New Challenges for Energy Management

An Insight into the EDF's Nuclear Outage Scheduling Problem

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Contents

EDF Energy Management Process

Long term — **Mid term** — **Short term**

>10 years
Investments

5-10 years
Nuclear Power Plant Outage Scheduling

1-5 years
- Water values of large energy storages
- Load balance simulation
- Fuel supply
- Risk analysis
- Hedging strategies

Week
- Security analysis
- Maintenance of conventional thermal units
- Options
- Hedging

Day
Unit commitment

Infra-day
- Adjustment market
- Re-declarations

← **Stochastic** — **Uncertainties on parameters** — **Deterministic** →

← **Simplifed / Agregated** — **Production units representation** — **Accurate** →

Twenty years of heavy changes

- From monopolistic national utilities to interconnected energy markets
- From centralized to decentralized production means, from "stupid" (☺) to "smart" power grids
- From uncontrolled CO_2 emissions to CO_2 markets and penetration of renewable energy sources
- From low retail prices to high retail prices
- In France, from 60 to 40 nuclear power plants ?

Do our "old fashioned" models/methods still operate ?

Some usual approximations do not make sense any more :

- Deterministic view of the problems in no longer acceptable, even on the short term horizons
- Relaxations of some unit operating constraints usually performed are no longer possible, even on the long term horizons
- Decomposition schemes usually implemented may be obsolete (Eg. does a "price decomposition" scheme still makes sense in a totally decentralized production/distribution/consumption system ?)
- ...

We need more accurate, more stochastic models, and new resolution methods to cope with them

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Problem (1/2)

- $\approx$ 60 *Nuclear Reactors* (NR) (index $i \in \{1...I\}$) which have to be stopped periodically for refueling and maintenance operations (index of cycles $k \in \{1...K\}$)
- $\approx$ 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 $j \in \{1...J\}$)
  - NRs' production cost is much less than CGs'
  - NRs' installed capacity represents about 50% of the total installed capacity
  - Essentially, NRs' outages have to be scheduled during low demand periods

Problem (2/2)

Find the optimal outage schedule and refuel quantities of the NRs 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 NRs and the CGs
- The scheduling and resources constraints for the NRs' 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 : $Pmax_{j,t}^\theta$;
- *Maximum and minimum power* of the NRs, affected by incidents between the outages : $Pmax_{i,t}^\phi$, $Pmin_{i,t}^\phi$.
- *Current stock* of the NRs : X_{i,t_0}^λ ;
- *Outages duration* of the NRs : $Lga_{i,k}^\psi$;

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
  - The units *productions* are re-optimized at short-term horizons by other models
- *Outages dates* and *refuels* are recomputed every month on a sliding horizon starting from the current state of the system, without modifying them during the current month
  - We do not search for *strategies*, *feedback laws*, or *decision rules* for the outages dates or the refuels (and a fortiori for the productions), that would enable to calculate the optimal future decisions using the observations

In terms of automatic control, neither open-loop (hopefully) nor pure closed-loop but *Model Predictive Control process*

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Current Formulation (EURO/ROADEF Challenge 2010)(1/3)

Variables :

- $a(i,k)$: Outage date of unit i at cycle k (*week number*, discrete)
- $r(i,k)$: Refueling of unit i at cycle k (*energy*)
- $x(i,t,\omega)$: Stock level of unit i at the beginning of time step t on scenario ω (*energy*)
- $p(i/j,t,\omega)$: Production level of unit i/j on time step t on scenario ω (*power*)

Data :

- $C_{i,k}$ (resp. C_i^T) : Proportional cost of fuel of unit i at cycle k (resp. at the final instant T)(€/MWh)
- $C_{j,t}^{\omega}$: Proportional production cost of unit j on time step t on scenario ω (€/MWh)

Current Formulation (EURO/ROADEF Challenge 2010)(2/3)

Objective : to minimize the NRs refueling cost plus the expectation of the production cost on the whole set of scenarios :

