A Survey on Constructing Rosters for Air Traffic Controllers

Richard Conniss
Department of Computing and Mathematics,
University of Derby, UK
R.Conniss@derby.ac.uk

Abstract— **In this survey the state-of-the-art technology and the literature to date are discussed. In particular, we will discuss the gap in the literature concerning rostering staff to tasks by qualifications, with the inclusion of restrictions on a measure of task familiarity, which is a unique consequence of the structure of ATC operations.**

Keywords— Knowledge discovery; OR in defence, Scheduling, Metaheuristics, Human resource planning

I. Introduction

Personnel scheduling has been an active area of research since the 1950's. Over the years the approaches used have changed dramatically in terms of solution approach. The modern availability of cheap and ubiquitous computing resources has allowed for entirely new methods to solve problems. New industries have also appeared over the decades as technologies have improved. Examples such as the creation of call centres and the growth of a civilian aviation industry have presented new and interesting challenges to the scheduling of staff. Changes in employment practice have also created entirely new problems that once would have not existed e.g. the need for part time or flexible working, and European working time regulations are recent real world constraints on any rostering system.

This paper provides a survey on this topic.

II. Problem Statement

The ATC rostering problem shares some features with standard rostering problems reported in the literature, and at the same time has some unique features that required a special attention. More specifically, all controllers start their careers by attending a specialised training college to learn the basic skills of ATC. Once a new controller arrives at their unit, they must undertake a period of on the job training. At any given unit there will be a set of controlling tasks, or positions, for which the new controller must become proficient.

In particular, the majority of ATC units have multiple control positions, each with unique demands and training requirements. Ideally, all controllers will be in the position of becoming endorsed in all aspects and this is where the first main difference with other scheduling problems occurs. In fact, if a controller holds an endorsement in a specific position they are subsequently expected to staff that task as required.

This is quite different to the use of qualifications in other rostering problems. For example, in many nurse rostering problems qualifications are associated with the seniority of an employee. Loosely speaking, the assignment is penalised by the solution method, if a more qualified nurse is assigned to a task that would more normally be undertaken by a more junior colleague. In fact, the senior nurse is certainly qualified to undertake such task, but it would be regarded as an inefficient use of resources as salary is linked to seniority.

For controllers, the need to maintain familiarity with all tasks for which they are qualified is safety critical. In fact, skill fade is a crucial problem and can lead to potentially catastrophic effects on the safe movement of aircraft. Controller's salaries are excluded from rostering decisions as their remuneration has no effect on their ability to execute a task. Therefore, controllers should be regularly assigned to each of the positions for which they hold endorsements. One way of measuring this familiarity is known as currency, which is used as a measure of an individual's competence for a task.

Currency is defined as the number of days since a controller has completed a reasonable amount of work in a position. . Values for currency are updated on a daily basis, and the current limit is set at 30 days. If a controller violated this restriction, they would have to undergo a period of retraining and re-qualify for that position. Clearly this situation will add to the training burden of a unit, and should be avoided wherever possible, achieving this can be a difficult task for most units.

Like any employee, controllers require rest breaks throughout the working day. In the civilian ATC world there are very strict and legally binding working rules and conditions to ensure the safety of aviation operations. In particular, the rules specifically address the maximum durations for a controller to work in a position, frequency of rest breaks, and meal breaks. For UK ATC operations such rules are defined in the Scheme for Regulation of Air Traffic Controllers Hours (SRATCOH) which is published by the Civil Aviation Authority.

To give a controller a break in a particular position, another qualified controller must replace them. This transfer of responsibility requires a formal handover procedure to ensure that the incoming controller is aware of the location and intentions of all aircraft receiving a service, the local weather conditions, unusual variations to normal procedures, temporary airspace restrictions and any other information deemed necessary for safe operations. As a consequence, this prevents controllers from switching tasks instantaneously, as this process will always need at least a few minutes to complete. In the case of multiple controllers requiring breaks over several time periods, some chain of moves must be found that simultaneously gives all controllers a suitable set of breaks. The main objective of rostering is therefore, to produce a single day roster which guarantees that qualified controllers are appropriately assigned to positions, given breaks and whilst maintaining currency.

One of the most difficult aspects of the process for the watch supervisors, whom are the senior controllers in charge of daily operations, is the initial creation of the daily schedule. With so many permutations of controllers and qualifications, it can be extremely challenging to construct a roster that is feasible.

