

# Staff assignment using network flow techniques

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## **Résumé**

La détermination des horaires du personnel est une tâche à faire dans toute organisation de plusieurs employés. Dans cette recherche, nous revisitons sa modélisation comme un problème de coût minimum à débit maximal dans un réseau. Cette modélisation possède l'avantage de permettre une résolution par un algorithme s'exécutant en temps polynomial. Outre les contraintes de disponibilité et de compétences, nous considérons comme un ensemble de contraintes supplémentaires : la charge contractuelle de travail, la satisfaction des employés traitée sous l'angle de contraintes de rotation, les tâches nécessitant plusieurs employés, des incompatibilités de tandems, ne pouvant être affectés à une même tâche. Nous considérons plusieurs type de coûts à minimiser : les heures supplémentaires, les catégories d'employés, les retards dans l'accomplissement des tâches, les profits associés à l'exécution des tâches. Nous analysons aussi les limites de notre modèle, en montrant différents types de contraintes qui transforment le problème en un problème NP-dur.

## **Mots-clés**

Affectation de personnel, Théorie des graphes, Classe P

## **Summary**

Staff scheduling, also known as timetabling, is a task to be done in any organization with several employees. In this paper, we revisit its modeling as a minimum cost maximum flow problem in a network, which has the decisive advantage to be solvable with a polynomial time algorithm. Besides the usual availability and skills constraints, we consider additional constraints : targeted workload, satisfaction of employees seen as rotation constraints, tasks requiring several employees, pairs of employees which can not be assigned to a same task. We consider several cost specifications : types of employees, overtime, delayed tasks, profit associated with the execution of a task. We also analyze the limits of our model, showing types of constraints that transform the problem into an NP-hard problem.

## **Keywords**

Rostering, Graph Theory, Class P

# 1 Introduction

Staff assignment problems, or more generally assignment problems, consist in assigning  $n$  persons, seen as resources, to  $s$  tasks or services. In real life staff assignment has to take into account numerous constraints such as time constraints, qualifications constraints, contractual constraints, etc. Some problems only ask for a feasible solution, in which all constraints are valid. Others need also to find an optimized schedule in the sense of maximizing or minimizing an objective function. We present in this paper a model for staff assignment problem which uses network flow techniques and still remains solvable in polynomial time. Staff scheduling, which is the process of building timetables for employees, has been studied since at least 1954, for example by Edie [7] and Dantzig [6]. Recent reviews of the literature on assignment problems can be found in [3, 16] and a survey on staff scheduling can be found in [10, 9].

In this survey [9], a partition of staff scheduling problems into six modules is proposed : demand modeling, whose aim is to determine how many staff are needed at different times over some planning horizon, days off scheduling, shift scheduling, line of work construction, task assignment and staff assignment. Applications are then described in transportation systems, call centers, health care systems, protection and emergency services, civic services and utilities, venue management, financial services, hospitality and tourism, retail, manufacturing. Three main solution approaches are described : constraint programming, meta-heuristics and mathematical programming. The same authors have written an annotated bibliography of some 700 references in personnel scheduling and rostering. This collection of references is classified by module, by applications area and by solution method.

Choosing the best rostering implies not only that all constraints inherent to the enterprise are valid, but also to maximize employee's satisfaction. In [15], it is shown, using a learning model, that rotation is more profitable than specialization if there is uncertainty about employees and/or technology. It is argued that, using rotation, firms learn better about matches between employees and jobs. As discussed in [9], several methods can be used to solve rostering problems, but the choice of a method strongly depends on the type of rostering problem to be solved. In this paper, some rostering problems are shown to be polynomially solvable using network flow techniques. In [11], a network model is proposed to solve a scheduling problem in which services have specific processing requirements, release time and due date on uniform parallel machines. The model is then adapted to tackle three optimization problems : the maximum lateness problem which consists in the minimization of the last service completion time, the minimum completion problem whose goal is to maximize the minimum completion rate, and the maximum utilization problem, which, given a collection of disjoint intervals, minimizes the maximum amount of work assigned to each interval. In [2], a network flow model is constructed to represent a sequence of shifts of work and rest periods over several weeks. Workforce rotation is also treated, and the authors extend their model to include precedence constraints between different types of shifts, as well as bounds on the number of consecutive working periods in a same shift. Although network flow models are appropriate for a wide variety of problems, they face some strong limitation on the set of shift scheduling constraints. In [12], the authors characterize the complexity of two variants of the standard assignment problem. With additional split preference constraints, the problem can still be solved as a minimum cost maximum flow problem, whereas adding join preference constraints makes the problem NP-hard.

