A Case-Study about Shift Work Management at a Hospital Emergency Department with Genetic Algorithms

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ABSTRACT

Organising shifts, or work rosters, is a problem that affects a large number of businesses where staff are subject to some kind of work rotation or other. Researchers in the fields of Operations Research and Artificial Intelligence have devised several systems in an attempt to optimise the problem. This paper focuses on the problem of medial staff shift rotation at a hospital emergency department, and attempts to establish a method to automate its management by applying genetic algorithms. It also analyses one of the duty rosters that came out of the proposed solution.

Categories and Subject Descriptors

I.2.8 Problem Solving, Control Methods, and Search.- *Heuristic methods*

General Terms

Algorithms, Management.

Keywords

Timetabling; Rostering; Genetic Algorithms; Health Services; medical straff.

1. INTRODUCTION

The aim of rotation schemes is to decide the order work should be done in to achieve the aims and comply with the policies laid down by an organisation. Although there is abundant literature on the subject [2], [8], [9], [10], [16], there is nevertheless no all-encompassing solution for every single problem, as each case has its own unique constraints and characteristics.

Devising a work timetable, or roster, begins with a number of objectives, or resources, and a set of processes to be applied in order to make optimal use of these resources. Depending on the type of problem at hand, the order each of the processes is applied may be crucial to solving the problem, as would be the case, for example, in an educational setting where each student has to have a set number of classes per subject per week. In an example of this sort, the student would be the object and the hours of class would be the process, and time-tabling of the subjects would not be relevant.

An initial approach to solving this type of problem might begin with integer linear programming [7], whose model will now be commented on, was the forerunner of this approach :

$$\text{Minimize} \sum_{k \in K} c_k X_k$$

Subject to:

$$\sum_{k \in K} a_{kt} X_k \ge b_t \qquad \forall\, t \in T$$

$$X_k \ge 0 \text{ and integer}$$

where K is the complete shift package, T is the time period to be covered by the scheme, b_t is the number of staff members required for the period t, c_k is the cost of assigning a member of staff to shift k, a_{kt} is equal to one if the period t is a work period for shift k and is otherwise zero, and X_k is an integer defined as the number of staff assigned to shift k.

Linear programming can most certainly be applied to simple cases involving a small number of staff. However, it does not work entirely satisfactorily when applied to more complicated cases, and sometimes it is not even applicable, in which case one has to resort to using heuristic techniques, which can provide solutions that satisfy all the conditions stipulated at the outset even though they do not come up with the best solution. Nevertheless this technique entails the following drawbacks:

- Optimal (or near-optimal) solutions cannot be generated by the mere evaluation of a polynomial. Furthermore, the range of possible solutions is too extensive for a non-directed search method to work efficiently.
- Advanced search techniques that employ heuristic methods to downsize the range of possible solutions cannot be guaranteed to find an optimal (or near-optimal) solution.
- The problems involving time planning are complicated by the minutiae of each particular case, and such constraints should be included in the definition of the search domain.
- Real-life time planning problems often include constraints that cannot be represented in the search algorithm with any degree of real precision.

Yet despite such drawbacks, there have been a plethora of applications of heuristic techniques, and different variants of these problems can be found in the literature. From Brusco et al. [3], how apply heuristic techniques to optimise shifts, or duty rosters - in the airline industry- to White and White [17] or Burke et al.[4] how also apply Tabu Search in this field, several researchers have tried to solve the problem of rostering in an efficient mode. Ernst et al. [8], and Bechtold et al. [1], among others, provide a good reviews and comparisones of the different heuristic methods that have been applied in this field.

Genetic Algorithms (GA) were first employed to address the problem of time-tabling to organise the lecture timetable at an Italian university [6]. They have since helped to provide further breakthroughs in the field, the most importants of them being documented in [5], [18].

