THE SHIFT SCHEDULING PROBLEM:
DIFFERENT FORMULATIONS
AND SOLUTION METHODS

CAHIER N° 146
juillet 1997

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received: April 1997.

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Résumé

Le problème de construction de vacations (SSP) consiste à déterminer un ensemble de vacations permettant de couvrir une courbe de charge étendue et variable tout en minimisant les coûts. La formulation du SSP comme un problème de couverture d'ensembles a été largement étudiée et une variété d'heuristiques de résolution ont été proposées. Après un tour d’horizon de la littérature, nous proposons une contribution originale...
1 Introduction

Manpower scheduling problems occur in organizations for which the operating day exceeds the staff working day or the operating week is longer than the legal work week and the demand varies over each time period. Examples include the scheduling of nurses in hospitals, operators in telephone companies and ground crews in airports. To provide continuous service and to meet the requirements for all activity periods, employees work on multiple-shifts: the problem is then to schedule working time and rest time for every employee.

Research interest in manpower scheduling problems focuses on three kinds of problems: the shift scheduling problem, the days-off scheduling problem and the tour scheduling problem. The first problem consists of finding the best set of allowable shifts to cover the staff requirement for each time period. The planning horizon is usually a day. The second and third problems aim at constructing schedules for several consecutive weeks, indicating if each day is a working day or not for the days-off problem and determining the working hours for the tour scheduling problem. This paper deals with the Shift Scheduling Problem (SSP).

As early as 1954, Dantzig formulated the SSP as a set-covering problem. He solved it without the integrity constraints and noticed that, even if the optimal solution might be fractional, it hardly was. He also noted that the insertion of breaks causes a large increase in the number of decision variables. Moreover, Bartholdi (1981) showed that this problem is NP-complete. Although solving the relaxed problem is relatively easy, finding an optimal integer solution can become very difficult for realistic problems.

Many approaches for solving the SSP have been proposed since Dantzig. As shown by Segal (1974), the problem ignoring breaks can be modeled as a network-flow problem, for which the variables are guaranteed to be integral as long as the requirements are. But this formulation is far from most real world situations and researchers have worked on problems including breaks. Segal himself considered a scheduling problem for telephone operators in which the shifts may include one lunch break and up to two relief periods, depending on their length. He solved separately the shift assignment by his network flow...
(1985); Bechtold and Showalter (1987)... Bechtold et al. (1991) conducted a comparative analysis of several heuristics and showed the superiority of the heuristics of Keith (1979) and Morris and Showalter (1983). Morris and Showalter also suggest different ways to round the relaxed LP solution.

The different approaches found in the literature usually suppose no understaffing. Jacquet-Lagrèze and Meziani (1988) worked on allowable understaffing. Looking for a balance between cost and service quality, they pointed out the bicriteria aspect of the problem. Easton and Rossin (1991) suggested equivalent alternate solutions to integrate several criteria.

In his thesis, Thompson (1988) compared a procedure that starts with a break-less LP formulation and insert the meal breaks in a second step to a LP formulation which includes only a single break position. As the first approach gave very poor results, Thompson concluded that more flexibility in the allowable break options is essential for the minimisation of the labor amount scheduled.

Bechtold and Jacobs (1990) pointed out that the explicit representation of the shifts in Dantzig's model implies a dramatic increase of the number of alternate shifts when a higher flexibility is desired (starting time, shift length, assignment of breaks). For this reason, they present an implicit formulation of the breaks to match explicitly represented shifts. Their model, tested with four different labor requirement patterns and ten shift-length combinations proved to be better than the Dantzig's model in terms of execution time and memory size requirements. Thompson (1995) improved this latter model by implicitly matching meal breaks to implicitly represented shifts. His variables represent first the number of shifts from the same shift pattern that begin (or end) at any period, and second, the number of breaks for each shift pattern, beginning at each period. He considers thus about 15,000 alternate shifts and succeeds solving the problem. Recently, Aykin (1996) proposed another implicit approach to treat the problem with multiple break windows. All the possible shifts are enumerated explicitly without breaks, and for each shift and break window, he defines a set of variables, each one representing the number of shifts that begin their break at each possible start time of the break window. Compared to the explicit formulation, this approach can save a large number of variables when shifts involve several breaks as opposed to one. Note, however, that due to the problem size, all these models are solved by heuristic procedures.