The remainder of this paper is organized as follows : Section 2 describes the considered problem and gives its formulation as a mathematical programming problem. Section 3 describes a graph model and refers to polynomial time algorithms to solve the problem. Limitations of our model in terms of additional constraints, or extensions of the problem, are discussed in Section 4. Finally, Section 5 gives our conclusion.

## 2 Problem description

The considered problem consists in assigning workers to services over a time horizon. It involves time constraints, availability, skill, workload and rotation constraints. The time horizon is divided into periods, during which services may be processed. Each service is associated with one or several periods, during which it may be processed, and may be associated with a set of necessary skills. Each worker has his own subset of availability periods, his own subset of skills, a contractual due working time, and may express preferences for some services. The objective function to be optimized considers both assignment costs and the satisfaction of the staff. Its mathematical formulation as an integer programming problem IP is as follows :

Let's consider the following indicator variable  $x$ .

$$x_{ijt} = \begin{cases} 1 & \text{if worker } i \text{ is assigned to service } j \text{ at period } t \\ 0 & \text{otherwise} \end{cases}$$

where

$$\begin{aligned} i &\in \{1, \dots, N\} \text{ which represents the set of workers} \\ j &\in \{1, \dots, M\} \text{ which represents the set of services} \\ t &\in \{1, \dots, T\} \text{ which represents the set of periods} \end{aligned}$$

Skills parameters, availability parameters and contractual due time parameters are represented as

$$S_{ij} = \begin{cases} 1 & \text{if worker } i \text{ has the required skills to perform service } j \\ 0 & \text{otherwise} \end{cases}$$

$$A_{it} = \begin{cases} 1 & \text{if worker } i \text{ is available at period } t \\ 0 & \text{otherwise} \end{cases}$$

$$A_{jt} = \begin{cases} 1 & \text{if service } j \text{ may be processed at period } t \\ 0 & \text{otherwise} \end{cases}$$

$$P_i \in \mathbb{N}^* \quad \text{contractual number of working periods for worker } i$$

$$P_j \in \mathbb{N}^* \quad \text{required number of periods to perform service } j$$

The constraints to be satisfied are the following ones :

- a) Each worker may only be assigned to at most one service per period

$$\sum_j x_{ijt} \leq 1 \quad \forall i, t$$

- b) Each service may only be processed by at most one worker per period

$$\sum_i x_{ijt} \leq 1 \quad \forall j, t$$

- c) A service may be processed only by workers with required skills

$$x_{ijt} \leq S_{ij} \quad \forall i, j, t$$

- d) Assigned workers must be available at the designed period

$$\sum_j x_{ijt} \leq A_{it} \quad \forall i, t$$

- e) Services must be processed during due periods

$$\sum_i x_{ijt} \leq A_{jt} \quad \forall j, t$$

- f) Contractual due working time must be respected

$$\sum_{j,t} x_{ijt} \leq P_i \quad \forall i$$

- g) Service completion. In the basic case,  $P_j = 1 \quad \forall j$

$$\sum_{i,t} x_{ijt} \geq P_j \quad \forall j$$

The objective function to be minimized is composed of several components. We consider four components : the level of a worker, its contractual due working time, the rotation between assigned services, and its wishes about service assignment.

- $L \in \mathbb{N}^*$  is a vector of size  $n$  which represents the level or status of the workers. For example, the status could be "internal worker" or "external worker". The values are assumed to be in increasing order, which means that a higher value indicates a greater priority. For example, "external worker" may be represented by 1 and "internal worker" may be represented by 2.
- $H = (h)_{i,t} \quad i \in \{1, \dots, n\} \quad t \in \{1, \dots, T_h\}$   
is a matrix of historical assignments, also called rostering or "line of work".  $h_{it}$  gives the assignment, if any, of worker  $i$  at period  $t$ . From  $H$ , the number  $T_{ij}$  of periods since last assignment of worker  $i$  to service  $j$  can be deduced, as well as the number of worked period  $Hw_i$  of worker  $i$ .

