

# Using Constraint Programming and Local Search for Scheduling of Electricité de France Nuclear Power Plant Outages

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**Abstract:** The French nuclear park comprises 58 nuclear reactors distributed through the national territory on 19 geographical sites. They must be repeatedly stopped, for refuelling and maintenance. The scheduling of these outages has to comply with various constraints, regarding safety, maintenance logistic, and plant operation, whilst it must contribute to the producer profit maximization. We present in this paper a new approach for modelling and solving this problem. It combines three optimization techniques: constraint programming, local search and linear programming. Constraint programming and local search are combined to solve the problem in approximated way. They search, relatively to an heuristic cost criterion, a good outages schedule. The linear programming is used to precisely evaluate the quality of the solutions found and to produce marginal costs used for updating the heuristic cost in order to escape from the local optima. The effectiveness of the approach is tested on the simple heuristic cost criterion which consists to minimize the numbers of outages in winters. The experimental results are satisfactory.

**Keywords:** Constraint Programming, Local search, Linear Programming, Scheduling, Cumulative Constraint.

## 1 Introduction

For modelling and solving optimization problems, Constraints Programming (CP) [2] have been proved to be a very flexible approach. CP can be applied to express in a very flexible way real-world problems and using a good enumeration strategy, it may produce a good first solution. However, it cannot be used to solve straightly some constraint and optimization problems. For such problems, local search methods [1] give, in general, very good practical results, that is near-optimal solutions in reasonable computing time.

In attempt to gain both efficiency of local search and the flexibility of constraint programming, recent research has started addressing the combination of these two techniques (e.g., [3] presents an overview of possible uses of local search in constraint programming). In [4] local search is viewed as a sequence of auxiliary problems which are described and solved by constraint programming.

Our aim in this paper is to show that combining CP with local search constitutes a powerful approach to model and solve a real world problem. It consists of the scheduling of outages of the nuclear power plants of the french utility for electricity supply, Electricité de France (EDF).

This paper is organized as follow. In section 2 we describe the problem and the conventional approach currently used to solve it. Section 3 informally presents our alternative approach to model and solve the problem, based on three components. Section 4 focus on the constraint based local search component. We conclude by presenting our future work in section 5.

## 2 Problem description

EDF nuclear park comprises 58 nuclear reactors distributed through the national territory on 19 geographical sites. They must be repeatedly stopped, for refuelling and maintenance. The scheduling of these outages has to comply with various constraints, regarding safety, maintenance logistic, and plant operation, whilst it must contribute to the producer profit maximization.

This problem consists of two dependent sub-problems :

1. determining a schedule of nuclear power plant outages, on an horizon of 5 years, for the 58 reactors. The schedule must satisfy constraints in order to comply with the limitations of the resources which are necessary to achieve the refuelling and maintenance operations. These constraints are designated as "placement constraints".
2. determining an optimal production plan, i.e. a quantity of energy to produce by each reactor at each step of time (week). The production plan must satisfy the "production constraints" (upper bound on production, refuelling laws, ... ).

The objective is to satisfy the demand for electricity at lower cost.

At the present time, this problem is modelled and solved by techniques of Mixed Integer Linear Programming together with decomposition techniques. In this approach it appears as a very hard problem combining about 5000 binary variables, 20000 continuous variables and 15000 constraints. Moreover, because the decomposition leads to separate the problem in sub-problems, each one dealing with a particular site, some placement constraints relating reactors of different sites are not satisfied. In addition, the search space of outages schedule is reduced in order to maintain an acceptable computing time. This makes it possible to have models of reasonable size but the solutions found are only locally optimal. Moreover, the resulting software is complex and the architecture adopted does not offer a very good flexibility.

## 3 An alternative approach

In order to deal with the drawbacks above, we developed a new approach allowing to separate the problem in two sub-problems : determining a schedule of the nuclear power plant outages and determining a production plan. Precedent studies carried out at EDF Research and Development Division have concluded that it was possible to replace the real criterion to be optimized by an heuristic one depending only on the start dates of the outages. To produce this heuristic criterion one must take into account the demand for electricity to be satisfied and the cost of different productions means (nuclear fuel, coal, gas, ...). Indeed, at each step of time, the energy produced by the nuclear park can be insufficient to satisfy the demand and more expensive energy sources must be used. Thus, the availability of the nuclear park is the key feature used to construct the heuristic criterion. We propose here an architecture allowing to implement an approach based on this criterion. It consists of three main components. The first one is a constraint based local search (CPLS) component which models and determines, relatively to the heuristic cost criterion, a good outages schedule. Taking into account the fixed outages schedule, the second component, named "PLAFIGE" and based on linear programming techniques, determines an optimal production plan. The third component constitutes an interface between the two others. It initializes the cost criterion and updates it by using information resulting from the two first components. This updating aims at improving solutions found.

