound algorithm to find integer optimal solutions.

Venkataraman, R. and M. Brusco. (1996). "An Integrated Analysis of Nurse Staffing and Scheduling Policies." *Omega* 24(1), 57–71.
Notes. The paper focuses on the analysis of policies for nurse workforce management. A mathematical model of a general scheduling problem arising from the analysis is also given.

Verbeek, P.J. (1991). "Decision Support Systems – An Application in Strategic Manpower Planning of Airline Pilots." *European Journal of Operational Research* 55(3), 368–381.
Notes. The author discusses the idea of Decision Support Systems in general and the application to manpower planning at KLM airlines in particular. The problem involves deciding on how the workforce of pilots should change through a combination of training and recruitment to cover expected changes in fleet over a 10 year period. Various subproblems are described which are solved heuristically with opportunity for human intervention.

Vohra, R. (1987). "The Cost of Consecutivity in the (5, 7) Cyclic Staffing Problem." *IIE Transactions* 19(3), 296–299.
Notes. A mathematical expression of calculating the minimum workforce size is derived in order to generate a days-off schedule in which each employee works five consecutive days and takes two consecutive days off. Here demands during the week are variable.

Vohra, R. (1988). "A Quick Heuristic for Some Cyclic Staffing Problem with Breaks." *Journal of Operational Research Society* 39, 1057–1061.

Notes. The paper describes a heuristic, set covering method applied to cyclic rosters with specified days off and rest breaks in shifts.

Volker, M. and P. Schutze. (1995). "Recent Developments of HOT II." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 334–348. Springer.

Notes. The paper describes extensions and enhancements to the HOT system for transit vehicle and crew scheduling. The enhancements have affected all parts of the system and made it more usable. In particular, the crew scheduling and crew rostering modules have been enhanced. The crew scheduling and crew rostering components are carried out within an interactive framework.

Wallis, H. (1985). "Experiences in Computer Assisted Scheduling Installations in North America." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 11–18. North-Holland.

Notes. This paper describes a scheduling system that has been developed, implemented and being used at a few businesses in North America.

Ward, R., P. Durant, and A. Hallman. (1981). "Problem Decomposition Approach to Scheduling the Drivers and Crew of Mass Transit Systems." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 297–312. Amsterdam: North-Holland.

Notes. This paper decomposes the bus crew scheduling problem into two parts. The first part schedules the late and middle duties using a set partitioning approach, while the second part heuristically refines the duties to form a workable schedule.

Wark, P., J. Holt, M. Rönnqvist, and D. Ryan. (1997). "Aircrew Schedule Generation Using Repeated Matching." *European Journal of Operational Research* 102(1), 21–35.

Notes. The crew scheduling problem considered in this paper is a variation of the standard problem in which a third pilot may optionally be used in addition to the standard two pilot crews in order to allow longer duty periods. A heuristic algorithm is described by the authors which starts with each segment being a separate pairing and then iteratively combines pairings using a perfect matching algorithm until no improvement in cost can be achieved. The solution is then perturbed by breaking pairings heuristically and another set of local search iterations is run. The complication introduced by the possibility of using a third pilot is handled by switching back and forth between creating crew pairings and third pilot pairings. Computational results are presented for a data set with 203 flight legs, which indicate that better results are achieved by the heuristic than by the human schedulers or a restricted column generation approach.

Warner, D. (1976a). "Nurse Staffing, Scheduling, and Reallocation in the Hospital." *Hospital and Health Services Administration* 21(3), 77–90.

Notes. This paper reviews three topics in the area of nurse scheduling: Nurse staffing requirement and workforce planning; Nurse scheduling; and Nurse reallocation by assigning floating nurses in order to cope with variability of demand.

Warner, D. (1976b). "Scheduling Nursing Personnel According to Nursing Preference: A Mathematical Programming Approach." *Operations Research* 24(5), 842–856.

Notes. The paper describes the processes involved in formulating the objective and constraints for a nurse rostering system. Nurse preferences are captured via a sheet that the nurses use to rank their aversions to certain shift patterns. The objective is to provide coverage for different nurse grades. The IP is solved using a specially designed (Balinty and Blackburn) algorithm. Examples are given of the implementation of the system in several hospitals.

Warner, D. and J. Prawda. (1972). "A Mathematical Programming Model for Scheduling Nursing Personnel in a Hospital." *Management Science* 19(4), 411–422.

