

Scheduling of EDF's reactor outages

State of the art, current works and new roads

M. Porcheron

EDF R&D OSIRIS

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- 2 Current approaches
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Production portfolio

- ≈ 60 Nuclear Power Plants (NPP), which have to be periodically stopped and refuelled (indice $i \in \{1...I\}$)
- ≈ 50 "Conventional" Thermal Units (CTU), which can continuously produce (e.g. fuel, coal, gas units)(indice $j \in \{1...J\}$)
- ≈ 50 groups modeling Sells/Purchases on the Markets (MG) (indice $g \in \{1...G\}$)

Problem to be solved

- Find a NPP outage planning and refueling quantities which minimize a "production cost" over a time horizon of 5 to 10 years
- While satisfying :
 - ▶ The load demand on each time step $t \in \{1 \dots T\}$
 - ▶ NPP, CTU and MG operating constraints
 - ▶ Scheduling and resource constraints on NPP outages
- Some important features of EDF portfolio :
 - ▶ NPP production cost is much more lower than CTU and MG ones
 - ▶ NPP installed power represents about 60% of the whole installed power
 - ▶ Basically, NPP outages must take place during periods of low demand

Uncertainties

- *Load demand* to be satisfied on each time step, D_t^δ ;
- *Prices and capacities* of sells/purchases on the spot market, correlated to demand through temperature : $C_{g,t}^\delta, Pmax_{g,t}^\delta$;
- *Availability* of CTU (affected by production losses due to faults) : $Pmax_{j,t}^\theta$;
- *Initial stock level* of NPP : X_{i,t_0}^λ ;
- *Duration of outages* of NPP : $Lga_{i,k}^\psi$;
- *Availability* of NPP (affected by production losses due to faults occurring between outages) : $Pmax_{i,t}^\phi$.

We note $\Omega \subseteq \Delta \times \Theta \times \Lambda \times \Psi \times \Phi$ the whole stochastic space, ω a given scenario in Ω

Optimization process

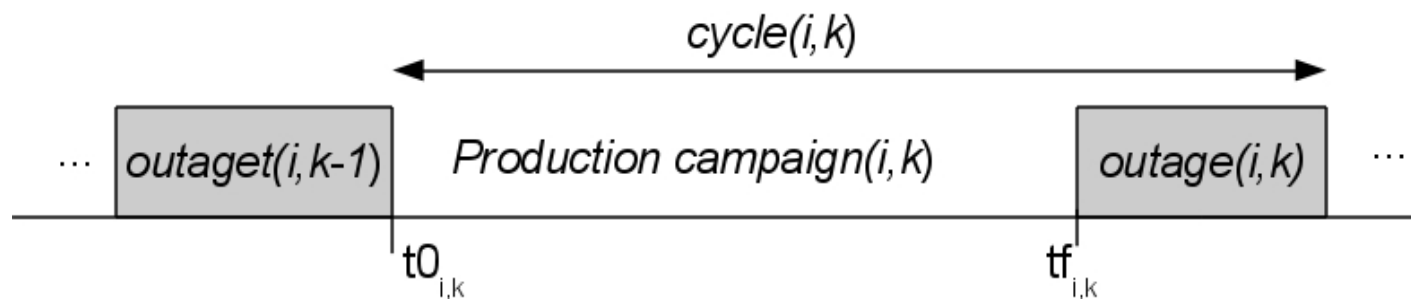
- *Outage dates* and *refueling quantities* are the decision variables applied in the operational process of EDF ; *unit productions* are re-optimized at shorter time horizons ;
- *Outage dates* and *refueling quantities* are recomputed monthly, without adapting them during the forthcoming month.
 - ▶ **Open-loop process** : NPP optimal planning is monthly recomputed on a sliding pluri-annual horizon in the current state of the system ; We **do not** look for *strategies/feedback laws* of outage placement, which would enable to calculate future optimal decisions starting from observations.