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

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

$s.t.$

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

+ operating constraints for NRs (some of them non-linear) and CGs
+ scheduling and resources constraints for the outages of the NRs

Current Formulation (3/3)

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

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

With numerous auxiliary binary variables, the problem can be modeled as a huge MILP... the frontal resolution of which is untractable

Current Method Overview (1/2)

Heuristic Local Search in the neighborhood of the scheduled obtained the previous month

Hypotheses and simplifications :

- $\Omega \subseteq \Delta \times \Theta$: only the randomness of the *demand*, the *cost* and the *maximum power* of CGs are taken into account
  - Outage durations, initial stocks, and max/min powers of NRs are considered deterministic
- Basically we pre-calculate an approximation of the average cost function around the value obtained the previous month, and we use this approximation to guide the search for the new planning.
- One unique time step per week

Current Method Overview (2/2)

- Principles
  - Gradient descent method to reach local optima and simulated annealing to escape from them
  - Various heuristics to evaluate interesting "moves", i.e. shifting of outage dates
- Advantages
  - Fast, users can do several iterations with the decision-helping tool
- Drawbacks
  - No guaranty of optimality, no bounds on the distance to the optimum
  - Loss of the extreme scenarios
  - Loss of demand variation inside the week and of infra-weekly constraints

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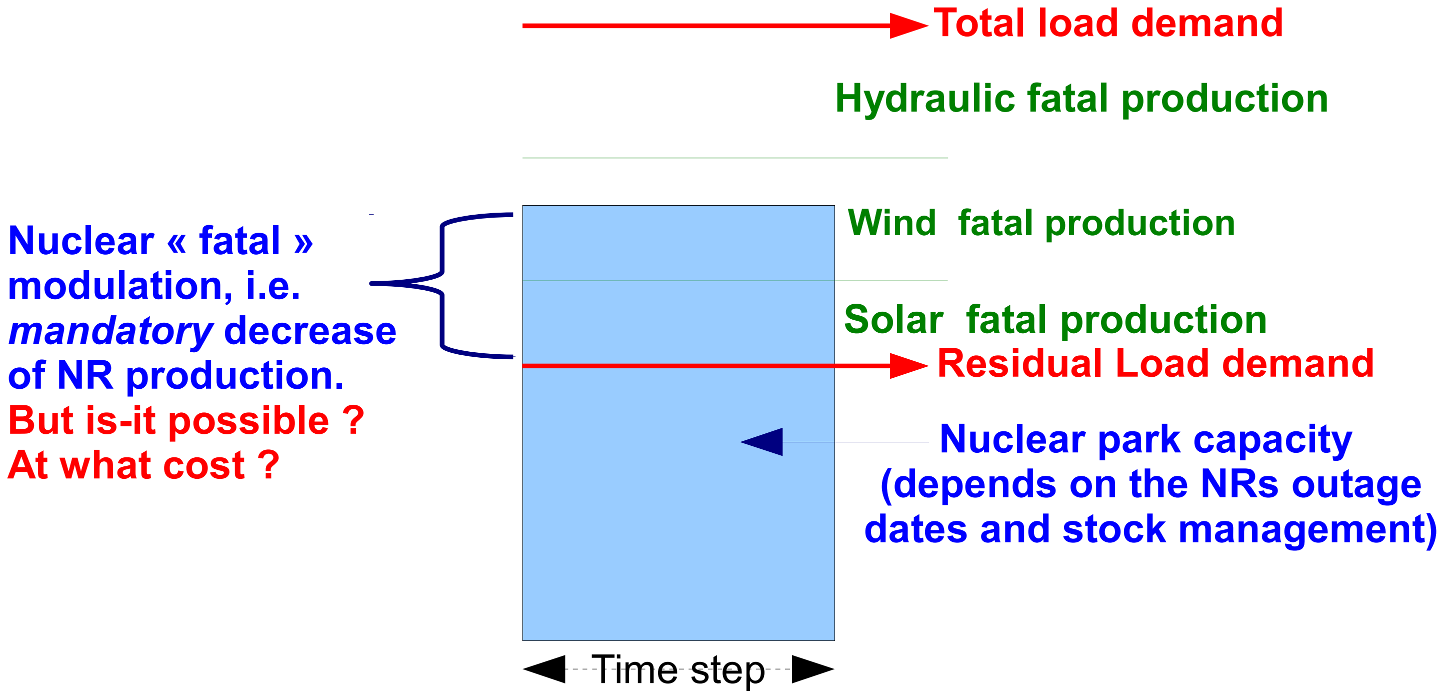
A concrete illustration of the consequences of Renewable Energy penetration (1/2)