–  $W = (w)_{ij} \quad i \in \{1, \dots, n\} \quad j \in \{1, \dots, m\}$

is a matrix of assignments wishes.  $w_{ij}$  gives the assignment wish of worker  $i$  for service  $j$ . The values of  $W$  are assumed to belong to  $\{1, \dots, k\}$ , where  $k \geq 1$ ,  $k \in \mathbb{N}^*$ . The values are assumed to be in increasing order, which means that a higher value indicates a greater priority. For example,  $k = w_{ij_1} > w_{ij_2} = 1$  means that worker  $i$  prefers to be assigned to service  $j_1$  rather than to service  $j_2$ .

The components of the objective function are formulated as follows :

a) Workers of higher levels are preferred

$$\sum_{ijt} \frac{1}{L_i} x_{ijt}$$

b) Rotation among services assignments is preferred

$$\sum_{ijt} \frac{1}{T_{ij}} x_{ijt}$$

c) Workers who are farthest from fulfilling their contractual due working time are preferred

$$\sum_{ijt} \frac{Hw_i}{P_i} x_{ijt}$$

d) Wished services assignments are preferred

$$\sum_{ijt} \frac{1}{W_{ij}} x_{ijt}$$

According to what is considered more important, priorities can be assigned to each component of the objective function. Then, if we partition the set of components with respect to priority (two components belong to the same part if and only if they have the same priority), our priorities induce a total order  $>$  on the parts of the partition. For example, if a and c both have the highest priority, followed by b, and d has the lowest priority, then a partition of the components into  $S_1 = \{a, c\}$ ,  $S_2 = \{b\}$  and  $S_3 = \{d\}$  induces the following total order :  $S_1 > S_2$ ,  $S_1 > S_3$ ,  $S_2 > S_3$ .

Assuming such a total order  $>$  exists, it is possible to define a single objective function which satisfies the priorities associated to the parts. The principle is to set coefficients  $\alpha(c)$  to each component  $c$  of the objective function in such a way that if two different components  $i, j$  belong respectively to two different parts  $P_1, P_2$  with  $P_1 > P_2$  then the smallest possible variation (obtained by changing a single variable from 0 to 1) of  $i$  is strictly larger (hence more important) than the maximal possible variation of  $j$  (obtained by changing all variables from 0 to 1), which is at most the maximum weighted value of  $j$ .

Without coefficient, each component of the objective function is bounded by  $u = n \cdot m \cdot T$ . Let us fix the coefficient for  $\alpha(d)$  to 1. The smallest possible unweighted variation for (b) is  $\frac{1}{\max_{i,j} T_{ij}}$ . In order to ensure that the smallest variation of (b) is always larger than the maximum value of (d), a possible choice for its coefficient is

$$\alpha(b) = n \cdot m \cdot T \cdot \max_{i,j} T_{ij}.$$

The smallest possible variation for (a) is  $\frac{1}{\max_i L_i}$ . Since the maximum weighted value for (b) is not more than  $(n \cdot m \cdot T)^2$ , a possible choice for the coefficient is

$$\alpha(a) = (n \cdot m \cdot T)^2 \cdot \max_i L_i.$$

Finally, the smallest possible variation for (c) is  $\min_i \frac{Hw_i}{P_i}$ , therefore a possible choice for the coefficient is

$$\alpha(c) = (n \cdot m \cdot T)^2 \cdot \max_i \frac{P_i}{Hw_i}.$$

Finally, the objective function is defined as :

$$\text{Obj} = \min \sum_{ijt} \left( \alpha(a) \frac{1}{L_i} + \alpha(c) \frac{Hw_i}{P_i} + \alpha(b) \frac{1}{T_{it}} + \alpha(d) \frac{1}{W_{ij}} \right) x_{ijt}$$

### 3 Resolution

Integer programming is widely used for solving rostering problems, and it offers a lot of flexibility for including constraints of various types. However, solving an integer program is NP-hard. We focus here on a modeling using graph concepts. As will be discussed, this modeling has some limitations, but it permits a resolution in polynomial time.