Any automated approach that could achieve an effective rostering management would have positive effects on flight safety in general. Breaks are monitored continuously, which places additional pressure onto the supervisor's workload, and occasionally controllers can be left in position for an unsuitable length of time. For example, late notice changes to staffing, last minute medical appointments, meetings off site, and even the rare controlling incident can all have a negative impact. Planning for these events is almost impossible and as such supervisors are constantly dealing with new inputs of information, throughout a shift.

An effective algorithm to produce valid rosters has to consider all of the above restrictions placed on controlling staff. Following a number of conversations with senior ATC staff at RAF Cranwell, a variety of key requirements for a daily roster have been identified. These include:

- All operational demand for the flying program must be met by qualified controllers.
- Controllers must have suitable rest breaks.

III. State-of-the-Art Approaches to Rosters for Air Traffic Controllers

Much of the literature associated with real world scheduling or rostering problems is concerned with the health, transport and service industries. The most prolific research area by far is that of nurse rostering. The review paper by Burke et al (Edmund K. Burke, De Causmaecker, Vanden Berghe, & Van Landeghem, 2004) gives many good examples of the use of rostering in this industry, and papers by De Causmaecker and Vanden Berghe (Bard & Purnomo, 2005; E. Burke & Curtois, 2010; De Causmaecker & Vanden Berghe, 2011; Smet, Bilgin, De Causmaecker, & Vanden Berghe, 2014) show both the breadth of applications and the continued interest in this industry.

All personnel rostering problems necessarily focus on rostering staff to tasks. Early approaches to rostering often used the techniques of Linear Programming (LP) and the applications to scheduling using the simplex method developed by Dantzig in the1960's. Generally, rostering is treated as a set covering problem, to ensure sufficient staff to cover the required demand. LP methods work well for small problem instances. Often they are used to solve smaller sub problems after the larger problem has been decomposed. Hojati and Patil (Hojati & Patil, 2011) describe an approach that splits a problem into an LP to solve the shift allocation part, then use a second LP to assign employees to tasks. There are other examples of hybridising with other methods (Côté, Gendron, & Rousseau, 2010) and it appears that most modern approaches to rostering need to have something else included to make the LP work well. Traditionally, LP models focused on the use of inviolable hard constraints, rules that require satisfaction to produce feasible solutions. More recently, soft constraints have been added to models to allow a certain degree of flexibility in the types of solution obtained. Techniques such as goal programming have been used to attempt to allow preferences to be expressed in LP formulations. The ability to violate a constraint to some degree can be a very useful methodology to tackle particular classes of difficult real world problems.

Soft constraints are often used in heuristic solution approaches. Because of the NP-hard nature of rostering problems, they are often a valuable tool to solve large instances of a problem, and aim to provide a solution that is good enough, but rarely optimal in a mathematical sense. The majority of modern real world rostering problems benefit from some form of heuristic or metaheuristic approach, because the constraints of a particular problem are generally easier to satisfy, to some degree, when defined as soft constraints and heuristics are better suited to dealing with these formulations. Heuristics also tend to scale better, and are often easier to implement computationally. Paquete et al (Paquete, Chiarandini, & Stützle, 2004) gives a good introduction to the use of heuristics in scheduling, specifically for multi objective problems. Metaheuristics can be classified as either deterministic or stochastic methods. Deterministic methods are mathematically guaranteed to find a solution to the problem, eventually.

One of the least researched areas in the literature on rostering is that of military rostering. Only a handful of examples exist in the literature. Wang (Wang, 2005) reviews techniques for workforce planning, and assesses the suitability of these methods for use in a military training environment. Safaei (Safaei, Banjevic, & Jardine, 2011) discusses a case study of military aircraft maintenance planning, and shows the benefits of utilising a mixed integer approach to model jobs for a skilled workforce. Li (Haitao Li, 2009) presents a model for shipboard staff scheduling, using both mixed integer methods and Tabu Search. The authors conclude that a mix of techniques may be required to solve these large, multi-skilled staff problems, including Constraint Programming techniques. Zadeh (Zadeh, Storey, & Lenarcic, 2009) describes an application for scheduling multiple crew to patrol boats for the Australian Navy. McGinnis et al (McGinnis & Fernandez-Gaucherand, 1994) gives a detailed model for use in US military recruit training using mathematical, decision and heuristic procedures to produce useful results.

