Scheduling of outages of EDF nuclear power plants

Problem, current improvements and big challenges

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Contents

Problem (1/2)

- ≈ 60 *Nuclear Reactors* (REP) (index $i \in \{1...I\}$) which have to be stopped periodically for refueling and maintenance operations (index of cycles $k \in \{1...K\}$)
- ≈ 100 *"Classical" groups* (CG) which can produce continuously, including *Conventional Thermal Units* (e.g. oil, coal, gas) and *Market Groups* modeling the exchanges of the sport market (index $j \in \{1...J\}$)
  - REPs' production cost is much less than CGs'
  - REPs' installed capacity represents about 60% of the total installed capacity
  - Essentially, REPs' outages have to be scheduled during low demand periods

Problem (2/2)

Find the optimal outage schedule and refuel quantities of the REPs for a time horizon of 5 to 10 years

While satisfying :

- The electricity demand for every time step $t \in \{1 \ldots T\}$
- The operating constraints of the REPs and the CGs
- The scheduling and resources constraints for the REPs' outages

Uncertainties

- *Demand* to satisfy for every time step : D_t^δ ;
- *Price and volume* of buying/selling at the spot market, correlated with the demand through temperature : $C_{j,t}^\delta$, $Pmax_{j,t}^\delta$;
- *Maximum power* of the *Conventional Thermal Units*, affected by hazardous faults : $Pmax_{j,t}^\theta$;
- *Current stock* of the REPs : X_{i,t_0}^λ ;
- *Outages duration* of the REPs : $Lga_{i,k}^\psi$;
- *Maximum and minimum power* of the REPs, affected by incidents between the outages : $Pmax_{i,t}^\phi$, $Pmin_{i,t}^\phi$.

We set $\Omega \subseteq \Delta \times \Theta \times \Lambda \times \Psi \times \Phi$ the stochastic space,
ω one “scenario” in Ω

Operational process

- The *outages dates* and the *refuels* are the only decisions applied through the operational process
- They are recalculated every month for a sliding horizon starting from the current state of the system, without modifying them during the current month
- The units *productions* are re-optimized at short-term horizons by other models
- We do not search for « strategies », « feedback laws », « decision rules » for the outages scheduling or the refuels (and a fortiori for the productions) that would allow us to calculate the optimal future decisions using the observations

"Model Predictive Control process" in terms of automatic control

Contents

Current Formulation (1/2)

$$\underset{a(i,k),r(i,k)p(i,t,\omega),p(j,t,\omega)}{Min}\Big\{\sum_{i,k} C_{i,k}\cdot r(i,k)$$

$$+\sum_{\omega}\pi(\omega)\big[\sum_{j,t} C^{\omega}_{j,t}\cdot p(j,t,\omega)\cdot dt-\sum_{i} C_i^{T}\cdot x(i,T,\omega)\big]\Big\}$$

$$s.t.$$

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

+ operational constraints for REPs (some of them non-linear) and CGs

+ scheduling and resources constraints for the outages of the REPs

- Cf. ROADEF/EURO Challenge 2010

Current Formulation (2/2)

One very big, stochastic, combinatorial, non-linear problem :

- Variables $a(i,k)$ and $r(i,k)$: robust variables *here and now*, independent of scenarios
- Variables $p(i,t,\omega)$ and $p(j,t,\omega)$: stochastic variables *wait and see* or *recourse*, dependent of scenarios (Recall : which are not applied as they are in practice)
- Size : $I \approx 60, K \approx 5, J \approx 100, T \approx 5 \times 50 \times 40, |\Omega|$ huge

Current hypothesis and simplifications (1/2)

- Outages duration, initial stocks and max/min power of REPs are considered deterministic :
  - $\Omega \subseteq \Delta \times \Theta$: only the randomness of the *demand*, the *cost* and the *maximum power* of CGs are taken into account
- Target production of REPs, together with associated costs and productions of CGs, are pre-calculated in average over the set of scenarios for some given hypotheses on the total availability of the REPs' park
- Time step duration : week