Notes. The paper describes the IP formulation of a model for nurse rosters designed to minimise the shortage cost of nurses over a given planning period. Demand for nurses is assumed to be known. Constraints relating to capacity and substitutions between different nurse grades are considered. The problem is posed as a mixed integer quadratic programming problem. This problem is decomposed into a multiple choice programming problem with quadratic subproblems. Results are presented for rosters developed for six wards in a 600 bed hospital.

Warner, M., B. Keller, and S. Martel. (1991). "Automated Nurse Scheduling." *Journal of the Society for Health Systems* 2(2), 66–79.

Notes. This paper reviews various issues involved in developing and implementing nurse scheduling systems. The review reflects many of the issues relating to computer implementations of rostering and hospital systems in the early 1990s.

Weaver, A. and A. Wren. (1970). "Scheduling Buses and Their Crews." In *Proceedings of PTRC Symposium on Public Road Transport Analysis*, pp. 58–63.

Notes. The authors first describe the general process of developing bus and crew schedules before concentrating on a method for developing crew schedules, given a vehicle schedule. In particular this paper develops a constructive method for delivering solutions after peak period allocations are handled. The schedule is then improved using one of four methods.

Wedelin, D. (1995). "An Algorithm for 0–1 Programming with an Application to Airline Crew Scheduling." *Annals Operational Research* 57, 283–301.

Notes. The author presents a novel algorithm for solving set partitioning and set covering problems. The algorithm is based on co-ordinate ascent for the Lagrangean dual. The main feature is the use of a perturbation parameter to guide the algorithm to a primal feasible solution. Depending on the value of the perturbation parameter the algorithm, can also be interpreted as a dynamic programming or greedy method. For more implementation details and extensions of this method, see (Sanders et al., 1999; Mason, 2001).

Wei, G., G. Yu, and M. Song. (1997). "Optimization Model and Algorithm for Crew Management during Airline Irregular Operations." *Journal of Combinatorial Optimization* 1, 305–321.

Notes. The problem of repairing crew schedules for an airline after a disruption has occurred is discussed in this paper. The authors present a depth first branch and bound algorithm that can quickly generate one or more feasible solutions. The initial repair of broken pairings and further pairing generation is performed using a shortest-path algorithm. The authors also provide detailed results of their method.

Weil, G., K. Heus, P. Francois, and M. Poujade. (1995). "Constraint Programming for Nurse Scheduling." *IEEE Engineering in Medicine and Biology* 14(4), 417–422.

Notes. This paper describes how to solve a typical nurse scheduling formulation using CLP. The paper covers the constraints and implementation in some detail. However, the discussion of results is limited.

Weir, J.D. and E.L. Johnson. (2004). "A Three-Phase Approach to Solving the Bidline Problem." *Annals of Operations Research* 127, Special Issue on Staff Scheduling and Rostering, 283–308.

Notes. This paper describes a three phase approach for solving the airline crew rostering problem. In order to address quality of life as well as crew fatigue issues, a new set of rules are introduced. Integer linear programming approaches are used for solving all subproblems in the three phases.

Wermus, M. and J. Pope. (1994). "Scheduling Harbor Pilots." *Interfaces* 24(2), 44–52.

Notes. A cyclic roster for harbour pilots is generated using a simple heuristic algorithm. A roster is a sequence of on days, off days and stand-by days. Having stand-by days is a distinguished feature that is not considered in the traditional days-off scheduling problem.

Willers, W., G. Proll, and A. Wren. (1995). "A Dual Strategy for Solving the Linear Programming Relaxation of a Driver Scheduling System." *Annals of Operations Research* 58, 519–531.

Notes. In this paper, the authors present a mathematical programming framework for solving bus driver scheduling problems. The underlying model is a combination of set partitioning and set covering constraints. The model accommodates two objective functions – cost minimization and driver number minimization. Along with two construction heuristics, this paper also describes a dual simplex approach for solving the model.

Williamson, R. (1985). "BUSMAN: The United Kingdom's Integrated Approach to Transit Scheduling." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 19–43. North-Holland.

Notes. This paper presents a detailed overview of BUSMAN, an integrated bus fleet and crew scheduling system which had, at the time of publishing this paper, been implemented at various client sites in the UK. The paper provides a system view of the software, including inputs, outputs and links between the various optimization modules contained in BUSMAN. Typical output reports are also provided in this paper.