- Wind and solar productions are random, intermittent and can be viewed as a "fatal" production (i.e. no storage available) which *lowers* the load demand that NRs and CGs must fulfilled
- ⇒ Increase of the "fatal modulation" of the nuclear park.



Objectives

1. We need to consider these scenarios in the problem ⇒ an average view of the random demand is no longer acceptable
2. We need to consider constraints that should limit the NRs modulation ⇒ weekly view of the time step is no longer acceptable

Towards :

- "Exacts" methods providing with bounds on the global optimum
- A better treatment of the stochasticity of demand and prices/capacities on the spot market
- A better treatment of NR's operating constraints

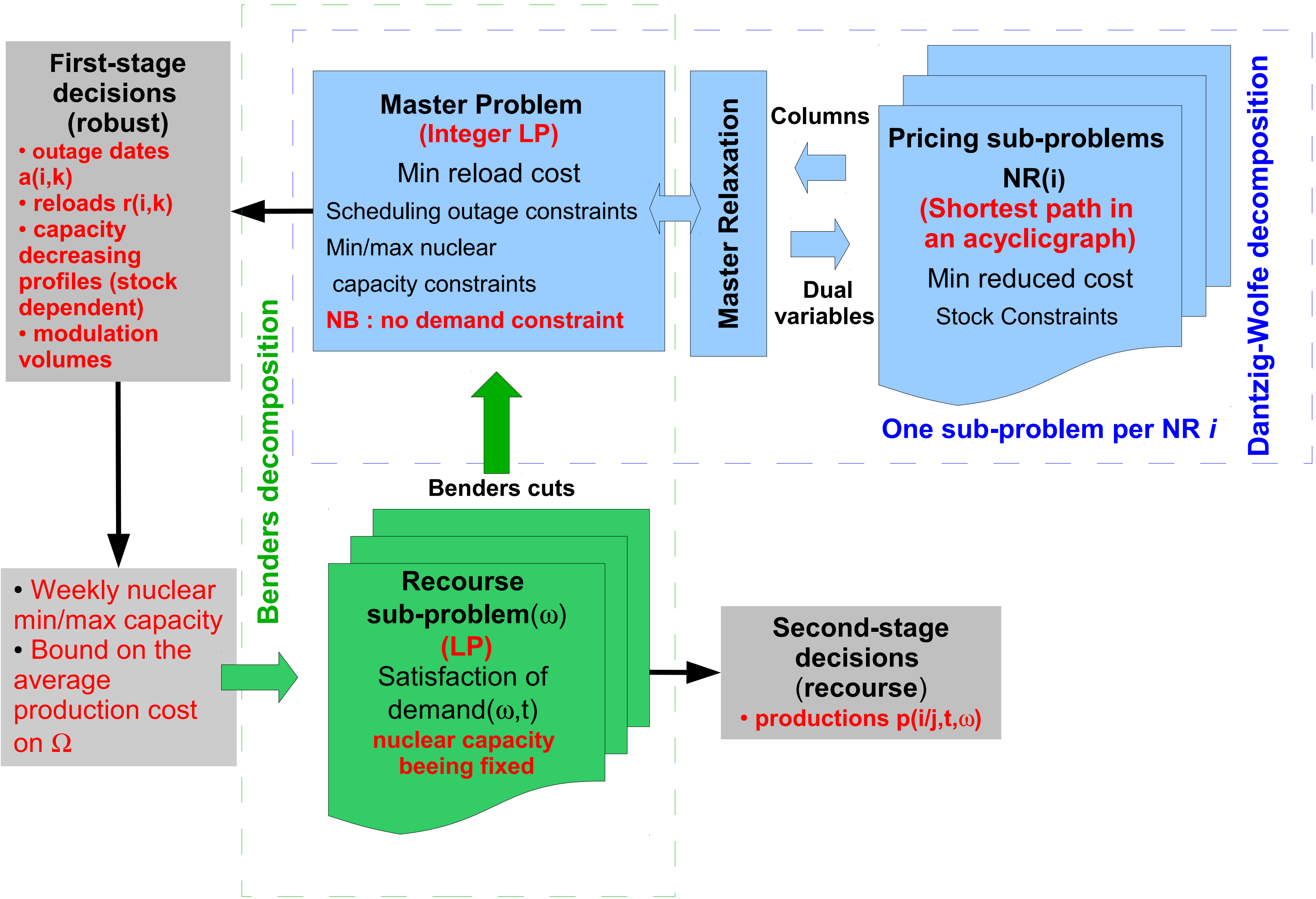
Current works

Recall that a frontal resolution of the MILP is not possible
$\Rightarrow$ **Reformulation and decomposition techniques**

Works in progress in collaboration with academic teams :

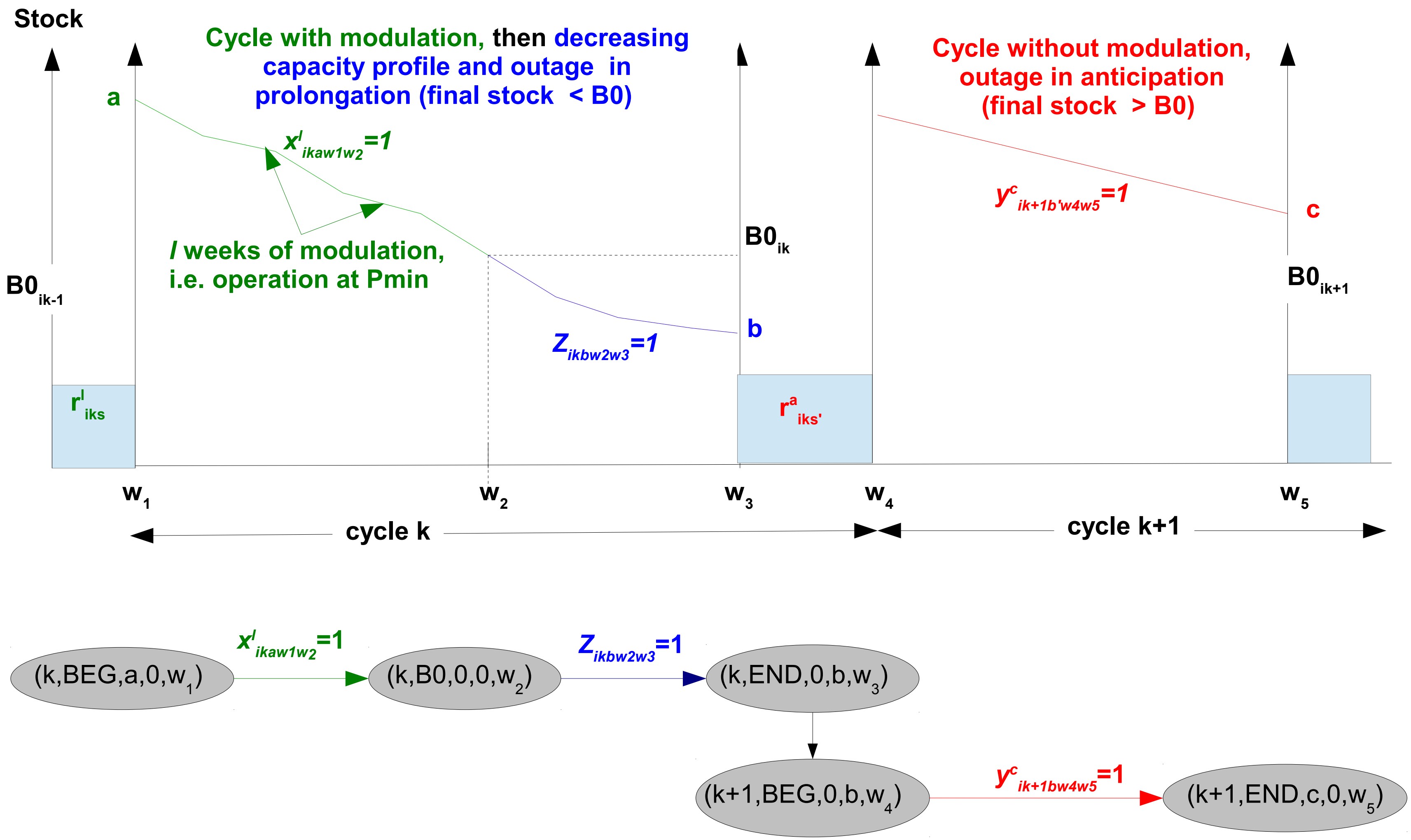
- INRIA/Bordeaux RealOpt (F. Vanderbeck)
  part of J.Han's post-doc, preleminary research work of Boris Detienne, and PGMO post-doc to come.
- LIPN/Paris XIII OCAD (R. Wolfler), GSCOP/CNRS (V. Jost)
  C. Pira's PGMO post-doc.