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- Time step duration : week

Advantages

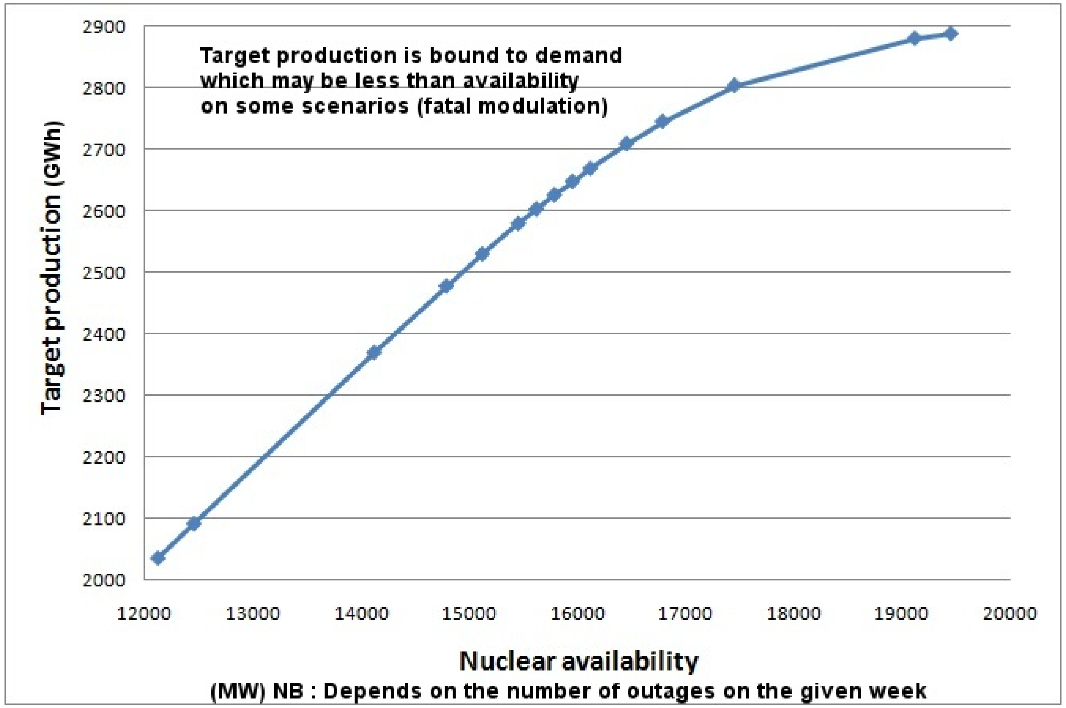
- No need to recalculate CGs production for every time step and every scenario

Disadvantages

- Loss of the extreme scenarios
- Loss of demand variation inside the week and infra-weekly constraints

Current hypothesis and simplifications (2/2)

For target production of REPs, cost and production of CGs and for every week we have a function of the following type :



Contents

A first step

1. Improving the current resolution method
    - *Artemis : a better local search (to follow)*
2. Implementing robustness of the schedule facing the uncertainty on outage duration
    - Possibly taking advantage of an additional recourse on the reload
3. Investigating the problem of the stability of the solutions, along the re-optimizations performed monthly on a receding horizon.
    - Outage dates are very constrained decisions which cannot easily be changed. Today constraints are added to the problem in order to keep the new solution close to the one computed the previous month. Could we do better ? What about taking into account future re-optimizations i.e. recourse on the outage dates into the problem ?

One step beyond

1. The formulation is anticipative : the future of every *demand* scenario is considered to be known the moment the decisions are taken → the true production cost is underestimated.
2. The offer/demand equilibrium is incomplete.
    - Some means of production are missing (hydroelectric plants...)
    - Some constraints are missing (dynamic constraints for the operation of the units, reserve constraints...)
3. The stochastic space is still incomplete : uncertainties on REPs' max/min powers and stocks are not taken into account.
4. What about schedule *strategies* ? Necessary to implement a closed-loop process using a simulator to reproduce the monthly re-optimization → "the" big challenge.