This article is divided into a number of sections. First of all the nature of the shift roster problem at the casualty department and the working constraints that were involved are described. The genetic algorithms used in this work are then analysed, as are the tests used to optimise them. Finally, two duty rosters that came out of the method proposed are commented on, the main conclusions to be drawn from this work are described, and future research lines are suggested.

2. THE DISTRIBUTION OF SHIFTS IN A HOSPITAL EMERGENCY DEPARTMENT

Establishing duty rosters, or work calendars, for the medical staff of a hospital emergency department does not fit into a general behavioural pattern because of the heterogeneity of such a unit's structure [16]. This heterogeneity is due to many factors, such as the extent or range of the services offered (which depends on the category of the hospital, and therefore on the hospital's catchment area), the work mode (shifts, on call, or a combination of both), the type of staff contract (full time or part-time staff member, etc.), and the kind of work that is undertaken (general emergencies, outpatient service, mobile intensive Care Units, emergency care with other departments), and other factors.

This all means that specific results from any study of a daily shift distribution will only be valid for a single casualty department where the above-mentioned factors have been defined *a priori*. This particular study focuses on shift management for the casualty department of a secondary level hospital with a 500 bed capacity. The department has 11 beds for general emergencies, and 13 beds for patients under observation. Hiring is a combination of some staff with permanent contracts, and others with temporary ones; the work mode combines shifts and being on call, and the type of work does not differ from what would be expected in a general casualty department. The general characteristics of the service are as follows.

a) There is a medical staff of 16 people (permanent contracts; this number of staff was obtained based on the work of Graff and Radford [12]), and an indeterminate number of temporary staff who work shifts and/or are on call when permanent staff are unable to do these duties because of certain constraints that apply.

b) Department staff work in different modes depending on whether the day is a working day or a holiday. Saturdays, Sundays, local, regional and national holidays, Christmas Eve and New Year's Eve are all classed as holidays, when work is organised as a twenty-four hour on-call period (starting at 10 a.m.). The remaining work days are organised into shifts, either in the morning (from 8 a.m. to 3 p.m.), afternoons (from 3 p.m. to 10 p.m.) or nights (from 10 p.m. to 8 a.m.). Additionally, every working day somebody must also be on call for 24 hours (from 8 a.m.) – called the 'stand-by duty' – to look after and supervise patients who are under 24 hour observation (maximum) before either being discharged or hospitalised.

3. CONSTRAINTS

The constraints imposed on the shift management system can be divided into two different types: 'hard' constraints, which must necessarily be complied with, and 'soft' constraints, which need not be catered for, although any solution which does manage to include them will be better considered for having done so.

The hard constraints are the following:

- A minimum number of staff should be assigned to each shift. As a general rule for working days, four members of staff will be assigned to the morning and afternoon shifts, two will be assigned to the night shift and one person will be on 24-hour stand-by call. On Saturdays, Sundays and holidays, the department will work in on-call mode, whereby four members of staff will generally work for an uninterrupted 24-hour period.
- Whenever the on-call work mode is being worked at least two of the 16 members of staff should be on call
- Any member of staff who is on 24-hour stand-by call during a working day, on call over a holiday period or who works a night shift will not work the following day.
- Constraints imposed by periods of illness and holidays should be catered for.

The soft constraints are as follows:

- Each member of staff should be on call three times a month (one of them a 24- hour standby call during a working day)
- All members of staff should, if possible, work the same number of Saturdays and Sundays per month.
- Staff should be on the same shift for a whole week.
- The same order of shifts from one week to the next, based on a morning, afternoon and evening pattern should be maintained if possible.
- The 24-hour standby shifts on working days should be linked to the night shift.
- The day before being on call it is preferable to work the morning rather than the afternoon shift.
- The number of different types of shift should be shared out amongst staff as fairly and as equally as possible.
- Temporary staff will be resourced as little as possible.
- Temporary staff will only be on call during holidays and for the 24-hour stand-by working day shift.