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Cycles

- (i, k) : the cycle formed by the $kieme$ production campaign and the $kieme$ outage of unit i
- $t0_{i,k}$: starting instant of cycle (i, k)
- $tf_{i,k}$: ending instant of cycle (i, k) campaign (= starting instant of cycle (i, k) outage)



Variables and data

Variables :

$x(i, t, \omega)$: Stock level of unit i at the beginning of time step t on scenario ω (*energy*)

$p(i, t, \omega)$: Production level of unit i on time step t on scenario ω (*power*)

$a(i, k)$: Outage date of unit i at cycle k (*week number, discrete*)

$r(i, k)$: Refueling of unit i at cycle k (*energy*)

Data :

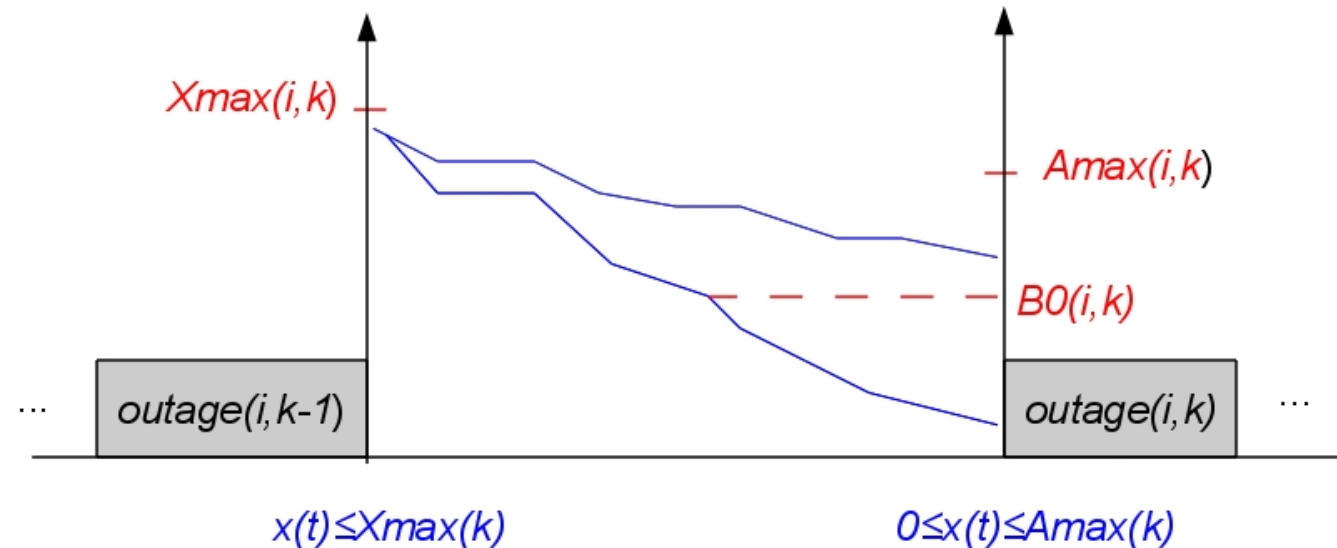
X_{i,t_0}^ω : Initial stock level of unit i on scenario ω (*energy*)

$Lga_{i,k}^\omega$: Duration of the outage of unit i at cycle k on scenario ω (*number of weeks*)

$C_{i,k}$ (resp. C_i^T) : Proportional cost of fuel of unit i at cycle k (resp. at the final instant T)(Euro/MWh)

Stock level constraints and dynamics

- Bounds on the stock level at then beginning of an outage and after refueling
- Bounds on the refueling quantity $r(i, k)$



- Refueling :

$$x(i, t0_{i,k}, \omega) - B0_{i,k} = r(i, k) + \frac{(q_{i,k}-1)}{q_{i,k}} (x(i, tf_{i,k-1}, \omega) - B0_{i,k-1})$$