Contents

Problem formulation (1/2)

$$\underset{a(i,k),r(i,k),p(i,t),p^s(t)}{Min} \Big\{ \sum_{i,k} C_{i,k} \cdot r(i,k) - \sum_{i} C_i^T \cdot x(i,T)$$

$$+ \sum_t \left[C^{th}(na(t),t) + C^s(na(t),t) \cdot p^s(t) \cdot dt \right] \Big\}$$

$$s.t. \sum_i p(i,t) + p^s(t) = D_t^N(na(t)), \ \forall t$$

+ na(t) being a function of REPs outage schedule and production

+ operational constraints for REPs and substitution group

+ scheduling and resources constraints for the outages of the REPs

- $na(t)$: nuclear availability
- $C^{th}(na,t)$: total cost of CGs
- $C^s(na,t), p^s(t)$: cost and production of substitution group
- $D_t^N(na)$: target production for REPs

Problem formulation (1/2)

Objective : minimize the total cost of the schedule

- Cost of nuclear stock
- Cost of CGs
- Production cost of substitution group (voluntary modulation)

By using the **decision variables**

- Outages dates
- Nuclear production

While satisfying the **constraints**

- Nuclear offer-demand equilibrium
- Scheduling and resources constraints
- Operational constraints of the reactors

Why a new method ?

Frontal resolution of the problem's **MILP** formulation ?

- \+ Global optimum can be theoretically calculated
- − . . . in high CPU time

Local search using **price decomposition** and **MILP/LP**s formulations ?

- \+ Fast method
- − . . . with no theoretical guarantee of optimality and loss of the coupling "inter-site" constraints

Why a new method ?

Frontal resolution of the problem's **MILP** formulation ?

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Local search using **price decomposition** and **MILP**/**LP**s formulations ?

- \+ Fast method
- – . . . with no theoretical guarantee of optimality and loss of the coupling "inter-site" constraints

⟹ Develop a different *Local Search* type method, based on the potential observed at the challenge ROADEF/EURO 2010

- Using heuristics
- Preserving the coupling constraints between sites
- Proposing outages permutations and « winter jumps »
  - Winter jump : an outage scheduled before winter is moved after winter.

General methodology

Meta-heuristic applied : combination of *gradient descent* + *simulated annealing*

Use of heuristics for the research of outages movements

- **evaluate marginally** the cost/profit of a movement
- study only combinations of movements that **do not violate** any constraints
- propose **winter jumps**

Use of heuristics to evaluate the cost of a schedule

- **operational**, to guarantee the realism of the production planning
- **mathematical**, in order to approach the economical optimum

Algorithm

Step 1 Repair the violations of the initial schedule

- scheduling and resources constraints
- minimum and maxixum cycle length

Step 2 Gradient descent

- to reduce the cost
- while satisfying all "hard" constraints
- penalizing "soft" constraints

Step 3 Simulated annealing

- to avoid local minimum

Step 4 Winter jumps

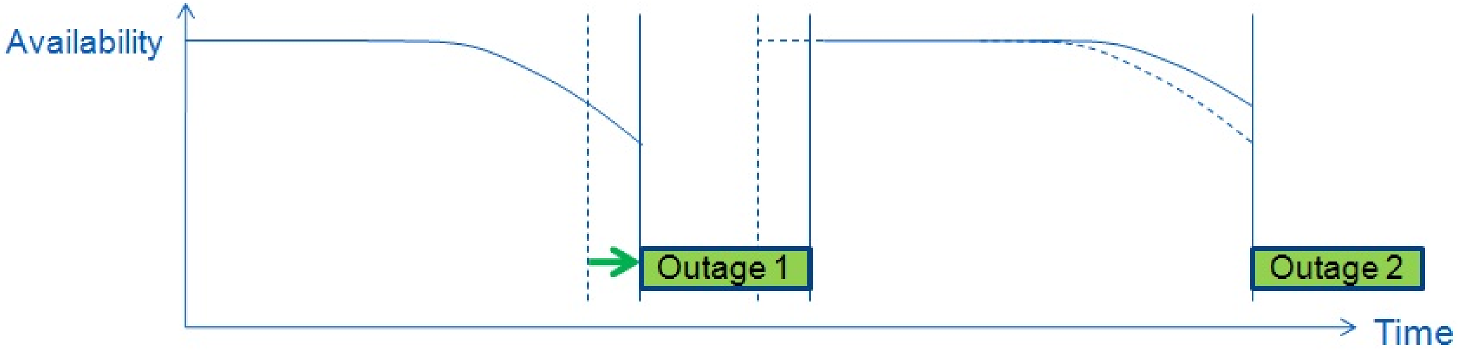
Within *reasonable* CPU time, evaluate
the *maximum* number of *profitable* movements

Contents

Movement proper cost

Remark : if an outage is moved forward, then due to availablity variation, total cost will :

- decrease the weeks just before the outage
- increase the weeks where the outage is moved
- decrease the weeks of stretch at the end of the cycle



An *approximation* of all these costs can be easily calculated and their sum is defined as the *proper cost* of the movement.