An in-depth analysis of these constraints clearly shows how difficult it is to find a solution to this time-tabling problem. Remember too that the time-tabling is on a monthly basis, and that the work load should be fairly shared out amongst all the staff. This means that any shift roster system should include a 'memory' to include the yearly subtotals of shifts worked by each member of staff. Given these difficulties, a weighting was applied to each of these softer constraints, and a ranking of the relative importance of each factor to the solution was established.

4. RESULTS AND DISCUSSION

Genetic Algorithms arose towards the end of the 60s and were intended to solve a number of problems of industry that were difficult to solve with the methods available at the time. The basic iteration cycle of GAs proceeds on a population of individuals or chromosomes each one representing a point in the search space of potential solutions to a given optimization problem. An iteration cycle consists of two main steps: first a selection procedure and then a recombination [13]. This cycle is repeated a number of generations. In order to evaluate the good qualities of an individual, that is, the adaptation degree of the individual to the environment, the fitness function is used. The value produced by this function for an individual is used during the selection procedure in such a way that an individual has a selection probability for reproduction according to its fitness value. Therefore, reproduction directs the search towards regions of the search space where the average fitness of the population improves [11], [14].

A number of difficulties arise when genetic algorithms are applied to the problem. The major ones are defining the fitness function and the type of solution that the algorithm should work on. The way chromosomes are handled is different depending on the type of constraint:

- Solutions that fail to take into account the hard constraints are deemed infeasible, so a function is incorporated that modifies the genes of the infeasible individuals to make them feasible.
- Solutions that fail to fulfil the soft constraints are weighted as a function of how ideal each individual is; individuals fulfilling these constraints have a higher fitness.

4.1 Handling Infeasible Solutions

Any solutions not fulfilling the hard constraints listed above is considered infeasible. The aim of eliminating infeasible solutions is justified by the size of the domain; if they were not eliminated the domain would be too large and the algorithm would not be able to evolve satisfactorily. In the initial approach to the problem, this automatic correction did not exist, but this led to obtained of poor quality solutions. For this reason, the automatic reparation mechanism was introduced.

The transform function of the infeasible solutions works as follows: when there is an infeasible solution, an available member of the permanent staff is chosen at random and in succession until one of them can cover the shift. If the shift cannot be assigned to any of them, it is assigned to one of the temporary staff. If the shift cannot be assigned to any of the temporary staff either, the function indicates that finding a solution that fulfils all the criteria is impossible.

4.2 Calculating Fitness

Once the feasibility of the proposed solution has been checked, its quality should be analysed. A number of criteria that have already been described (the soft constraints) are laid down, and they are given points, the sum of which is the fitness. Not all constraints are equally important, so they need to be weighted so that some of them - the most important ones - are almost always fulfilled. Moreover, each of them has different levels or degrees of acceptability. For example, it is not the same for a member of staff on morning shift to work five shifts a week as it is for him to work four or three. To cater for this, it was decided that points should be awarded to the fitness function not only in the light of the week constraints but also in the light of their quality.

To determine how acceptable quality levels are, the solution proposed should be analysed week by week and for each staff member; thus, for the 'same week, same shift' constraint, a solution that assigns a particular member of staff the same shift for the five working days of a given working week is given a top, or maximum, score (level 6). A higher score is given to a solution that assigns a higher number of the same shift-type whenever the same shift does not cover a whole working week (in other words, four morning shifts scores higher than three, and so on and so forth).

To fulfil the `maintain the shift order from one week to the next` constraint, at the end of each week each member of staff`s shift is stored, so when the following week is analysed this value is built into the calculation, and higher scores are given to solutions that incorporate a schedule rotation that runs morning-afternoon-evening-morning` weekly.

Besides the weekly analysis, Saturdays and holidays are also subject to analysis in order to evaluate the 'morning shift rather than afternoon shift before an on-call period' criterion, which is a soft constraint. Thus, higher scores are assigned to a solution that assigns a morning shift for the day before. Finally, a monthly analysis is also carried out for each individual member of staff, in an attempt to assign three on-call sessions (one of them a 24-hour one) to each staff member. The further the distance from this criterion, the lower the score.