For several years the authors of this paper have been working on the SSP for major French companies including Air France and Aéroports de Paris. The emergence of Constraint Logic Programming (CLP) methods (see Esquirol et al. (1995); Ilog (1995)) provided an opportunity to test an implicit formulation of the problem, avoiding the difficulty of dealing with the huge number of alternate shifts that are generated in the classical approach. Section 2 describes the SSP. Section 3 relates our experience with the implicit formulation for which we compare two resolution methods: CLP and Integer
Linear Programming (ILP). Both methods lead to very disappointing results when compared to the classical approach as it is shown in Section 4. Section 5 presents research work done on the classical set covering formulation in order to solve large scale industrial problems whose size increases with the demand of companies for more flexibility and efficiency. First, we propose a heuristic yielding an almost optimal integer solution. Second, we conduct an experimental study to evaluate the quality of the solutions as flexibility increases.

2 Description of the Shift Scheduling Problem

2.1 Definitions

The planning period is the smallest time interval for which the staff requirement is defined. This is often simply called period.

A shift describes the presence of one or more employees on a day, indicating the work and break periods. It is characterized by a beginning time, an ending time, up to three break times, all corresponding to the beginning of a planning period. Each shift has a certain cost.

The shift length is the number of planning periods (often expressed as a number of hours) between the shift beginning and ending times, including the break lengths.

The length step is the minimum difference in possible shift lengths. It is a multiple of the planning period.

The beginning window is the time interval during which a shift should begin.

The beginning step is the minimum time interval between two consecutive shift beginnings. It is a multiple of the planning period.

A break is a succession of planning periods during which the employee does not cover the requirement.

The break window is the time interval during which the break can be assigned.

The break step is the minimum time interval between two consecutive alternate breaks. It is a multiple of the planning period.

2.2 Assumptions for the experimental study

The following assumptions correspond to the experimental study conducted at Aéroports de Paris.
1. The planning period is 10 minutes (requirement is given for each 10 minutes period).

2. The shift length is limited by a minimum length and a maximum length.

3. All breaks are of the same length, an integer multiple of the planning period (meal-breaks only, up to two per shift).

4. The break windows are the same for all shifts. There is mainly one break window for each shift but some very long shifts cover two break windows and some short ones do not cover any.

5. The shift cost is a linear function of the shift length.

6. Understaffing is not allowed.

3 Testing an implicit formulation of the SSP

3.1 The implicit model

3.1.1 Introduction to the model

Our implicit formulation of the problem aims at finding a set of individual shifts, assuming two main decision variables for each employee: beginning and ending times of his shift. In order to model the breaks, we need for each shift one additional variable per break (since we assume that all breaks are of the same length). Typically, for a situation involving 100 employees and allowing a high level of flexibility scheduling (10 minutes for all steps), number of main decision variables rises here to only 300 against about 100,000 in the classical set covering approach (see section 4). However, to test the formulation, we started this work with a simplified break-less version.

Both the CLP and ILP resolution methods require additional technical variables. First, the number of shifts in the solution is not known. We thus have to consider a maximum number of shifts and the possibility for the model to generate a smaller number (thanks to binary variables \( b_j \)). Second, we must introduce binary variables for the requirement covering constraints (variables \( a_{ij} \), which are data in a classical set covering formulation).

3.1.2 Data

\[
\begin{align*}
  n & = \text{number of planning periods } i, \\
  m & = \text{maximum number of shifts } j, \\
  w_i & = \text{requirements for period } i, \\
  w_{max} & = \text{maximum requirement,} \\
  d_{min} & = \text{minimum shift length,} \\
  d_{max} & = \text{maximum shift length,} \\
  c_{max} & = \text{maximum total surplus for the entire requirement curve.}
\end{align*}
\]
3.1.3 Variables

first period of shift (spinning period)
3.2 The ILP approach

The use of LP leads us to model the problem in a specific way. We assume here that if a shift is not selected, its length is null.

