Scheduling of EDF nuclear power plants outages :
problem, current approach and areas of research in progress

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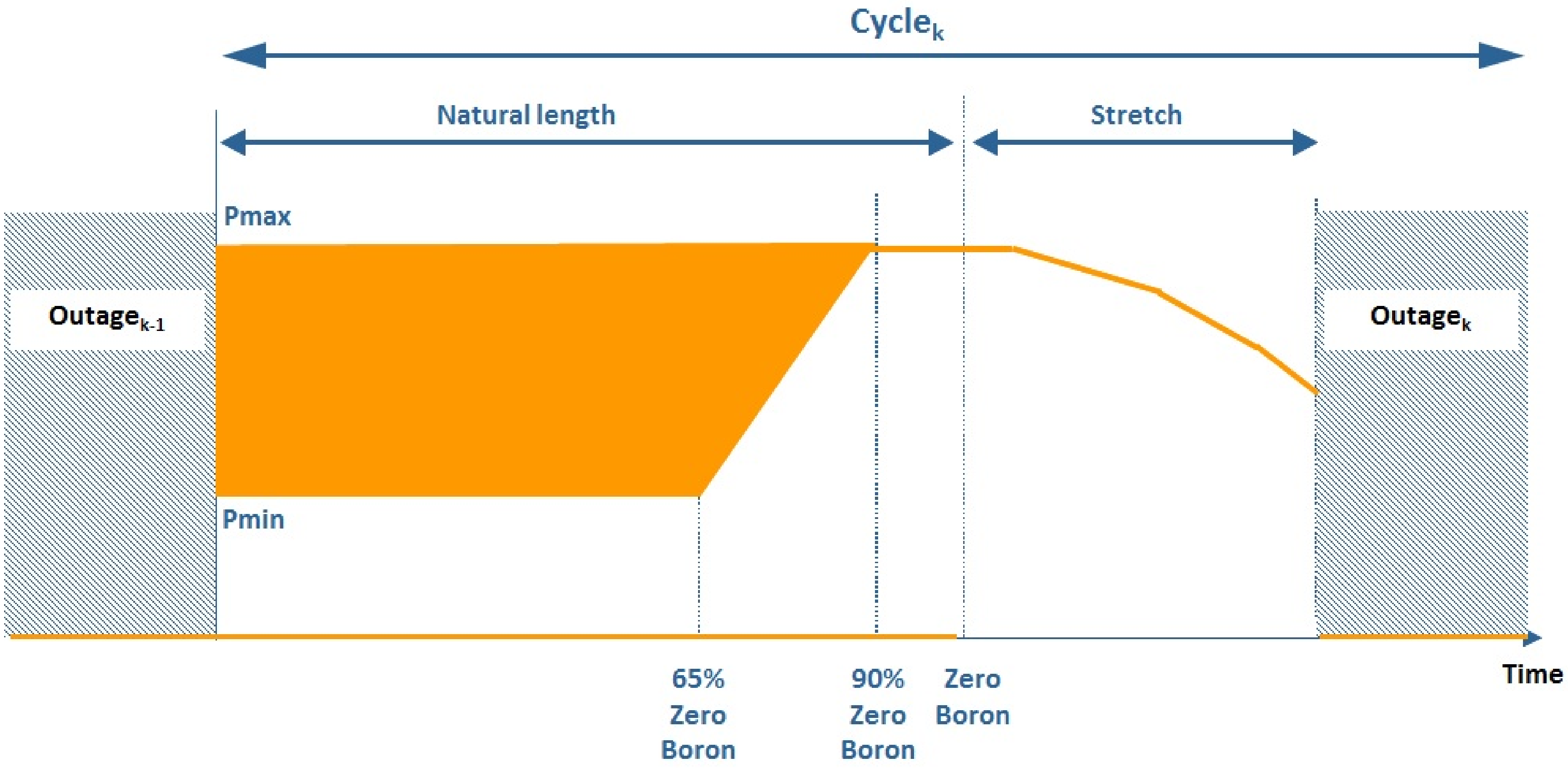
Electricity generation

- $\approx$ 60 *Nuclear Reactors* (REP) (index $i \in \{1...I\}$) have to be stopped periodically for refueling and maintenance operations (index of cycles $k \in \{1...K\}$).
- $\approx$ 100 *"Classical" Groups* (CG) can produce continuously, including *Conventional Thermal Units* (e.g. oil, coal, gas) and *Market Groups* modeling the exchanges with the spot market (index $j \in \{1...J\}$).
  - REPs' production cost is much less than CGs'.
  - REPs' installed capacity represents about 50% of the total installed capacity and 70% of "thermal" capacity.
  - REPs' production represents about 73% of the total production.

REPs' constraints (1/2)

Concerning the production cycle :



REPs' constraints (2/2)

Concerning the outages :

- Specific timeframe for the beginning/ending of the outages.
- Maximum number of overlapping outages.
- Maximum weeks of overlapping for pairs of outages.
- Minimum weeks of spacing for pairs of outages.

Objective

Find the optimal nuclear outage schedule for a 5-year time horizon,

while satisfying :

- the residual thermal demand ;
- the operating constraints of the REPs and the CGs ;
- the scheduling and resources constraints for the REPs' outages.