Willis, R. and S. Huxford. (1991). "Staffing Rosters with Breaks: A Case Study." *Journal of the Operational Research Society* 42(9), 727–731.
Notes. A shift scheduling problem is formulated as a set covering model. An integer programming approach is presented for automatically generating rosters of full time and part time call centre staff. The paper considers the placement of shifts and break times and uses the concept of restricted shift start times to cover for fluctuating workforce demand. The model was applied to call centres in Australia.

Wilson, E. and R. Willis. (1983). "Scheduling of Telephone Betting Operators – A Case Study." *Journal of the Operational Research Society* 34(10), 991–998.
Notes. This paper describes the task of scheduling operators for a betting organisation. Telephone betting is subject to extreme peaks in demand, making forecasting difficult. Once estimated the demand is used to perform shift scheduling using typical integer programming techniques.

Wilson, L., P. Prescott, and L. Aleksandrowicz. (1988). "Nursing: A Major Hospital Cost Component." *Health Services Research* 22(6), 773–796.
Notes. The paper discusses a number of the costs associated with the provision of nursing care including DRG, LOS and other measures of patient illness. Not specifically associated with nurse rostering but useful for an understanding of some of the costs that may appear in a rostering application/product.

Wolfe, H. and J. Young. (1965a). "Staffing the Nursing Unit, Part I: Controlled Variable Staffing." *Nursing Research* 14(3), 237–243.
Notes. The paper describes different factors that need to be taken into account to be able to define an index of care so as to determine the nursing levels needed to deal with the variation in patient numbers and acuity resulting from emergency admissions.

Wolfe, H. and J. Young. (1965b). "Staffing the Nursing Unit, Part II: The Multiple Assignment Technique." *Nursing Research* 14(3), 299–303.
Notes. The paper describes a model for the assignment of nursing and clerical ward staff to multiple tasks needed to care for, admit and discharge, patients in a ward.

Worthington, D. and M. Guy. (1988). "Allocating Nursing Staff to Hospital Wards: A Case Study." *European Journal of Operational Research* 33, 174–182.
Notes. A constructive approach is proposed to estimate daily nursing workloads on hospital wards. The fundamental idea of this study is that patients can be categorized according to their level of dependency on nurses.

Wren, A. (1968). "A Review of Computer Scheduling of Buses and Crews." In *Proceedings of Public Transport Analysis Seminar*, pp. 42–47.
Notes. This is one of the earliest review papers in Bus driver scheduling. This paper was, preceded – to the best of our knowledge – only by (Elias, 1964; Bennett and Potts, 1967, 1968) in the published literature. In this paper, the author first describes the unpublished constructive heuristic that Deutsch developed while at London Transport. The paper also reviews the earlier published works in the literature.

Wren, A. (1974). "Computer Scheduling of Buses and Crews: A Review." In *Proceedings of the Sixth Annual Seminar on Public Transport Operations Research.*
Notes. This review of research into bus and bus driver scheduling focuses heavily on the authors own work in bus scheduling. It has been superseded by (Wren, 1981b).

Wren, A. (1975a). "Bus Crew Scheduling by Computer: A Pilot Study for Greater Manchester Transport." Technical Report, University of Leeds, Operational Research Unit Report ULORU-17.
Notes. This technical report gives the results of a pilot study in which some test data sets from Greater Manchester Transport were run through the author's computer software to create bus schedules and crew duties.

Wren, A. (1975b). "Scheduling by Computer – Buses and Crews: A Report on a Pilot Study Undertaken

for London Transport." Technical Report, University of Leeds, Operational Research Unit Report ULORU-15.
Notes. This technical report gives the results of a pilot study in which some test data sets from London Transport were run through the author's computer software to create bus schedules and crew duties. The results indicate that considerable additional work was needed before the software could be used by London Transport on a regular basis.

Wren, A. (1976). "Bus Crew Scheduling by Computer: A Report on a Pilot Study Undertaken for Coras Iompair Eireann, Dublin City Services." Technical Report, University of Leeds, Operational Research Unit Report ULORU-20.
Notes. This technical report documenting work carried out in bus driver scheduling for the Dublin City Services. It documents some of the idiosyncracies of Dublin's bus driver problem and how the driver pairing generation algorithm was adapted to meet these.

Wren, A. (ed.). (1981a). *Computer Scheduling of Public Transport. Urban Passenger Vehicle and Crew Scheduling: International Workshop Held at the University of Leeds*. Amsterdam: North-Holland.
Notes. This paper reviews the progress made in bus and driver scheduling during the 1960s and 1970s using methods such as heuristic search and set covering based approaches.