Movement total cost

However, movements can violate scheduling and ressources constraints

Objective : having calculated the proper cost of all movements, take into account the costs of moving other outages in order to repair constraints violations.

Dependencies

- For every possible movement :
    - enumerate the constraints that are violated,
    - enumarate the movements that can repair each violation,
    - keep the minimum cost for every violation.
- The total cost of a movement is defined as the sum of its proper cost and all the above minimum costs.

Heuristics (1/2)

Gradient descent

1. Calculate the total cost of all movements.
2. Apply the movement with the least negative total cost
3. Repair violations and **evaluate** the new schedule.
4. Did the cost decrease ?
   - Yes The movement is accepted.
   - No It is added at the tabou list.
5. Are there any more movements with negative total cost, excluding the tabou list ?
   - Yes Go to 2.
   - No STOP.

Heuristics (2/2)

Simulated annealing

1. Initialize temperature.
2. Calculate the proper cost of all movements.
3. Apply a quasi-random set of movements.
4. Repair violations.
5. Use the gradient descent and **evaluate** the new schedule.
6. Did the cost decrease ?
   - Yes All the movements are accepted.
   - No Accept all the movements with a probability depending on the current temperature.
7. Update temperature. Is it equal to zero ?
   - Yes STOP.
   - No Go to 2.

Contents

Methodology (1/2)

Objective : having an outage schedule, optimize the production of every REP for every time step.

Algorithm

1. Initalize the production : all REPs produce at maximum.
    - constraints violation, no optimization.
2. For every week, starting from the beginning of the period and avancing forward :
    - given the nuclear availabilty, calculate the target production,
    - decide which REP should modulate in order to absorb the total modulation.
3. If the result is satisfying, STOP. Otherwise go to 2.

Methodology (2/2)

Problem : how to decide which REP should modulate ?

- 1^{st} priority : satisfy the **constraints**
  - two constraints can be violated because of non-optimal modulation : **maximum anticitipation** and **prolongation**
- 2^{nd} priority : decrease the **total cost**
  - the modulation can be used in order to **decrease** the **stretch** $\Longrightarrow$ **decrease total cost**

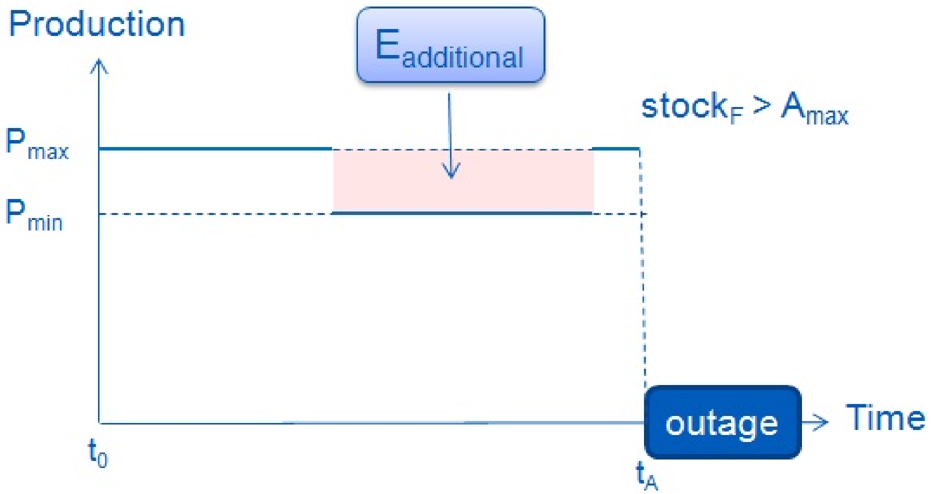
Since there is no proportional cost, *sort* the REPs
in order to represent the above two criterions of *priority*

Nuclear plants classification : 1^{st} priority (1/2)