Resolution scheme currently investigated (INRIA/RealOPt) (1/3)



Resolution scheme currently investigated (INRIA/RealOPt) (2/3)

Pricing Sub-Problem (one per $NR(i)$) :



Resolution scheme currently investigated (INRIA/RealOPt) (3/3)

Recourse Sub-Problem

NB : $(\underline{q}_{i,w}, \overline{q}_{i,w}, \gamma)$ coming from the Master Problem

- CG's expectation cost minimizing constraint :
  $$\sum_{\omega} \pi(\omega) \sum_{j,t} C^{\omega}_{j,t} p(j,t,\omega) \leq \gamma$$
- Production sub-problem (one per demand/market scenario ω) :
  - Demand constraint : $\forall (t), \ \sum_{i} p(i,t,\omega) + \sum_{j} p(j,t,\omega) = D^{\omega}_{t}$
  - Nuclear Min/max capacity constraints :
    $$\forall (i,w), \ \sum_{w' \leq w} \underline{q}_{i,w} \leq \sum_{w' \leq w, t \in w} p(i,t,\omega) \leq \sum_{w' \leq w} \overline{q}_{i,w}$$
  - Bounds on production :
    $$\forall (i/j,t), \ 0 \leq p(i/j,t,\omega) \leq Pmax^{\omega}_{i/j,t}$$

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A first step

1. Implementing robustness of the schedule facing the uncertainty on outage duration
   - Possibly taking advantage of an additional recourse on the reload
2. 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 ?

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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 NRs' 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.

References I

1. M. Porcheron, A. Gorge, O. Juan, T. Simovic, G. Dereu. *Challenge ROADEF/EURO 2010 : a large-scale energy management problem with varied constraints*. EDF R&D, 2010.
2. M. Porcheron, P. Bendotti, N. Dupin *Planification des Arrêts des Réacteurs Nucléaires d'EDF Extensions au challenge EURO/ROADEF 2010*. ROADEF 2012. Angers. 2012.
3. N. Dupin. *A 2-stage Robust Optimization Model for Planning Nuclear Maintenances with Uncertainty on their Durations*. ISCO 2012. 2nd International Symposium on Combinatorial Optimization. Athens, April 17-21 2012.
4. N. Dupin, M. Porcheron, P. Bendotti *Towers a multi-stage robust formulation for the Nuclear Reactor Outage Scheduling Problem*. EURO 2012. Vilnius. 2012.