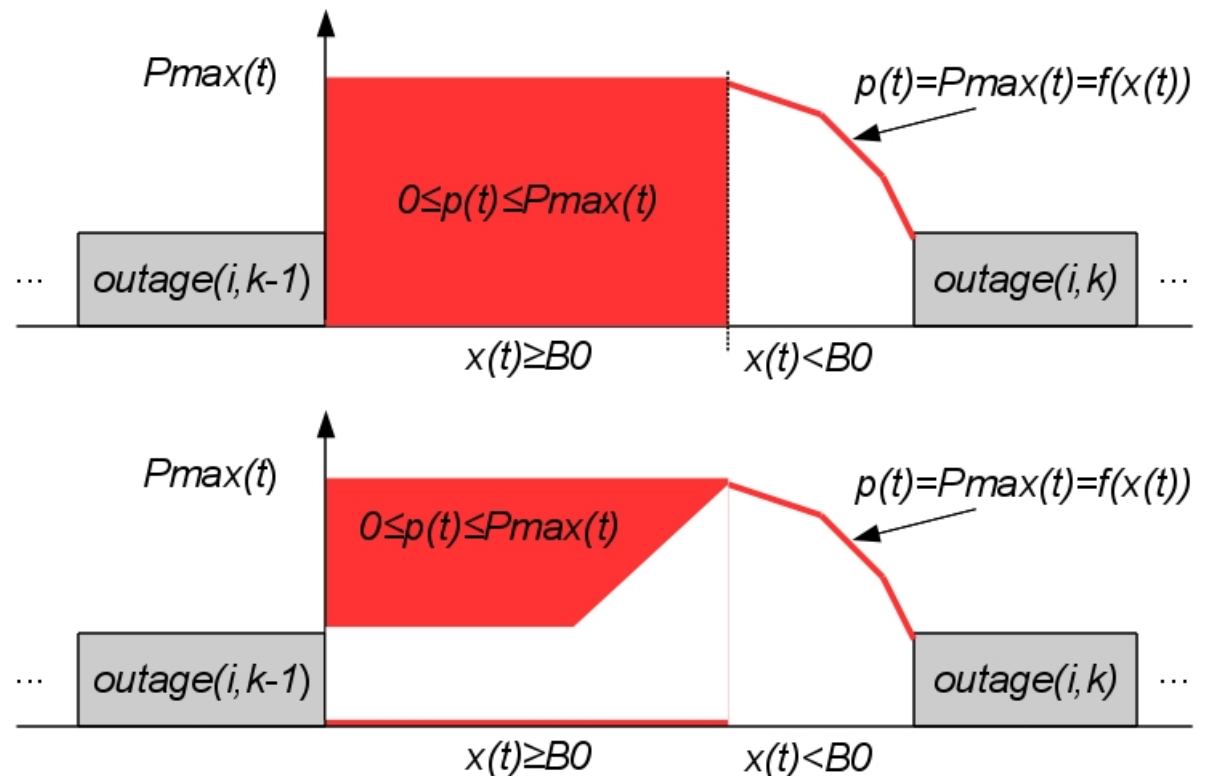
- Production campaign :

$$x(i, t_0 + 1, \omega) = X_{i,t_0}^\omega - p(i, t_0, \omega) \cdot dt$$

$$x(i, t + 1, \omega) = x(i, t, \omega) - p(i, t, \omega) \cdot dt, t > t_0$$

Production constraints

- Production must be null during outages
 - ▶ Coupling between discrete and continuous variables ...
- Bounds on production



NB : after the "Zero Boron" threshold, *non-linear* decreasing profile depending on the stock → Numerous state variables mandatory to impose the exact command...

Constraints on outages dates and resources

- Some maintenance operation must be done after or before a given date
 - ▶ Earliest/latest dates
- Some delay has to be enforced between maintenance operations occurring during different outages
 - ▶ Minimum spacing/maximum overlapping
- Bounds on the maximal loss of nuclear power have to be complied with
 - ▶ Maximal number of outages overlapping on a given time period
- Specialized maintenance teams/tools have to be shared by different outages, possibly with a delay between successive operations
 - ▶ Limited quantities of resources used during outages

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Variables, Data and Constraints

NB : for the sake of simplicity, CTU units are modeled with cost and maximal power depending on the scenario, which allows to represent groups of sells/purchases on the market (MG) in the same set.

- Variables :

$p(j, t, \omega)$: Production of CTU unit j at time-step t of scenario ω (power)

- Data : production cost and maximal power available depending on the scenarios : $C_{j,t}^\omega, Pmax_{j,t}^\omega$

- A single constraint, bounds on the maximal power available :
 $\forall(j, t, \omega), 0 \leq p(j, t, \omega) \leq Pmax_{j,t}^\omega$