4.3 How the Genetic Algorithm works

The characteristics of the Genetic Algorithm applied to the problem will now be described. An initial population is first created randomly, and whether each individual complies with the obligatory constraints is checked; if this is not so, the individual is corrected. If it is impossible to fulfil the constraints that are imposed with the staff that is selected, the calculation algorithm stops, and either the constraints are cut down or the number of staff is increased. Once the initial population has been generated each of the individuals is evaluated for fitness (how ideal the solution is).

The encoding selected for the solution is made up of a set of integer numbers, each of which stands for a member of staff. Figure 1 is a graph showing the encoding that was chosen, taking the defect configuration as a base, that is, assuming that there are four staff members for the morning and afternoon shifts, two for the night shift, one for the 24-hour working-day standby duty, and four who are on call over holiday periods. The individual represents the rostering of a moth.

Working day											Holiday				
M				T				N		B	G				
3	4	6	7	1	5	2	9	14	13	8	11	10	12	15	...

Staff members 1, 2, 5 and 9 do the afternoon shift
Staff 13 and 14 do the night shift
Staff member 8 covers the 24-hour stand-by duty
Staff members 10, 11, 12 and 15 are on call over the holiday

Figure 1: Part of the encoding of an individual

The reproduction stage comes next, where the best individuals are selected by stochastic sampling, they are crossed (two point crossover), mutations are made (order mutation) [15]. Replacement is then done and a new population is obtained.

Before continuing with the iterations, it is checked whether the maximum number of generations or the level of convergence required has been reached. Once the process is over, the best solutions are selected from amongst the final population.

4.4 Determining the parameters of the Genetic Algorithm

Neither the values of the mutation and crossover probabilities nor the size of the population can be established by applying general rules. Testing has to be carried out until you come up with values with the best performance, and even then there can be no guarantee that a set of values will be the most adequate ones whatever the problem to be solved might be, because the optimum set of values depends on the constraints that were applied, on the number of holidays in the month, and on any other variable, such as absence through illness.

In consequence, and in view of the limitations that have been commented on, a number of experiments were run using different sets of values to observe and analyse which of them might lead to a final solution that was close to being optimum. The most representative results of the experiments that we ran will now be commented on, thereby highlighting the differences that arise as the values of different parameters are altered.

The intervals within which values for the experiments were chosen were obtained by consulting the considerable documentation in the subject [15]. It should be pointed out that 20 tests were run for each set of parameters in order to eliminate the random factor that is implicit in experiments involving Genetic Algorithm; thus, the graphs obtained have been calculated by taking the average of the 20 experiments. The results were obtained on a PC at 230 MHz, and the average time taken for each 200 generation simulation was 110 seconds.

Analysis of the mutation probability indicated that the quality of the solutions increases as the value of the probability decreases. Best results were achieved with a probability of 0.01. Figure 2 demonstrates this effect. Crossover probability has shown itself to have a minor influence on shift management. A crossover probability value of 0.6 was applied to get the final solution reasonably close to the objective. As for population size, there is a slight improvement in the quality of the solution when this increases. A population size of 100 individuals was therefore opted for.

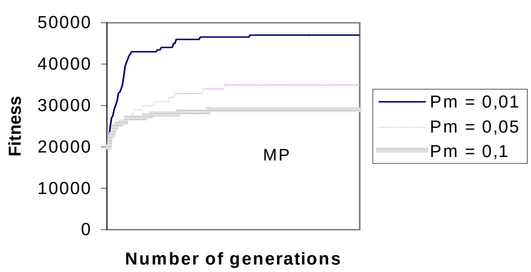

Figure 2. The evolution of fitness in response to different types of mutation probability (pm=mutation probability)

5. RESULTS AND DISCUSSION

The results for two possible weightings of soft constraints will now be described (c.f. table 1), scored on a scale of 1 to 10 (from lowest to greatest priority).