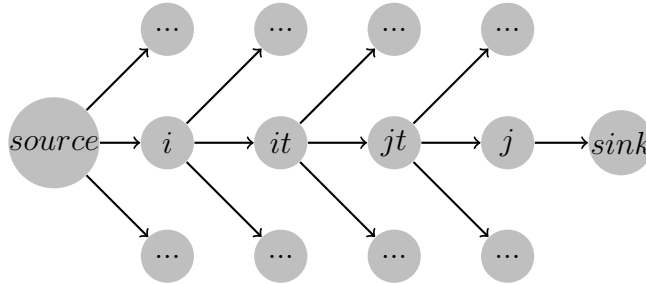


FIGURE 1 – Graph model of the staff assignment problem.

Let's consider the following graph  $G = (V, E, w, c)$ , illustrated with Figure 1 where  $V$  is a set of vertices,  $E$  a set of arcs,  $w$  a cost function on the arcs and  $c$  a capacity function on the arcs. More precisely, the set  $V$  of nodes is defined as

- a source node  $s$
- each worker  $i$  is a node
- each couple  $(i, t)$  such that worker  $i$  is available at period  $t$ , is a node
- each couple  $(j, t)$  such that service  $j$  is available at period  $t$ , is a node
- each service  $j$  is a node
- a sink node  $t$

The set  $E$  of arcs is defined as

- the source  $s$  is linked to each worker  $i$  by arc  $(s, i)$
- node  $i$  is linked to each node  $(i, t)$  by an arc  $(i, (i, t))$

- node  $(i, t)$  is linked to node  $(j, t)$  by an arc  $((i, t), (j, t))$  if worker  $i$  has the necessary skills to perform service  $j$ .
- node  $(j, t)$  is linked to service  $j$  by an arc  $((j, t), j)$
- Each service  $j$  is linked to the sink  $t$  by an arc  $(j, t)$

The capacity function  $c$  is defined as

$$c : E \rightarrow \mathbb{R}$$

$$e \mapsto \begin{cases} P_i(1 + \epsilon) & \text{if } e = (s, i), \text{ where } \epsilon \geq 0 \\ P_j & \text{if } e = (j, t) \\ 1 & \text{elsewhere} \end{cases}$$

The cost function  $w$  is defined as

$$w : E \rightarrow \mathbb{R}$$

$$e \mapsto \begin{cases} \alpha(a) \frac{1}{L_i} + \alpha(c) \frac{Hw_i}{P_i} & \text{if } e = (s, i) \\ \alpha(b) \frac{1}{T_{ij}} + \alpha(d) \frac{1}{W_{ij}} & \text{if } e = ((i, t), (j, t)) \\ 0 & \text{elsewhere} \end{cases}$$

This multi-skilled rostering problem has been formulated as a minimum cost maximum flow problem. A maximum flow in this network cannot exceed the number of tasks, if all task have only one period length, or the total number of needed working periods. Since they are all to be performed, a solution exists if and only if the maximum flow in this graph is  $m$ . Finding a minimum cost staff schedule consists in finding a maximum flow (hence of value  $m$ ) at minimum cost in the network. Several algorithms are known to solve this problem efficiently, i.e. in polynomial time. One of them consists in first finding a maximum flow of any cost for instance using the Edmonds-Karp algorithm [8], then in finding the minimum cost flow using negative cost circuits reductions to iteratively decrease the cost until the minimum is reached [13]. Alternatively, a minimum cost flow can be found in a more direct way with the Busacker-Gowen algorithm [4], which starts from a null flow, and iteratively increases it by finding shortest paths from the source to the sink according to the costs and the residual capacities. In [5], various combinations of shortest path and negative cost circuit detection algorithms are presented. As shortest path computation is the basis of network flow methods, it is important to consider very efficient algorithms. As far as we know, the best polynomial time shortest path algorithm is given by Ahuja *et al.* [1].