Class REP_+

- REPs that violate the maximum anticipation at the end of the current cycle
- Inner-class criterion :

$$riskAnticipationViolation = \frac{stock_F - A_{max}}{E_{additional}}$$

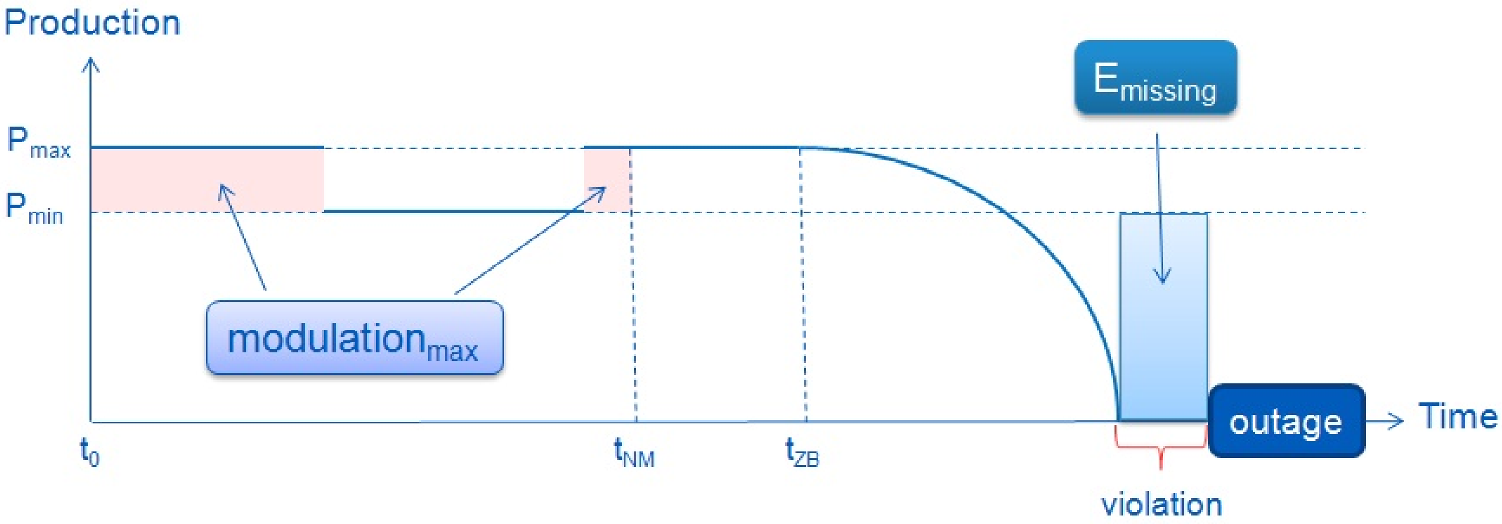


Nuclear plants classification : 1^{st} priority (2/2)

Class *REP_*

- REPs that violate the maximum prolongation at the end of the current cycle
- Inner-class criterion :

$$riskProlongationViolation = \frac{E_{missing}}{modulation_{max}}$$



Nuclear plants classification : 2^{nd} priority

Class REP_{cost}

- REPs that do not violate any stock constraint at the end of the current cycle
- Inner-class criterion :

$$profit_{Modulation} = -\frac{Profit(P_{max}) - Profit(P_{min})}{P_{max} - P_{min}}$$

Remark : by producing less (minimum power) :

$\Rightarrow$ REP stretch decreases,

$\Rightarrow$ REP availiablity increases,

$\Rightarrow$ CGs cost decreases.

By producing more (maximum power), cost increases.

Allocate modulation

Problem : for a given week and target production, reallocate the modulation between the REPs

Allocate modulation

Problem : for a given week and target production, reallocate the modulation between the REPs

Production > Target Production

- Decrease the production using firstly the $REP\_$ class and next the REP_{cost}.

Allocate modulation

Problem : for a given week and target production, reallocate the modulation between the REPs

Production > Target Production

- Decrease the production using firstly the REP_{-} class and next the REP_{cost}.

Production = Target Production

- Reorganise the production by exchanging blocks of energy between classes
  - REP_{-} and REP_{+}, REP_{-} and REP_{cost}, ...

Allocate modulation

Problem : for a given week and target production, reallocate the modulation between the REPs

Production > Target Production

- Decrease the production using firstly the REP_{-} class and next the REP_{cost}.

Production = Target Production

- Reorganise the production by exchanging blocks of energy between classes
  - REP_{-} and REP_{+}, REP_{-} and REP_{cost}, ...

Production < Target Production

- Increase the production using firstly the REP_{+} class and next the REP_{cost}.