Despite this lack of work in the literature, the military offers great scope for many rostering problems as it is subdivided into many trades or branches, which are similar to civilian industries. In fact, the military covers most of the other application areas in the literature with personnel working in transport, logistics, engineering, security, health and aviation. Furthermore, there are more specialised occupations such as the infantry and fighter control that suggest new areas of potential research. One of the reasons of the lack of research in this field might be related to security aspects. However, it is more likely that researchers are just not familiar with the potential opportunities that the military offer for rostering research.

The most interesting areas in the staff scheduling literature concern the use of qualifications, or skills, to assign individuals to tasks and the planning of breaks for staff. Although skills are generally well incorporated into the body of literature, such as (Akbari, Zandieh, & Dorri, 2013; Cai & Li, 2000), nothing in the literature models staff skills in the same way as Air Traffic Control (ATC) rostering requires. Often, skills are fixed at the start and no allowance is made for staff to obtain additional qualifications. This leaves skills as merely an input to the rostering problem, rather than an integral part of the development of staff in an industry. However this element of training is required in ATC rostering. Similarly, most rostering problems fix staff to tasks for entire shifts. There are examples such as (Asensio-Cuesta, Diego-Mas, Canós-Darós, & Andrés-Romano, 2012; N Azizi & Liang, 2012; Nader Azizi, Zolfaghari, & Liang, 2010; Campbell, 2011) which deal with the rotation of staff through several tasks, generally to allow for workforce flexibility. The ATC industry requires staff to be competent in multiple disciplines and to regularly practice these skills.

Breaks have been integrated into a variety of problems, and to some extent break or tour scheduling is becoming a new sub-discipline in rostering. In particular, research carried out by Widl and Schafhauser (Schafhauser, 2009; Widl & Musliu, 2010; Widl, 2010) focuses on the design of break systems in a roster. This suggests that the break problem is complex to solve, it is very relevant to real-world rostering problems, and further research into integrating breaks into rosters would be a useful addition to the literature.

Tabu Search (TS) is a good example of a method that was successfully used in solving rostering problems. It is a heuristic method that moves through a search space, looking for the next best solution. The method keeps a record of previously visited solutions, and checks a newly found solution against this list. If the solution is contained in the list, the next best point is selected and the process continues. Bilgin et al (Bilgin, De Causmaecker, Rossie, & Vanden Berghe, 2012) used the technique to address a novel nurse rostering problem that included variable length shifts and planning periods. Musliu et al (Musliu, Schaerf, & Slany, 2004) used the prohibition techniques from TS as part of a larger mechanism to design shift patterns. Bellanti et al (Bellanti, Carello, Della Croce, & Tadei, 2004) used TS and compared it with greedy and local search procedures to demonstrate that TS can produce good results in reasonable time when applied to nurse rostering problems. TS has also been used in a military context, to plan Naval shipboard manpower planning (Haitao Li, 2009).

Simulated Annealing (SA) is a metaheuristic based on the physical process of cooling metals. It goes through the search space looking for better solutions, but with a finite probability that it will choose a worse solution. This probability changes during the course of search and is controlled by a cooling schedule, which reduces the probability of accepting worse solutions slowly as the search progresses. It has been used by (H. Li & Landa-Silva, 2011), in combination with evolutionary methods, as a method for heuristically solving multi objective optimisation problems. Bai et al (Bai, Burke, Kendall, Li, & McCollum, 2010) hybridise SA with an existing technique to show that performance gains can be achieved using this method.

Constraint Programming (CP) is a declarative method of solving rostering problems. It stemmed from research in AI, and is designed to allow a user to simply declare the constraints of a problem and let the software to select the most appropriate solution technique. Lapegue (Lapègue, Bellenguez-Morineau, & Prot, 2013) used the method to simplify the shift design problem. An early argument for the use of CP is given by Cheng et al (Weil, Heus, Francois, & Poujade, 1995) in the context of complex nurse rostering applications. Cheng et al (Cheng, Lee, & Wu, 1997) build on this work to show how more complex models can be developed for real world application.