Wren, A. (1981b). "A General Review of the Use of Computers in Scheduling Buses and Their Crews." In A. Wren (ed.), *Computer Scheduling of Public Transport, Urban Passenger Vehicle and Crew Scheduling*, pp. 3–16. Amsterdam: North-Holland.
Notes. This paper provides a brief review of work in the area of bus scheduling and bus crew scheduling up to 1975. It particularly focuses on work presented at the "Workshop of Automated Techniques for Scheduling of Vehicle Operators for Urban Public Transportation Services," held in Chicago in 1975.

Wren, A. (1987). "Vehicle and Crew Scheduling." In H. Keller (ed.), *Heureka'87 – Optimierung in Verkehrund Transport*, pp. 475–496.
Notes. This is a summary of the authors previous work in bus and bus driver scheduling. Methods reviewed include local search, mathematical programming (set covering) and interactive methods. The fact that local search works well for the loosely constrained bus scheduling problem but poorly for the much tighter driver scheduling problems receives special attention.

Wren, A. (1994). "Experiences with Genetic Algorithms for Bus Driver Scheduling." In *Proceedings of Conference on Adaptive Computing and Information Processing*, pp. 373–392.
Notes. An evolutionary algorithm for pairing optimization is described in this paper. Given a set of shifts, a subset is to be selected that covers all bus work segments. Individuals in the population are represented by sets of shifts, with offspring being created by selecting a cover from the union of two or three parents. Some computational results are produced to show that this type of algorithm produces reasonable results.

Wren, A. (1996). "Scheduling, Timetabling and Rostering – A Special Relationship?" In *Proceedings of the 1995 1st International Conference on Practice and Theory of Automated Timetabling*, Lecture Notes in Computer Science, Vol. 1153, pp. 46.
Notes. This paper explores the relationships between vehicle scheduling, job-shop scheduling, driver scheduling and personnel scheduling. While common methods such as simple heuristics, mathematical programming and meta-heuristics are regularly employed for some problem types, their degree of success has varied considerably across the problem types.

Wren, A. and P. Beecken. (1992). "Towards a European Standard for Scheduling." In M. Desrochers and J.Rousseau (eds.), *Computer-Aided Transit Scheduling – 2*, pp. 305–329. Springer.
Notes. This technical report gives some history of an IT project to develop a modular software system (CASSIOPE) for European public transport operators. It describes the history of this project, some of the data and integration issues and provides a comparison of two bus/driver scheduling systems that had been developed by members of the consortium.

Wren, A. and M. Chamberlain. (1988). "The Development of Micro BUSMAN: Scheduling on Micro-Computers." In J. Daduna and I. Wren (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 308, pp. 160–174. Springer.

Notes. This paper describes how the BUSMAN bus and driver scheduling software has been ported from a main-frame to a PC environment.

Wren, A. and N. Gualda. (1999). "Integrated Scheduling of Buses and Drivers." In N. Wilson (ed.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 471, pp. 155–178. Springer.

Notes. This paper describes the implementation of the software suite, developed over the years at Leeds University, at bus companies in three Brazilian cities. Given the particular operational processes and rules in these Brazilian cities, the computer software had to be modified slightly to offer an integrated bus and crew scheduling system. The new system resulted in initial bottom-line savings estimates of between 3–5%.

Wren, A. and R. Kwan. (1999). "Installing an Urban Transport Scheduling System." *Journal of Scheduling* 2, 3–17.

Notes. This paper describes the development and implementation of a computerised system for bus scheduling and bus crew scheduling. The paper draws on research that has been carried out by the authors in the past in this area. This paper documents particular implementation issues that deal with, amongst other things, contractual issues, proactive behaviour on the part of the implementing team, enthusiasm by the technology receptors and clever user interface development.

Wren, A. and J. Rousseau. (1995). "Bus Driver Scheduling – An Overview." In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling: Proceedings of the Sixth International Workshop on Computer-Aided Scheduling of Public Transport*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 173–187. Berlin: Springer.

Notes. The paper reviews the characteristics of the bus driver scheduling problem and the software systems that have been implemented to solve the problem.

Wren, A. and B. Smith. (1988). "Experiences with a Crew Scheduling System Based on Set Overing." In J. Daduna and A. Wren (eds.), *Computer-Aided Transport Scheduling*, pp. 104–118. Springer.

Notes. This paper summarises descriptions of the techniques used by the IMPACS bus driver scheduling software which have been published in other articles on this subject. An overview of the authors' current work in applying this software is also given.