## 4 Extensions and limits

Rostering problems consist in finding a roster which is feasible, i.e. satisfying all constraints, while optimizing a cost function. Unfortunately, it is not always possible to satisfy all constraints, so that a feasible solution can be exhibited. In such cases, constraints have to be checked in order to know which ones make the problem unfeasible. For instance, in our model, it is possible that some services are not done in the optimal solution. This might happen if the workload is not sufficient to support the demand in services. This restriction comes from the contractual due working time. If the lack of workload is not too big, this constraint violation can be fixed

by allowing overtime. To integrate it in the network flow model, new nodes  $i'$  are included as new workers, with in and out arcs similar to  $i$  (i.e, arcs  $(s, i')$ ,  $(i', (i, t))$ ). The capacity  $c(s, i')$  of the arc  $(s, i')$  corresponds to the maximal allowed overtime, and  $c(i', (i, t))$  is 1, for each arc of the form  $(i', (i, t))$ . In order to avoid, if possible, the use of overtime, the cost  $w(s, i')$  of arc  $(s, i')$  is set at a significantly larger value than  $w(s, i)$ . This is illustrated with Figure 2.

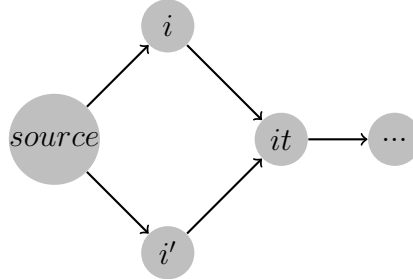


FIGURE 2 – Partial model with overtime constraint.

In real problems, a service often requires several sets of skills to be processed, or may take several periods to be done. One way to include this constraint is to split the task into several vertices, one for each set of skills, and one for each needed period. Cost and weight associated to the arcs remain the same. In the situation of several employees working at the same period on a same service, conflicts between pairs of workers might happen. To avoid conflicts, managers often try not to have such pairs working together. This case can still be included in a network flow model, with the addition of a new node, and the fusion of two nodes as shown in Figure 3.

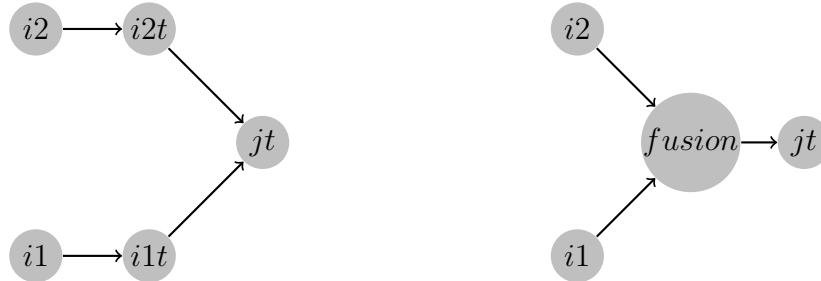


FIGURE 3 – Pair of incompatibles workers.

Although quite a lot of constraints can be included in a network flow model, there are several types of constraints that can not be included. For example, join preference constraints, in which couples of workers should be assigned the same service at the same time, can not be modeled in our network flow model. In [12], the authors proved that such a problem is NP-hard. Variations on staff assignment problems often lead to NP-hard problem, as proved by several authors (see among others [14, 17]).

## 5 Conclusion

In this paper, we revisit a network flow model for rostering problems. We first formulate such a problem as an integer program, in which the strong constraints are expressed as inequalities, and the weak constraints (employees' level, rotation, contractual working time and wishes) are incorporated in the objective function, with coefficients to express user-defined priorities. On the basis of this formulation, we then construct the network model, in which we ensure strong constraints satisfaction either through capacities on the arcs, or directly by the network structure, while the weaker constraints are expressed by setting appropriate weights on the arcs. We then discuss some extensions (overtime, multi-periods or multi-skills task, employees incompatibility) that could easily be added to our model and how, and finally point out the difficulty of including joint preference constraints.

Integer programming is a very popular model for rostering problems. This is due to its flexibility and the existence of powerful solution software. However, no efficient exact solution method exists when the problem becomes large. The above discussion intends to show the reader that the network flow model also has a lot of flexibility, through the freedom offered mainly by the capacity and weight functions, but also by the network structure. Moreover, contrary to integer programming, polynomial time algorithms exist to solve network flow models. Therefore, those models should be considered first by practitioners facing large scale rostering problems.

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