- The criterion minimized $F_0$ then becomes $\sum_{j=1}^{n} d_j$;
- The formulation of the shift length constraint must allow null length for non selected shifts ($b_j = 0$). Thus (4) becomes:

$$d_{\text{min}} b_j \leq f_j - t_j \leq d_{\text{max}}, \quad \forall j$$

(7)

Note that it is not necessary to introduce $b_j$ in the right hand side of the constraint since optimizing $F_0$ will give automatically null length for non selected shifts.

- The definition of the covering indicator $a_{ij}$ is slightly different compared to constraint (5). For a selected shift $j$ ($b_j = 1$), $a_{ij} = 1$ if shift $j$ includes the planning period $i$ and is useful to cover the requirement $w_i$. On the opposite, $a_{ij} = 0$ if shift $j$ does not include period $i$ or creates surplus in this period, i.e.,

$$a_{ij} = \begin{cases} 1 & \text{if } i \in [t_j, f_j[, \text{ and shift } j \text{ is useful in period } i, \\ 0 & \text{otherwise.} \end{cases}$$

This is expressed by:

1. the constraint:

$$t_j - T(1 - a_{ij}) \leq i \leq f_j + T(1 - a_{ij}) - 1$$

(8)

where $T$ is a constant large enough. In the linear model with $T = n$, this constraint becomes:

$$t_j + n a_{ij} \leq i + n, \quad \forall i, j$$

(8.1)

and

$$f_j - n a_{ij} \geq i - n + 1, \quad \forall i, j$$

(8.2)

(8.1) makes $a_{ij} = 0$ for $i < t_j$ and (8.2) makes $a_{ij} = 0$ for $i \geq f_j$.

2. When $i$ is in the interval $[t_i, f_i[$, the requirement covering constraints (6) force $a_{ij}$ to be equal to 1 if it is necessary.

3. Moreover, to make sure that all $a_{ij} = 0$ for a non-selected shift, we add:

$$\sum_{i=1}^{n} a_{ij} \leq d_{\text{max}} b_j, \quad \forall j$$

(9)
3.3 The CLP approach

The model as defined in section 3.1 can be directly applied as CLP offers many modeling facilities. With Ilog Solver, constraint (5) will be simply formulated as follow:

\[ a_{ij} = (b_j = 1) \text{ and } (t_j \leq i) \text{ and } (i < f_j) \]  
\[ (10) \]

If the model as described in section 3.1 is logically sufficient in order to describe the whole problem to a CLP solver, it is necessary to add some constraints which help to get better performance by reducing the combinatorial aspect. Such constraints are:

- Elimination of symmetrical equivalent solutions by forcing the solver to create all shifts by increasing beginning time:
  \[ t_j \geq t_{j-1} \]  
  \[ (11) \]

- Bounds restriction: the number of shifts is at least equal to the maximum requirement
  \[ \sum_{j=1}^{m} b_j \geq w_{max} \]  
  \[ (12) \]

- Help for shift generation on the first ascending part of the requirement curve: if \( w_i > w_{i-1} \) and \( i \) is in this part of the curve, then we need at least \( w_i - w_{i-1} \) shifts to start at period \( i \). Otherwise, we can say that, for each \( i \), the number of shifts to start should be less than \( w_i \). To formulate this, we define some new variables:

\[ s_{ij} = \begin{cases} 
1 & \text{if shift } j \text{ starts at period } i, \\
0 & \text{if not.} 
\end{cases} \]

This starting shift indicator is defined as follow:

\[ s_{ij} = (b_j = 1) \text{ and } (t_j = i), \quad \forall i, j \]  
\[ (13) \]

and the constraint is:

\[ \sum_{j=1}^{m} s_{ij} \leq \begin{cases} 
w_i - w_{i-1} & \text{for each } i \text{ on the first ascending part of the curve,} \\
w_i & \text{for the others } i. \end{cases} \]  
\[ (14) \]

Since the CLP approach does not optimize a function, we have to introduce a bound \( c_{\max} \) and the following constraint:

\[ \sum_{i=1}^{n} c_i < c_{\max} \]  
\[ (15) \]
The bound will be iteratively decreased until the problem appears to be infeasible.