Wren, A. and D. Wren. (1995). "A Genetic Algorithm for Public Transport Driver Scheduling." *Computers and Operations Research* 22(1), 101–110.

Notes. The authors describe a genetic algorithm for solving the set covering problem arising in bus crew scheduling. The set of feasible shifts is generated by the IMPACS system. Each member of the population consists of a set of shifts which cover all of the duties. Crossover consists of taking the union of two to five parents and eliminating shifts while this can be done without leaving any duties uncovered. This method is illustrated on a single data set with 539 shifts (columns).

Wren, A., R. Kwan, and M. Parker. (1994). "Scheduling of Rail Driver Duties." In T. Murthy, B. Mellitt, C. Brebbia, G. Sciutto, and S. Sone (eds.), *Computers in Railways – IV*, Vol. 2, pp. 81–89.

Notes. This paper presents a model that has been developed for delivering the number and types of shifts that are required to operate a train schedule. The method that is described in this paper is a modification of a method developed by some of the authors for bus driver scheduling, which involves solving a combination of a genetic algorithm and a set covering formulation.

Wren, A., B. Smith, and A. Miller. (1985). "Complementary Approaches to Crew Scheduling." In J. Rousseau (ed.), *Computer Scheduling of Public Transport 2*, pp. 45–52. North-Holland.

Notes. A set covering formulation for the bus driver pairing optimisation problem is presented in this paper. The problem is made tractable by severely limiting the set of shifts available. The choice of parameters for the ZIP software which solves the IP is also discussed. An interactive heuristic approach to the pairing optimisation problem is introduced briefly but not compared to the IP method.

Wright, M. (1991). "Scheduling English Cricket Umpires." *Journal of the Operational Research Society* 42(6), 447–452.

Notes. This paper discusses the assignment of cricket umpires to matches. An initial solution is constructed randomly and then local search is used to improve the solution.

Yan, S. and J. Chang. (2002). "Airline Cockpit Crew Scheduling." *European Journal of Operational Research* 136(3), 501–511.

Notes. This paper presents a case study of cockpit crew scheduling for C-Airlines. The set partitioning formulation is solved using a branch and price algorithm with a shortest path method for generating new pairings. Numerical results are presented for the international operations of C-Airlines.

Yan, S. and Y. Tu. (2002). "A Network Model for Airline Cabin Crew Scheduling." *European Journal of Operational Research* 140(3), 531–540.

Notes. Unlike most crew scheduling problems, the crew scheduling problems arising from China Airlines can be formulated as a pure network flow problem, which can be solved efficiently using a network simplex method.

Yan, S., T. Tung, and T. Tu. (2002). "Optimal Construction of Airline Individual Pairings." *Computers and Operations Research* 29(4), 341–363.

Notes. The authors present a detailed case study of crew scheduling for China Airlines. A set covering formulation is used to model the integrated problem of scheduling crews from multiple home bases for multiple cabin classes and aircraft types. The formulation is solved with a branch and price algorithm that uses a shortest path method to generate new columns.

Yang, R. (1996). "Solving a Workforce Management Problem with Constraint Programming." In *the 2nd International Conference on the Practical Application of Constraint Technology*, pp. 373–387. The Practical Application Company Ltd.

Notes. This paper discusses assignment of maintenance tasks to field engineers. Constraint programming is used to find the allocation which minimises the number of un-allocated tasks. Labelling strategies and propagation algorithms are discussed.

Yen, J. and J. Birge. (2000). "A Stochastic Programming Approach to the Airline Crew Scheduling Problem." Technical Report, University of Michigan.

Notes. This paper proposes a stochastic crew scheduling model for integrating disruptions and uncertainties in the evaluation of crew schedules, and devises a branching algorithm for solving the model. The proposed model is a standard two-stage stochastic integer program with recourse. Significant savings can be gained if delay effects on crew schedules are considered during the planning phase of crew scheduling.

Yunes, T. (2000). "Urban Transit Crew Management Problems: Constraint Logic Programming and other Techniques." Ph.D. Thesis, Institute of Computing, University of Campinas.

Notes. This dissertation studies a real world crew management problem for an urban transit bus company in Brazil. Two subproblems considered are crew scheduling and crew rostering. Each of these two problems are solved using mathematical programming, constraint logic programming, and a combination of both MP and CLP. Numerical results show that the combining method performed much better than the two approaches when taken in isolation.