References II

5. A. RozenKnop, R. Wolfler Calvo, A. Alfandari, D. Chemla, L. Létocart : *Solving electricity production planning by column generation*. Journal of Scheduling. December 2013.
6. J. Han, P. Bendotti, B. Detienne, G. Petrou, M. Porcheron, R. Sadykov, F. Vanderbeck *Extended Formulation for Maintenance Planning at Power Plants*. ROADEF Conference 2014, Bordeaux, France, February 2014.

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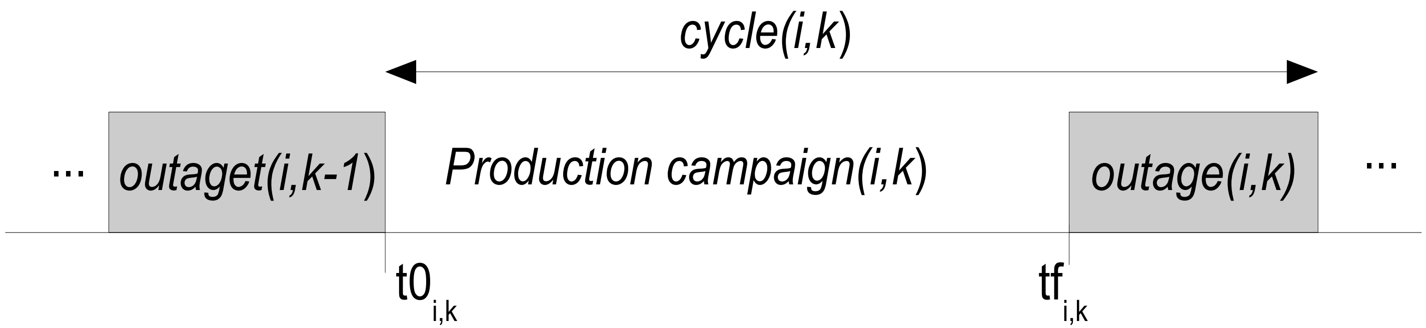
Cycles

- (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 :

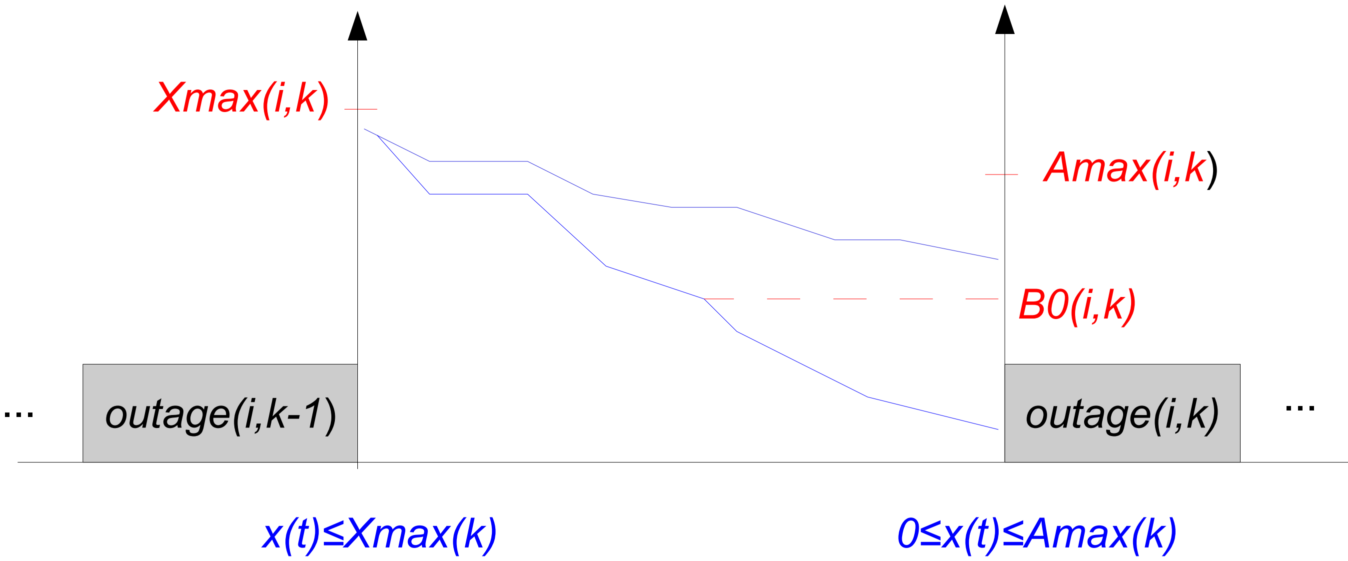
X^{ω}_{i,t_0} : Initial stock level of unit i on scenario ω (*energy*)