We stress the importance of the tuning strategy in order to achieve acceptable performance. It is necessary to finely control the order of the valuation of the variables. The most efficient method consists of giving values first to variables which should have a small effect on others. In the event that...
3.4.2 Test on a small problem with 48 periods

Three tests were performed with different bounds on the shift lengths.

The ILP approach was not able to produce any feasible solution within 20 minutes. The CLP found, for the 3 tests, a first solution in about 7 seconds but these solutions have no reason to be optimal ones since the resolution was stopped when the first solution was found. On the 3 tests, this first solution happened to be optimal one time. For the two other ones, they were far from the optimum (see table 1). Moreover, the CLP showed no ability to prove optimality or non-optimality in a reasonable time.

Both approaches were thus very disappointing even if CLP showed a capacity to generate feasible solutions quickly. Without going further with more examples, these first results were so bad compared to the classical
\[ n \quad = \quad \text{number of planning periods,} \]
\[ \mathcal{I} \quad = \quad \text{set of planning periods } (i = 1, 2, \ldots, n), \]
\[ m \quad = \quad \text{number of feasible shifts,} \]
\[ \mathcal{J} \quad = \quad \text{set of feasible shifts } (j = 1, 2, \ldots, m), \]
\[ x_j \quad = \quad \text{number of employees assigned to shift } j, \]
\[ c_j \quad = \quad \text{cost of one employee assigned to shift } j, \]
\[ a_{ij} \quad = \quad \begin{cases} 1 & \text{if period } i \text{ is covered by shift } j \\ 0 & \text{if not,} \end{cases} \]
\[ w_i \quad = \quad \text{requirements for period } i. \]

### 4.2 The ILP approach

This formulation of the SSP can be solved using a standard MIP package. For small problems, we obtain easily an optimal integer solution. Furthermore, in many larger problems, no branch and bound is required since the relaxed problem solution is integer. This can be explained by the almost unimodularity of the matrix. However, when the relaxed solution is fractional, it may be difficult to solve large scale problems without introducing some heuristic procedures. Such an heuristic is proposed in section 5.

Because of the usual difficulties met by branch and bound on large scale problems and to complete our comparison, we compared again the performances of this classical resolution method and the newer resolution approach which is the CLP, on the same formulation of the SSP. Some comparative results are given in section 4.4.

### 4.3 The CLP approach

We present here the CLP resolution of the set-covering formulation. For the needs of the method, the model is slightly different than the previous one. Note that, in a first time, we did not integrate the breaks in this approach.

The shifts library is represented as an object with three vectors: vector of beginning times, vector of ending times, vector of shift lengths. Variables \( x_j \) represent, as in the LP formulation, the number of employees assigned to shift \( j \). The domain of allowable values incorporates the integrity constraints. Unlike the LP formulation, \( a_{ij} \) is here a variable:

\[ a_{ij} = \begin{cases} x_j & \text{if planning period } i \text{ is covered by shift } j \\ 0 & \text{if not.} \end{cases} \]

We also define a vector of variables \( A_i \) with: \( A_i = \sum_{j=1}^{m} a_{ij} \).