Table 1: The weighting for soft constraints

Constraint	Solution 1 weighting	Solution 2 weighting
Each member of staff should be on call three times (including one 24-hour working day stint)	6	10
the amount of Saturdays and Sunday work in a month should be fairly shared amongst all staff members	8	8
Staff should keep the same shift during a whole week	9	9
The same order of shifts from one week to the next should be maintained if possible, as per the morning-afternoons-nights pattern	4	8
24-hour on call duties should be linked to the night shift	10	10
A morning shift is preferable to an afternoon shift the day before being on call	3	7
The number of shifts of the same type should be shared fairly amongst all the staff	6	5
Temporary staff will not be used as far as possible	2	2
Temporary staff will only do holiday and 24-hour on call shifts	9	5

It can be clearly seen how weightings used for the second solution require greater fulfilment of the most important of the soft constraints; in this way if a better duty roster is the outcome of this set of limitations (despite the extra computational effort required), the algorithm will prove its efficiency.

1st Solution (Table 2): the results from the first solution show that the hard constraints are always fulfilled. As far as soft constraints are concerned, the three-standby duty constraint (one of them a 24-hour working day duty), with a weighting of 6, has a fulfilment rate of 53.8% for permanent staff who are not assigned a day off (this figure rises to 75%, if only three on-call periods are required regardless of what type they are). Only staff members OP4 and OP9 have been assigned 4 on-call duties, and OP16 only has two. As far as balancing out Saturdays and Sundays is concerned, only OP11 and OP13 do not comply when the weighting is 8. The constraint of having the same shift for the whole week is complied with in 90% of cases (all but 7 out of 70 cases). The constraint of an ordered morning-afternoon-night pattern (weighting of 4) is achieved in 55.4% of cases, though only OP6 and OP13 keep to an organised structure for the whole month. The condition linking the 24-hour call shift to the nightshift (weighting 10) is complied with 100%, except for temporary staff. As regards the constraint that the day before an on-call session it is preferable to work a morning rather than afternoon shift (weighting 3), the proportion ration is 7 to 4 in favour. The number of on-call duties and night shifts is reasonably fairly shared amongst staff, which is not however the case for morning and afternoon shifts. The constraint on temporary staff working on-call duties or 24-hour call duty is complied with in every case.

Table 2: The first solution (M = morning, T = afternoon, N = night, G = on call , B = 24-hour call)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OP1	M	M	M	M			B		N		N			T		T	T	T			T	N		B		G		M	M	M	M
OP2	T	T	T	T		G		N		B			G			M	M	M			N		N		B			T	T	T	N
OP3	B		N				T	T	T	T	T			N		B		N			M	M	M	M	M	G		T	T	T	T
OP4	M	M	M	M	G		T	T	T	T	T			M	G		M	M			B		N		N			T	N		B
OP5		N		B			M	M	M	M	M	G		T																	
OP6	T	T	T	T		G		N		N				M		M	M	M	G		T	T	T	T	T				B		N
OP7	N		B				M	M	M	M	M			T		T	T	T			N		B		N		G		T	T	T
OP8	M	M	M	M			N		B		N		G			M	M	M			T	T	T	T	T	G		N		N	
OP9		B		N			T	T	T	T	T	G		N		N		B			M	M	M	M	M		G		M	M	M
OP10																T	T	T		G		M	M	M	M			B		N	
OP11	T	T	T	T	G		M	M	M	M	M			B		N		N				N		N		G		T	T	T	T
OP12	M	M	M	M			T	T	T	T	T		G			M	N		G		T	T	T	T	T			N		B	
OP13	N		N		G		M	M	M	M	M	G		T		T	T	T			M	B		N				M	M	M	M
OP14	T	T	T	T	G		N		N		B			M	G		N				M	M	M	M	M			M	N		T
OP15																															
OP16		N		N				B		N				M		M	M	M		G		T	T	T	T			M	M	M	M
TR1						G						G			G				G								G				
TR2						G							G						G								G				
TR3															G					G											
TR4																	B			G											
TR5																															
TR6																															