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Problem formulation

$$\begin{aligned} & \text{Min}_{a(i,k), r(i,k), p(i,t,\omega), p(j,t,\omega)} \left\{ \sum_{i,k} C_{i,k} \cdot r(i,k) \right. \\ & \left. + \sum_{\omega} \pi(\omega) \left[\sum_{j,t} C_{j,t}^{\omega} \cdot p(j,t,\omega) \cdot dt - \sum_{i,k} C_i^T \cdot x(i,T,\omega) \right] \right\} \end{aligned}$$

s.t.

$$\forall t, \omega \sum_i p(i,t,\omega) + \sum_j p(j,t,\omega) = D_t^{\omega}$$

+ operating constraints of NPP and CTU units

+ scheduling and resource constraints on outages of NPP units

Interpretation

A set of outage dates and refueling quantities for NPP units which minimize the refueling cost plus the the mean of the production cost of NPP and CTU units on the all set of scenarios

A huge combinatorial stochastic problem with multi-stage recourse :

- Variables $a(i, k)$ and $r(i, k)$: *Here and now* variables, independent of the scenarios
- Variables $p(i, t, \omega)$ and $p(j, t, \omega)$: *Wait and see* or *recourse* variables depending on the scenarios
- Size :
 $I \approx 60, Nbcycles \approx 5, J \approx 100, T \approx 5 \times 50 \times 40, |\Omega| enormous$

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- Deterministic NPP outage durations, NPP stock levels, NPP and CTU unavailability :
 - ▶ $\Omega \subseteq \Delta$: only random data on *load demand, prices and capacities of exchanges on the spot market* are taken into account

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Simplifications

- Average CTU costs/capacities and targeted NPP productions to fulfill, pre-computed on the whole set of scenarios, for a few global NPP park availability hypotheses (loss of extreme scenarios) ;
- Duration of the time-step : one week (loss of demand variations and dynamical constraints inside a week) ;
- Search of the best planning in the neighborhood of the planning computed the previous month (loss of solutions located outside the neighborhood considered)
- Decomposition by NPP sites (loss of the constraints coupling outages of plants located on different sites)

Resolution principle

- **Local search** implemented by iterations between two modules :
 - ▶ **M1** : A *LP* (re)optimizing the production once NPP outages have been fixed by **M2**
 - ▶ **M2** : A *MILP* (re)optimizing (locally moving) the outages dates using the *marginal costs* pre-computed or obtained by **M1**
- In practice, the planning is built by experts, using the tool in an interactive manner

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Resolution principle

- Same simplifications as above ;
- **Frontal resolution of the compact MILP formulation** of the problem (e.g. by IBM ILOG CPLEX) ;
- **Advantages** : global solution theoretically found on the research space, coupling constraints between outages of NPP located on different sites satisfied ;
- **Drawbacks** : computation time intractable except for limited research spaces.

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Best teams and approaches

- LIX (Polytechnique) : mixing PLNE for outage dates placement and heuristics for production and refueling optimization
- belImproved (Netherlander optimization company) : local search driven by simulated annealing
- elabs(Bouygues) : local search using *LocalSolver*
- LIPN (Université Paris Nord) mixing column generation for outage dates placement and LP for production and refueling optimization

Main lessons

- Good results were obtained in a limited computation time (1 h)
- Like EDF operational tool, almost every approach :
 - ▶ uses an **average scenario** ;
 - ▶ uses a **hierarchical resolution scheme** splitting the problem usually between outages dates placement and production/refueling optimization once major combinatorial decisions have been made ;
- Unlike EDF operational tool, every approach :
 - ▶ maintains all outage coupling constraints (**no decomposition by NPP subsets**) ;
 - ▶ when based on local search, explores **large neighborhoods** (eg. outage swaps, long outage moves as "winter jumps" ...)

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Toward a robust formulation I/II

- The current formulation corresponds to a **stochastic optimization** of a multi-stages problem with recourse :

$$\underset{x \in X}{\text{Min}} \{ f(x) + \mathbb{E}_\omega [Q(x, \omega)], Q(x, \omega) = \underset{y_\omega \geq 0}{\text{Min}} \{ g(y_\omega) \text{ s.t. } h(x, y_\omega, \omega) = 0 \} \}$$

- With *random outage durations*, a **robust** formulation seems more sensible :

$$\underset{x \in X}{\text{Min}} \{ f(x) + \underset{\omega \in \Omega}{\text{Max}} \{ Q(x, \omega) \}, Q(x, \omega) = \underset{y_\omega \geq 0}{\text{Min}} \{ g(y_\omega) \text{ s.t. } h(x, y_\omega, \omega) = 0 \} \}$$