The constraint (17) becomes then:

\[ A_i \geq w_i \quad \forall i \in \mathcal{I}. \quad (19) \]
We define $e_i$, the surplus as the difference between $A_i$ and $w_i$. We add some helpful constraints for the purpose of aiding the solution process by constraint propagation:

$$e_i \leq e_{\text{max}} \quad \forall i \in \mathcal{I}$$  \hspace{1cm} (20)

$$\sum_{i=1}^{n} e_i \leq E_{\text{max}}$$  \hspace{1cm} (21)

The last constraint corresponds to the objective function being minimised. The optimisation in CLP is performed by an iterative procedure. The procedure first obtains feasible solution and then add a new constraint to bound the objective function according to the last value found. Then it tries to find a new solution and so on.

4.4 Experimental results

4.4.1 Set-covering model tested on a very small problem with 10 periods

Data: correspond to 3.4.1. There is 18 alternate shifts.

Results:

- both approaches give a surplus of 2
- execution times on a P486 100Mhz:
  - ILP <1 second
  - CLP 41 seconds (12 iterations to find the optimal solution)

4.4.2 Set-covering model tested on a small problem with 48 periods

Three tests were performed with different bounds on the shift lengths, yielding to about 400 alternate shifts.

For the 3 tests, the ILP finds an optimal solution in less than 1 second. The CLP is much less efficient. For two tests out of three, a first solution was found within 1 second but no better one can be found within 20 minutes.

4.4.3 Comparison of the 4 approaches

Table 1 shows clearly that, among the 4 considered approaches, only the set-covering model, solved by ILP seems efficient for the SSP. The following section aims then at improving this approach to allow, at the same time, a high level of scheduling flexibility and a quasi-optimal resolution of the problem.
<table>
<thead>
<tr>
<th>Name</th>
<th>Length step in minutes</th>
<th>Begin step in minutes</th>
<th>Number of Shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>no break(a)</td>
</tr>
</tbody>
</table>

The table appears to be incomplete or contains unclear data. The first row is partially visible and seems to be missing some entries.
Test 1: Library B60-60 (3678 shifts)

<table>
<thead>
<tr>
<th>Day</th>
<th>(P')</th>
<th>(H)</th>
<th>total CPU(sec)</th>
<th>Difference $\frac{H-P'}{P'}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>643.3</td>
<td>648.3</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Tuesday</td>
<td>669.4</td>
<td>669.4</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Wednesday</td>
<td>654</td>
<td>657</td>
<td>5</td>
<td>56</td>
</tr>
<tr>
<td>Thursday</td>
<td>834.8</td>
<td>837.1</td>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>Friday</td>
<td>636.3</td>
<td>638.3</td>
<td>3</td>
<td>35</td>
</tr>
<tr>
<td>Saturday</td>
<td>651.6</td>
<td>651.6</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>Sunday</td>
<td>743.3</td>
<td>744.7</td>
<td>2</td>
<td>31</td>
</tr>
</tbody>
</table>

Average 0.29

Test 2: Library B60-20 (10686 shifts)

<table>
<thead>
<tr>
<th>Day</th>
<th>(P')</th>
<th>(H)</th>
<th>total CPU(sec)</th>
<th>Difference $\frac{H-P'}{P'}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>596</td>
<td>597</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>Tuesday</td>
<td>609</td>
<td>614</td>
<td>3</td>
<td>69</td>
</tr>
<tr>
<td>Wednesday</td>
<td>612.8</td>
<td>616.1</td>
<td>4</td>
<td>43</td>
</tr>
<tr>
<td>Thursday</td>
<td>782.9</td>
<td>783.6</td>
<td>2</td>
<td>52</td>
</tr>
<tr>
<td>Friday</td>
<td>584.9</td>
<td>584.9</td>
<td>0</td>
<td>53</td>
</tr>
<tr>
<td>Saturday</td>
<td>527.2</td>
<td>527.9</td>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>Sunday</td>
<td>707.5</td>
<td>710.5</td>
<td>3</td>
<td>50</td>
</tr>
</tbody>
</table>

Average 0.31

(P') = relaxed LP; (H) = integer solution given by heuristic

Table 3: The heuristic efficiency tested with two different libraries

5.3 Quality of solutions relative to the level of flexibility

The large number of shift alternatives increases the complexity but improves the labor utilisation. We study here, using our heuristic, the improvement of the solution relative to the library size. We define two ratios of productivity P1 and P2:

- **R**: Requirement, i.e., total number of hours required.
- **ProdH**: Productive Hours, i.e., number of hours spent working, exclusive of the breaks.
- **PaidH**: Paid Hours, i.e., including breaks.
- **Ratio P1** = $R / \text{ProdH}$ (%).
- **Ratio P2** = $R / \text{PaidH}$ (%).
<table>
<thead>
<tr>
<th>Library name</th>
<th># of Shifts</th>
<th>R</th>
<th>ProdH</th>
<th>PaidH</th>
<th>P1 %</th>
<th>P2 %</th>
<th>CPU sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>B60-60</td>
<td>3678</td>
<td>494</td>
<td>576</td>
<td>634</td>
<td>85.8</td>
<td>77.9</td>
<td>20</td>
</tr>
<tr>
<td>B60-30</td>
<td>6879</td>
<td>494</td>
<td>549</td>
<td>620</td>
<td>90.0</td>
<td>79.7</td>
<td>38</td>
</tr>
<tr>
<td>B60-20</td>
<td>10686</td>
<td>494</td>
<td>532</td>
<td>596</td>
<td>92.9</td>
<td>82.9</td>
<td>63</td>
</tr>
<tr>
<td>B60-10</td>
<td>20079</td>
<td>494</td>
<td>521</td>
<td>591</td>
<td>94.9</td>
<td>83.7</td>
<td>124</td>
</tr>
<tr>
<td>B30-30</td>
<td>12516</td>
<td>494</td>
<td>545</td>
<td>609</td>
<td>90.7</td>
<td>81.1</td>
<td>48</td>
</tr>
<tr>
<td>B30-20</td>
<td>18421</td>
<td>494</td>
<td>529</td>
<td>592</td>
<td>93.4</td>
<td>83.4</td>
<td>106</td>
</tr>
<tr>
<td>B30-10</td>
<td>36561</td>
<td>494</td>
<td>513</td>
<td>581</td>
<td>96.4</td>
<td>86.0</td>
<td>199</td>
</tr>
</tbody>
</table>

*Note that BX-Y corresponds to a length step of X minutes and begin step of Y minutes.*

Table 4: Solutions quality compared to different level of flexibility

![Figure 1: Productivity as a function of library sizes](image.png)

Table 4 shows that, as the flexibility increases, it becomes much easier to meet the requirements generating less and less surplus. With the B30-10 library, the productivity level is already over 96%. Obviously, the B10-10 library would possibly provide a better solution but with a very small improvement of productivity compared to the increase of the problem size (108,000 variables instead of 36,000). Looking at the requirement and covering curves, we could also observe that, when the number of feasible shifts allows it, even the peaks of the staff requirement are covered without generating much surplus around.

Figure 1 shows the productivity evolution (P1 is represented) while length step and begin step are becoming sharper. This figure leads us to two observations. First, and that is not very surprising, the improvement rate is very strong when flexibility is low and become weaker as flexibility increases. Second, and this is a more specific result of our experimental study, we can
notice that precision on the begin step is more efficient than precision on the length step. That is shown by the fact that the increase rate is stronger for the plain curve than for the dotted one. Consider for instance results obtained with B60-30. We clearly see that, increasing the size of the library, it is better to move to B60-20 (more precision on begin step) than to B30-30 (more precision on the length step). In this particular case, we can even notice that B60-20 dominates B30-30 with regard to the two criteria, productivity and number of shifts. If we consider now moving from B60-20, it is also better, in terms of productivity, to sharpen the begin step (B60-10) than the length one (B30-20). Even if this time, there is no dominated solution since B60-10 is a bit larger than B30-20, the improvement brought by B60-10 compared to B60-20 is only about 0.5% whereas the number of shifts is almost double. Of course, execution time increases also with flexibility but 3-4 minutes is still a reasonable time for getting such excellent results.

6 Conclusion
References