2nd Solution (Table 3): It can be seen from the results of the second solution that the hard constraints are always complied with. As for soft constraints, the one related to doing three standby duties (one of them a 24-hour duty), which had a weighting of 10, is complied with 100% for permanent staff who are not assigned a day off. Only OP 2 has two 24-hour duties of the three on call duties assigned to him. The balance of Saturdays and Sundays, which had a weighting of 9, is complied with 100%. The constraints regarding having the same shift for the whole week (weighted 9) is complied with 90% (as with the first solution, it fails to be complied with in just 7 out of 70 cases). The morning-afternoon-evening pattern constraint (weighted 8) is complied with at a rate of 76.4%, besides which 9 of the 16 permanent staff maintain this structured pattern throughout the month. The condition that 24-hour calls should be linked to night shifts, weighted 10, is complied with 100%, except for temporary workers. There is a 10 to 3 ratio in favour of working in the morning rather than the afternoon the day before being an call (weighted 7). The number of on-call duties and night shifts is fairly evenly spread amongst staff, although OP2 has been assigned 6 night shifts when the average is 3 to 4. The same cannot be said about morning and afternoon shifts. The constraint regarding temporary staff working G or B shifts (weighted 5) is met except for a single morning shift and a single afternoon shift.

Table 3: The second solution. (M = morning, T = afternoon, N = night, G = on call , B = 24-hour call).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OP1	M	M	M	M	G		T	T	T	T	T				G		B				M	M	M	M	M			T	T	T	T
OP2	T	T	T	T			N		N		B		G			M	M	M			B		N		N			M	N		N
OP3		N		N			M	M	M	M	M			M	G		N		G			N		B				M	M	M	M
OP4		B		N			T		N		N			M		M	M	M	G		T	T	T	T	T		G		T	T	T
OP5	M	M	M	M		G		T	T	T	T	G																			
OP6	N		B			G		N		N				T		T	T	T			M	M	M	M	M	G		T		N	
OP7	N		N				M	M	M	M	M	G		T		T	T	T			N		N		B		G		M	M	M
OP8	T	T	T	T				N		B		G		M		M	M	M		G		T	T	T	T			N		N	
OP9	M	M	M	M	G		T	T	T	T	T			N		N		B			M	M	M	M	M		G		T	T	T
OP10																N		N			T	B		N				T		B	
OP11	T	T	T	T				B		N			G			M	N				T	T	T	T	T	G		N		N	
OP12		N		B			M	M	M	M	M	G		T		T	T	T		G		N		N				M	M	M	M
OP13	N		N			G		M	M	M	M			T		T	T	T	G		N		B		N			M	M	M	M
OP14	T	T	T	T			N		B		N			M	G		M	M	G		T	T	T	T	T				N		N
OP15																															
OP16	M	M	M	M	G		T	T	T	T	T			N		B		N			M	M	M	M	M		G		T	T	T
TR1	B					G								B						G						G		B			B
TR2							B								G					G						G		T			
TR3					G		M						G																B		
TR4													G																		
TR5																															
TR6																															

6. CONCLUSIONS

In this job, a problem of difficult treatment by exact mathematical methods is approach. This problem consists of a hourly distribution for de medical staff at the Emergency Department in a Hospital. The complexity of the problem resides in the high number of constraints. So that heuristic methods, as Genetic Algorithms, were used in order to solve it. The use of this technique allows the treatment of different kind of constraints. Thus, it can be required that some constraints (hard ones) always fulfil the conditions, and other constraints (the soft ones) have a high degree of accomplishment with the conditions. In order to simplify the full accomplishment of the hard constraints, the use of a vector coding is proposed, which makes difficult the generation of solutions that do not fulfil the hard constraints, obtaining solutions adapted to the relative importance imposed to soft constraints, as well as the fact of providing solutions of practical application.

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