In the CPLS component, all the "placement" constraints are modelled. To do so, the well known global constraint cumulative is widely used (We have used the CHIP C++ library [5]). The outages schedule must be determined in such a way that there is a realizable production plan. Thus, the production constraints are integrated by using the Forward Checking method. At the root

of the search, in order to satisfy these constraints and taking into account the fuel stock levels, we calculate for each reactor the earliest and latest dates for the start of each outage. Each time a start date of an outage is fixed, we compute a lower and upper bounds for the stock level of the production period which will follow these outage. These bounds are then used to reduce the domain of the following outage, and so on. To produce the first satisfactory schedule, the heuristic search is based on the expertise of power plant operators. It aims at minimizing the unavailability of the nuclear park in winters (periods of keen demand). When the first schedule is determined, it is improved by local search. As in [4], the local search is viewed as a sequence of auxiliary problems which are described and solved by constraint programming. Each auxiliary problem is obtained by assigning to the current values the dates of outages of all plants *except one*. The resulting simple problem is solved to optimality with a branch-and-bound search. This process is iterated until reaching a local optimum.

The "PLAFIGE" component is used to precisely evaluate the quality of outages schedule. It express the real criterion to be optimized under the production constraints as a linear program (when all the start time dates of the outages are fixed, the remainder variables are continuous). The description of this component is beyond the scope of this article. We consider it as a black box. It receive a fixed outages schedule and determines an optimal production plan and some marginal costs. And then these marginal costs will be exploited at the interface component to update the heuristic criterion.

## 4 Modelling and optimizing the heuristic cost criterion

Let us introduce the following notations:

- $\langle i, k \rangle$  : the  $k$ -the outage of the plant number  $i$ ;
- $T_{ik}$  : the start time date of the outage  $\langle i, k \rangle$ ;
- $D_{ik}$  : the duration of the outage  $\langle i, k \rangle$ ;
- $Pmax_i$  : the maximal power of the plant  $i$ ;
- $Limit(t)$  : the fixed unavailability limit of the nuclear park at the step time  $t$ .
- $\varphi(t) = \sum_{\langle i, k \rangle: T_{ik} \leq t < T_{ik} + D_{ik}} Pmax_i$  : unavailability of the nuclear park at the step time  $t$ .

For each vector of unavailability limits, the following problem is solved at the CPLS component.

$$(CSOP) \begin{cases} \text{minimize} & Cost = \sum_t \eta(t) & (1) \\ \text{s.t} & CSP(T) & (2) \\ & \varphi(t) \leq Limit(t) + \eta(t), t = 1, \dots, \text{horizon} & (3) \end{cases}$$

where  $T$  is the vector of the start time dates of the outages,  $CSP(T)$  are the placement and production constraints to be satisfied,  $\eta(t)$  are finite domain variables and  $Cost$  is the finite domain variable to minimize.

The optimization process begins by stating the model and storing the current search state, then the first solution is searched. Let  $S$  represent the current solution and  $t_{ik}$  the current value of the  $T_{ik}$  variable. In order to improve the current solution, the local search takes place. A local move consists of changing the start time date of outages of only one plant. Let  $j$  the number of this plant. After restoring the stored search state, the constraints  $\{T_{ik} = t_{ik}, \forall \langle i, k \rangle : i \neq j\}$  are added to the  $(CSOP)$  problem and is solved to optimality with a branch-and-bound search. If the solution found is better than the current one, it is considered as the new current solution. The process is iterated by considering another plant and so on until a local optimum is

found. The corresponding schedule is then used by the "PLAFIGE" component to construct the production plan. This leads to evaluate in a precise way the quality of the outages schedule and produces interesting marginal costs. They are used at the interface component to update the heuristic cost in order to escape from the local optima. The fixed unavailability limits are increased or decreased according to the importance of the marginal costs.

The architecture allows to focus on the way the heuristic cost criterion is initialized and updated. Different possibilities are now under study. However, the effectiveness of the local search component is tested on the heuristic cost criterion which consists to minimize the numbers of outages in winters. The obtained experimental results are satisfactory. Indeed, we obtain, in few seconds (2 to 5), solutions with at most four parallel outages in winters.

## 5 Conclusion

In this paper a new architecture is proposed for modelling and solving the problem of scheduling of EDF nuclear power plant outages. It consists of three components. The first one, allows to model and solve the problem. It is a constraint based local search component which optimizes an heuristic cost criterion in order to guide the search. The second component allows to evaluate in a precise way the quality of the solutions found. It also provides interesting marginal costs useful to update the heuristic cost criterion in order to escape from local optima. The third component constitutes an interface between the two first one. It initializes and updates the heuristic cost criterion. The flexibility of the architecture allows to experiment several ways to construct and update the heuristic criterion. The effectiveness of the approach has been tested on the simple heuristic cost criterion which consists to minimize the numbers of outages in winters. The experimental results are satisfactory. We are now studying a better way to construct and update the heuristic cost criterion.

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