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

$C_{i,k}$ (resp. C_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 :

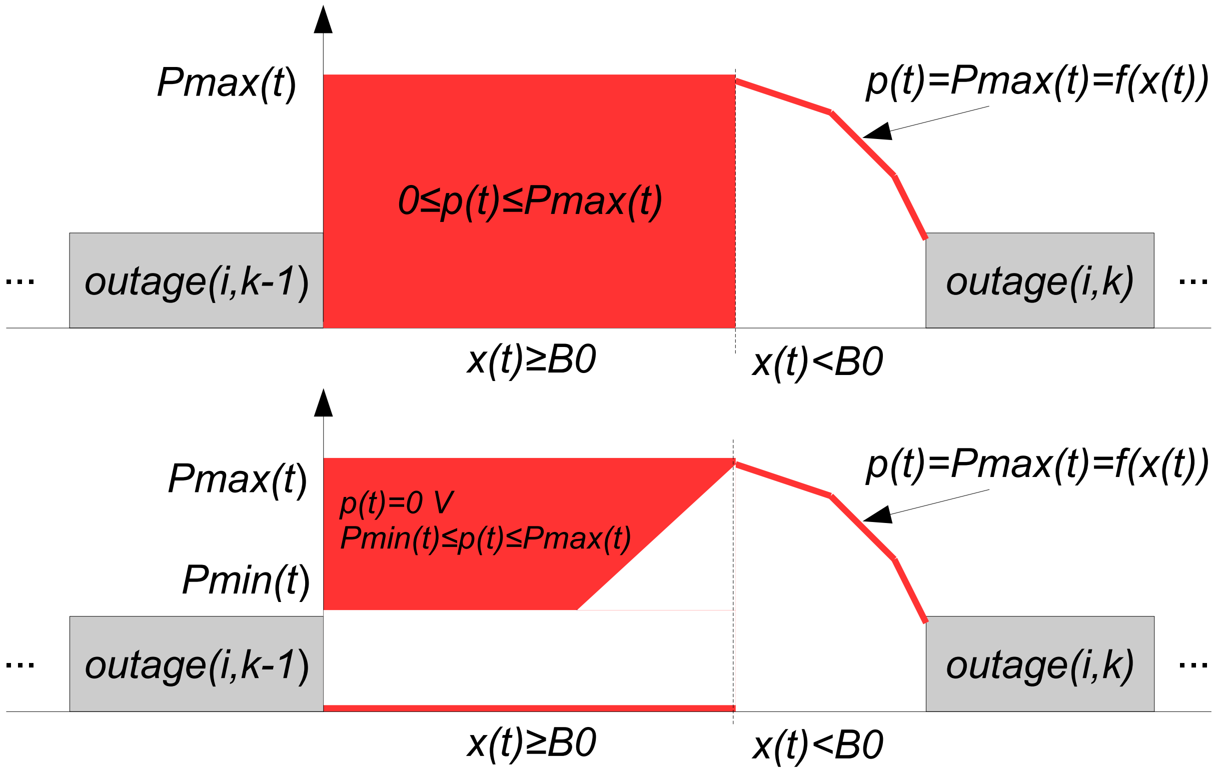
$$x(i,t0_{i,k},\omega) - B0_{i,k} = r(i,k) + \frac{(q_{i,k}-1)}{q_{i,k}}(x(i,tf_{i,k-1},\omega) - B0_{i,k-1})$$