Methodology (recall)

Algorithm

1. Initalize the production : all REPs produce at maximum.
    - constraints violation, no optimization.
2. For every week, starting from the beginning of the period and avancing forward :
    - given the nuclear availabilty, calculate the target production,
    - classify all the REPs,
    - decide which REP should modulate in order to absorb the total modulation.
3. If the result is stabilizing, STOP. Otherwise go to 2.

Contents

Still, a lot of work remains

Local search improvement

- Tune simulated annealing, stabilize the results and the performance
- Test *LocalSolver*
- Use of *CP* (repair explored, but non-feasible solutions)

Parallelism

- To work with *multiple scenarios*
- To explore multiple neighborhoods in parallel

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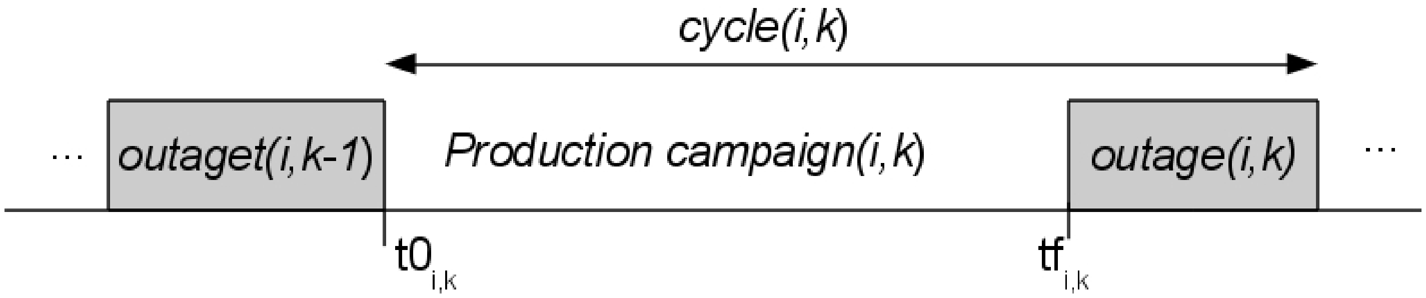
Contents

Cycles

- (i,k) : the cycle formed by the k_{ieme} production campaign and the k_{ieme} 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 :

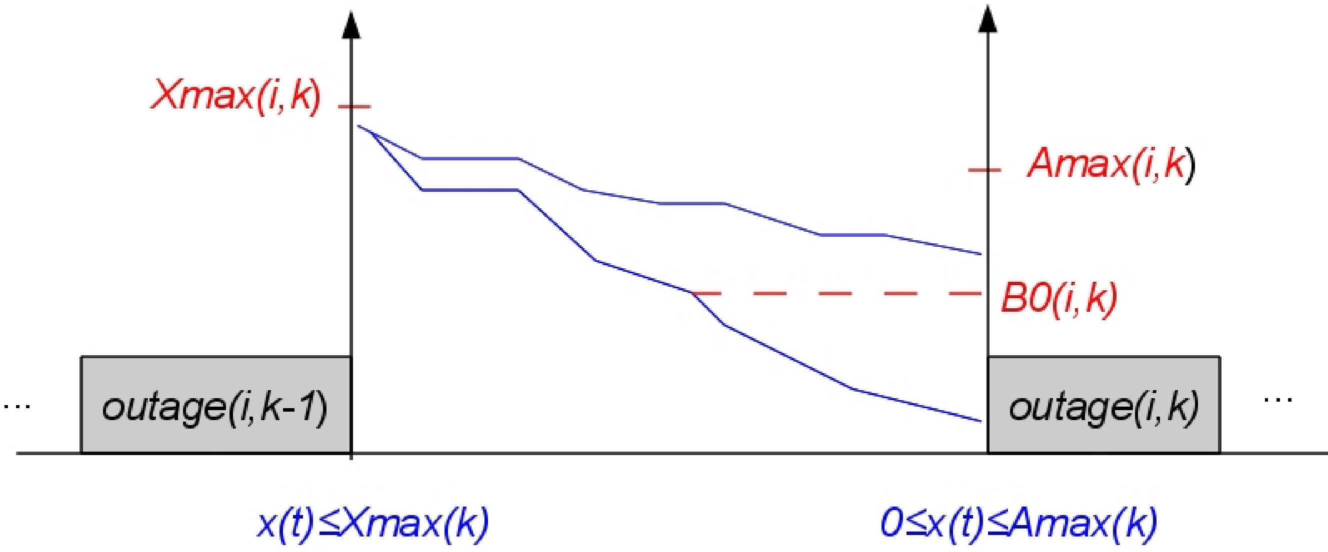
X^{ω}_{i,t_0} : Initial stock level of unit i on scenario ω (*energy*)