Yunes, T., A. Moura, and C. de Souza. (1999). "Solving Large Scale Crew Scheduling Problems with Constraint Programming and Integer Programming." Technical Report, University of Campinas.

Notes. This paper discusses the evolution of a column generation approach for solving a bus driver rostering problem. The progression of the paper includes pure integer programming formulation, a cute constraint programming formulation, and finally a hybrid formulation using constraint programming for column generation and integer programming for set partitioning. Analysis is made of the relative efficiencies, with very positive results for the combined method.

Yunes, T., A. Moura, and C. de Souza. (2000a). "A Hybrid Approach for Solving Large Scale Crew Scheduling Problems. In E. Pontelli and S. Vitor (eds.), *Lecture Notes in Computer Science*, Vol. 1753, pp. 293–307. Springer.

Notes. The authors present a set partitioning formulation for the bus driver scheduling problem which is solved using column generation. Two alternative methods for solving the column generation subproblem are compared. The first uses a constraint shortest path (dynamic programming) while the second uses a CLP formulation to find a set of feasible solutions (columns) with negative reduced cost. The results show that the CLP approach is much faster at generating new columns allowing larger problems to be solved more quickly.

Yunes, T., A. Moura, and C. de Souza. (2000b). "Hybrid Column Generation Approaches for Solving Real World Crew Management Problems." Technical Report, University of Campinas.

Notes. A crew management problem is divided into a crew scheduling and a crew rostering problem. Each of these two problems are solved using both mathematical programming and constraint logic programming. Hybrid methods using both column generation and constraint logic programming are designed for both crew scheduling and crew rostering problems. Numerical experiments are performed on real data in a bus company. Numerical results show that the proposed hybrid methods for both crew scheduling and rostering problems outperform either the column generation approach or the constraint logic programming method in isolation.

Yunes, T., A. Moura, and C. de Souza. (2000c). "Modeling and Solving a Crew Rostering Problem with Constraint Logic Programming and Integer Programming." Technical Report, University of Campinas.

Notes. This report provides some additional detail regarding the integer programming and constraint programming formulations used by these authors in (Yunes et al., 2000b). These are based on the ideas for crew scheduling in (Yunes et al., 2000a, 2000d) but applied to crew rostering. The results indicate that the constraint programming approach appears to be more effective in finding feasible solutions. The report also discusses some initial work towards developing a hybrid branch and price algorithm.

Yunes, T., A. Moura, and C. de Souza. (2000d). "Solving Very Large Crew Scheduling Problems to Optimality." In *Proceedings of the 15th ACM Symposium on Applied Computing*.

Notes. The crew scheduling problem for bus drivers is solved by a hybrid method. The master problem is a set partitioning problem while the column generation subproblem is solved using constraint programming. The subproblem includes the dual variables in a constraint that ensures only columns with negative reduced cost are found. The core ideas of this paper is also contained in (Yunes et al., 2000a) which treats other non-hybrid models in more detail.

Yunes, T., A. Moura, and C. de Souza. (2001). "Hybrid Column Generation Approaches for Solving Real World Crew Management Problems." In *Proceedings of the 27th Conferencia Latinoamericana de Informatica*.

Notes. A crew management problem is divided into a crew scheduling and a crew rostering problem. Each of these two problems are solved using both mathematical programming and constraint logic programming. Hybrid methods using both column generation and constraint logic programming are designed for both crew scheduling and crew rostering problems. Numerical experiments are performed on real data in a bus company. Numerical results show that the proposed hybrid methods for both crew scheduling and rostering problems outperform either the integer programming approach or the constraint logic programming method in isolation.

Zhao, L., A. Wren, and R. Kwan. (1995a). "Development of a Driver Duty Estimator." *Journal of the Operational Research Society* 46(9), 1102–1110.

Notes. The paper reports research on an estimator of bus driver duties. The estimator simulates in the manual scheduling process. It produces the number of duties likely to be required in a driver schedule. Duties are generated and added one by one to the driver schedule. However, the estimator does not yet include evaluations of the cost for duties.

Zhao, L., A. Wren, and R. Kwan. (1995b). "Enriching Rules in a Driver Estimator. In J. Daduna, I. Branco, and J. Paixao (eds.), *Computer-Aided Transit Scheduling*, Lecture Notes in Economics and Mathematical Systems, Vol. 430, pp. 236–247. Springer.

Notes. This paper describes improvements that have been made to a bus driver duty estimator, which assesses the number and type of duties required to cover a bus schedule.