- Production campaign :

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

Production constraints (1/2)

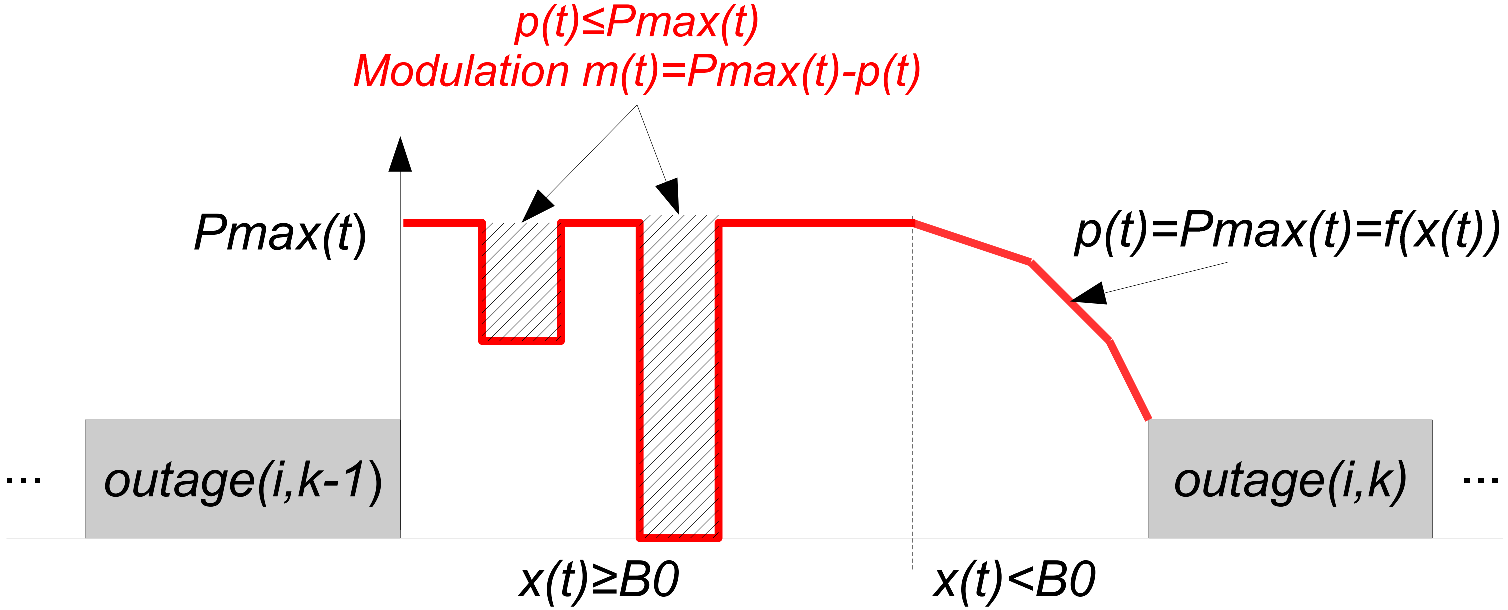
- Production must be null during outages
  - Coupling between discrete and continuous variables ...
- Bounds on production



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

Production constraints (2/2)

- "Modulation" maximum per cycle



$$\sum_{t \in (i,k)} m(t) \leq \overline{M}_{i,k}$$

(NB : Constraint coupling time steps inside a cycle).

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, 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 :
  $0 \leq p(j,t,\omega) \leq Pmax^{\omega}_{j,t}, \ \forall (j,t,\omega)$