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

$C_{i,k}$ (resp. C^T_i) : 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 :

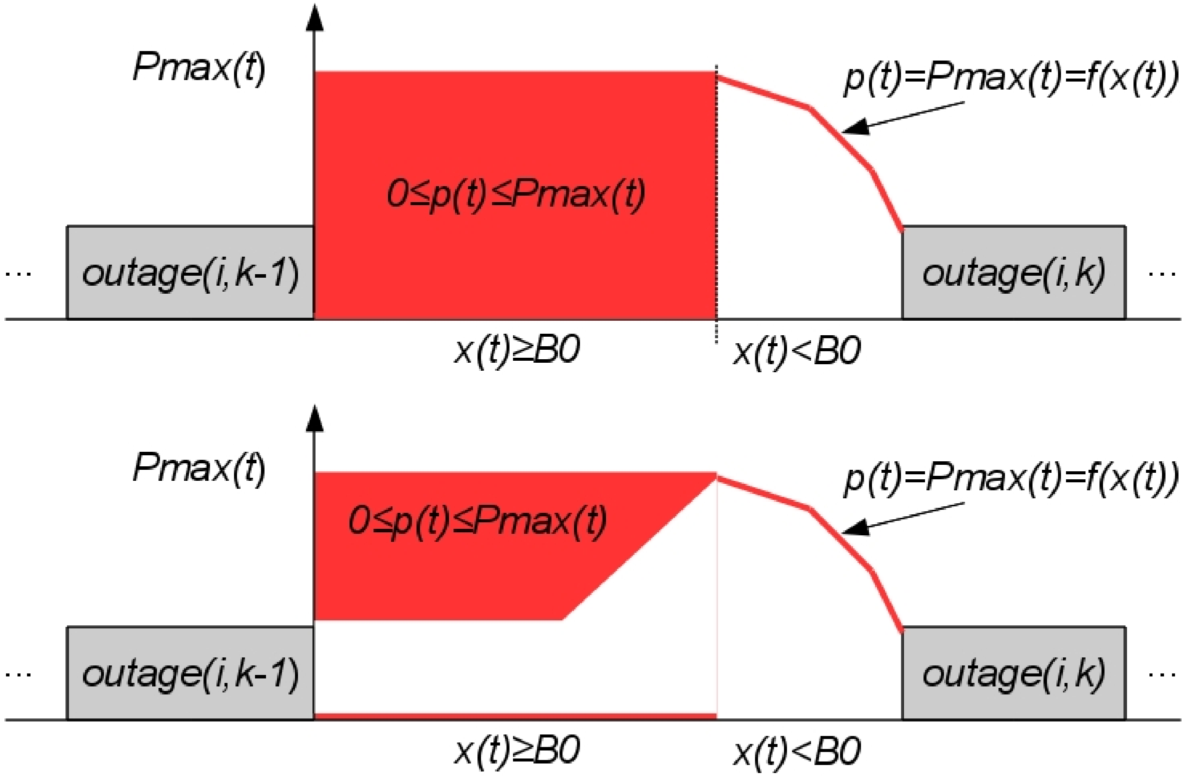
$$x(i,t0_{i,k},\omega)-B0_{i,k}=r(i,k)+\frac{(q_{i,k}-1)}{q_{i,k}}(x(i,tf_{i,k-1},\omega)-B0_{i,k-1})$$

- Production campaign :

$$x(i,t_0+1,\omega)=X^{\omega}_{i,t_0}-p(i,t_0,\omega)\cdot dt$$
$$x(i,t+1,\omega)=x(i,t,\omega)-p(i,t,\omega)\cdot dt, t>t_0$$

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

Contents

Variables, Data and Constraints

NB : for the sake of simplicity, CG 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 with conventional thermal units (CTU).

- Variables :

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

- Data : production cost and maximal power available depending on the scenarios : $C^{\omega}_{j,t}, Pmax^{\omega}_{j,t}$
- Constraints : bounds on the maximal power available : $0 \leq p(j,t,\omega) \leq Pmax^{\omega}_{j,t}, \ \forall (j,t,\omega)$