- *Outage dates and refuelings stay robust here-and-now variables, productions stay recourse variables, but we want solutions to be robust facing for example the worst-case on some uncertainty set for outage durations*

Toward a robust formulation II/II

- New stochastic space : $\Omega \subseteq \Delta \times \Psi$

$$\begin{aligned} & \underset{a(i,k), r(i,k)}{\text{Min}} \left\{ \sum_{i,k} C_{i,k} \cdot r(i, k) + \underset{\psi \in \Psi' \subseteq \Psi}{\text{Max}} \left\{ \underset{p(i,t,\delta,\psi), p(j,t,\delta,\psi)}{\text{Min}} \left\{ \right. \right. \right. \\ & \left. \left. \left. \sum_{\delta} \pi(\delta) \left[\sum_{j,t} C_{j,t}^{\omega} \cdot p(j, t, \delta, \psi) \cdot dt - \sum_{i,k} C_i^T \cdot x(i, T, \delta, \psi) \right] \right\} \right\} \right\} \end{aligned}$$

s.t.

$$\forall t, \delta, \psi, \sum_i p(i, t, \delta, \psi) + \sum_j p(j, t, \delta, \psi) = D_t^{\delta}$$

+ operating constraints of NPP and CTU units

+ scheduling and resource constraints on NPP outages

- N. Dupin's PHD, in collaboration with INRIA Bordeaux (F. VanderBeck) and INRIA Lille (E.G. Talbi)

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Modeling recourse on outage dates and refuelings I

Monthly re-computations of the planning and stability of the solution along this iterative process is not at all taken into account

→ New partition of the decision variables

- $a_m(i, k), r_m(i, k)$: outage dates and refueling quantities computed at month m : *robust here and now* variables, decided *before* stochastic data reveal itself
- *Recourse wait and see* variables, decided *after* occurrences of random events during the forthcoming month m and applied *during m* (NB : No outage moves during the forthcoming month !)
 - ▶ $p_m(i, t, \omega_m), p_m(j, t, \omega_m)$: *production* recourse
 - ▶ $dr_m(i, k, \psi_m) \in \mathbb{Z}$: refueling recourse for an underway outage (i, k) , facing an exceptional prolongation.

Modeling recourse on outage dates and refuelings II

- *Recourse wait and see* variables, decided **after** occurrences of random events during the forthcoming month m **and applied beyond m , through the re-optimizations**, i.e. *in the state of the system resulting from random events which have occurred during m* :
 $\forall n \geq 1$,
 - ▶ $da_{m+n}(i, k, \omega_{m+n-1}) \in \mathbb{Z}, dr_{m+n}(i, k, \omega_{m+n-1}) \in \mathbb{Z}$: *outage move and refueling* recourses applied at month $m + n$
 - ▶ $p_{m+n}(i, t, \omega_{m+n-1}), p_{m+n}(j, t, \omega_{m+n-1})$: *production* recourses applied during month $m + n$
- The good news : *outage move recourses* are tightly constrained because we can't move *close* outages

Post-Doctorat, accepted in PGMO/IROE in collaboration with LIX/Polytechnique (V. Jost) and LIPN/Université Paris XIII (R. Wolfer)

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Some other prospective works in progress

- Using SDP to get better bounds
A. Gorge's PHD, with LRI/Université Paris XI (A. Lisser)
- Tackling uncertainties through joint probabilistic constraints
Post-Doctorat, accepted in PGMO/IROE in collaboration with
LRI/Université Paris XII, (A. Lisser)

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Much remained to be done

- ① The formulation is **anticipative** : the future of each *load demand* scenario is considered known when decisions are taken → the real production cost is underestimated.
- ② **The load/demand balance is incomplete**
 - ▶ Some production units are missing (e.g hydraulic plants)
 - ▶ Some constraints are missing (e.g. accurate dynamic constraints on NPP operating)
- ③ **The random space is still incomplete** : random data on unit unavailability and NPP stock levels are discarded.
- ④ **What about scheduling strategies ?** : we should need them to implement a *closed-loop* process in a *simulator* implementing the monthly scheduling → **the big challenge**

References I

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