Cased Based Reasoning (CBR) is another AI technique that has been applied to solving rostering problems but to a smaller extent than meta-heuristics. It is based on learning from prior optimal solutions to problems, to find solutions to new problems. Beddoe et al, introduces CABAROST a CBR based system for staff rostering (Beddoe, Petrovic, & Li, 2009). Instead of formulating the nurse rostering problem as an optimisation problem, in which the violations of the soft constraints must be minimised, this system aims to mimic the way a personnel manager addresses the constraint violations in the roster. A discussion about the design of comparisons between different approaches to rostering is given by Petrovic and Vanden Bergh (Petrovic & Vanden Berghe, 2012), and is specifically focussed on the differences between CBR and metaheuristics when measured against several defined criteria.

There are many more approaches used in rostering including agent based modelling (Causmaecker, 2005), formal languages (Côté, Gendron, Quimper, & Rousseau, 2011), fuzzy goal programming (Pal & Moitra, 2003), variable neighbourhood search (E K Burke, Curtois, van Draat, van Ommeren, & Post, 2011); but no clear best approach has emerged.

Review papers such as (Alfares, 2004; Ernst, Jiang, Krishnamoorthy, Owens, & Sier, 2004) and the recent comprehensive work of Van den Burgh (Van den Bergh, Beliën, De Bruecker, Demeulemeester, & De Boeck, 2013) describe a myriad of methods for rostering. Rostering is an area where many approaches have been tried, often with minimal increases in solution quality or computational time. Recent work by (De Causmaecker & Vanden Berghe, 2011) and (Smet et al., 2014) have attempted to formalise the description of the rostering problem, to enable a better system for deciding between different approaches. Therein lies the difficulty in selecting an appropriate method to solve the controller rostering problem.

ATC schedules have some similar conditions and requirements to other types of rostering problems in other industries. In fact, all staff must be allocated to tasks, based on their professional qualifications, to ultimately produce a viable roster to maintain operations in an efficient manner. Staff must be given reasonable or legally mandated rest breaks and time off for both leave and between shifts. The differences in how controllers work lead to an unusual set of conditions and constraints that make this an interesting area of study. Essentially, the important characteristics of the problem depend on two main components, those of qualifications and currency.

IV. CONCLUSIONS AND FUTURE STEPS

This paper has presented a survey of a variety of rostering problems, specifically focussing on real world applications and genuine need for a solution method. The ability to algorithmically generate daily rosters is of great use to operational controllers and watch supervisors, alike.

One of the main questions concerns the best ways to address rosters for longer planning horizons. ATC units tend to fix staff onto rotating shift patterns to simplify this process. At Cranwell, UK staff tend to work a week of the same shift type at a time. These shifts are usually designated as early, day and late shifts and their durations tend to overlap. Using the current planning system, this eliminates the need for any consideration of shift patterns. However, there remains the problem of deciding how to allocate controllers to shift patterns to ensure suitable coverage so that normal operations can occur.

A possible solution would involve the scenario in which a valid roster is generated for a given planning horizon, which can be used as a template to create a more general version for future use. Some controllers share equal sets of qualifications and each such group can be classified as a controller type. Due to the structure of the training program at most units, there will only ever be a few of these groups and they will be relatively stable over time. When planning shift staffing, it therefore becomes possible to set limits on which type of controller can be assigned to which shift and still produce a valid roster. Rather than assigning specific controllers to positions, if types of controllers were assigned then this would allow the system to generate general rosters and experiment with different configurations of staff. These general rosters can also be rated for specific attributes e.g. the average number of positions worked by a controller in a day, as a more varied work day can assist in preventing boredom and dissatisfaction.

Other preferences can be easily added to the system. This is useful for temporary situations like annual competency checks. Controllers are regularly checked by a colleague to ensure they are capable to continue controlling in a particular position. Usually, the scheduling of these checks is complicated by the need to maintain ATC operations and currency. Using this algorithm, check preferences can be added to a roster before it is generated thereby removing the difficulty and because the algorithm is deterministic it is guaranteed that if a valid solution exists it will be found.

Finally, ensuring a fair allocation of tasks to controllers would be an obvious next step for the research. Initially, this type of investigation was hampered by the lack of any method to generate feasible rosters. Using fairness as measure of roster quality is a recent addition to the literature, but one which requires further investigation. One possible approach would use a multi-phase approach, beginning with the current algorithm to generate feasible rosters and then use a secondary heuristic method to maintain a fair task allocation over time.

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