Essentially, REPs' outages have to be scheduled during low demand periods.

Operational process

- The *outages dates* and the *refuels* are the only decisions applied through the operational process.
- They are recalculated every two months for a sliding horizon starting from the current state of the system, without modifying them during the current two months.
- The units *productions* are optimized at short-term horizons by other models.
- We do not search for « strategies », « feedback laws », « decision rules » for the outages scheduling (nor 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

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Uncertainties

- *Demand* to satisfy for every time step : D_t^δ ;
- *Price and volume* of buying/selling using *Market Groups*, 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 : $Pmax_{j,t}^\theta$;
- *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 $\Omega \subseteq \Delta \times \Theta \times \Psi \times \Phi$ the stochastic space, ω one “scenario” in Ω

Variables

- Robust variables *here and now*, independent of scenarios

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

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

- Stochastic variables *wait and see* or *recourse*, dependent of scenarios

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

  $s(i,t,\omega)$: Stock level of REP i at the end of time step t on scenario ω (*energy*)

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

Initial Formulation

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

$$+ \underset{\omega}{\mathbb{E}} \Big[\sum_{j,t} C^{\omega}_{j,t} \cdot p(j,t,\omega) \cdot dt - \sum_{i} C^{T}_{i} \cdot s(i,T,\omega) \Big] \Big\}$$

$s.t.$

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

+ 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.
- Stochastic, mixed-integer, non-linear problem.
- Size : $I \approx 60$, $K \approx 5$, $J \approx 100$, $T \approx 5 \times 50 \times 40$, $|\Omega|$ huge.

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Hypothesis and simplifications (1/2)

- Outages duration and hazardous faults of REPs are considered deterministic, refuelings are fixed :
  - $\Omega' \subseteq \Delta \times \Theta$: only the randomness of the *demand*, the *cost* and the *maximum power* of CGs are taken into account.
- Nuclear demand together with associated costs of CGs to satisfy the outstanding demand are pre-calculated in average over the set of scenarios Ω' for certain variations of the inital nuclear availability.
- Time step duration : week.

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Advantages

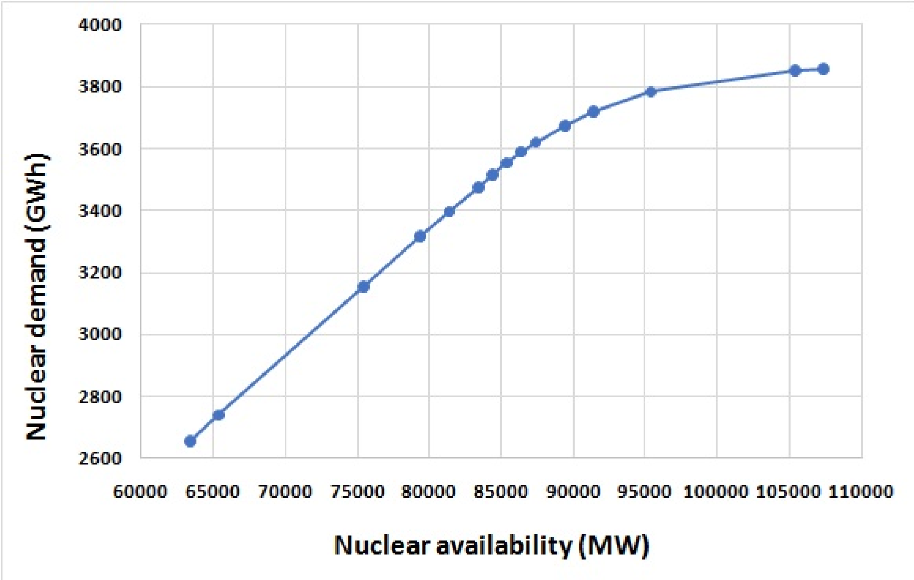
- No need to recalculate CGs production for every time step and every scenario.

Disadvantages

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

Hypothesis and simplifications (2/2)

For the nuclear demand and cost of CGs we have functions of the following type for every week :



- Nuclear availabilty : depends on the number of ongoing outages and the stretch.
- Nuclear demand : it can not be greater than the nuclear availabilty.

“Simplified” formulation

$$\underset{o(i,k),p(i,t)}{Min}\Big\{\sum_{i,k} C_{i,k}(o(i,k))\cdot r_{i,k} - \sum_{i} C_i^T \cdot s(i,T) + \sum_{t} C_t^{CG}(na(t))\Big\}$$

$$s.t.\ \sum_{i} p(i,t) = D_t^N(na(t)),\ \forall t,$$

+ operational constraints for REPs;

+ scheduling and resources constraints for the outages of the REPs.

- $na(t)$: nuclear availability at time step t, being a function of REPs outage schedule and production ;
- $C_t^{CG}(na)$: total cost of CGs, given the nuclear availability na at time step t ;
- $D_t^N(na)$: nuclear demand, given the nuclear availability na at t.

Improving previous resolution methods

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 nor feasibilty.

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⟹ Develop an *Iterated 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.

Iterated Local Search

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 always satisfying outages constraints ;
  - penalizing stock constraints.

Step 3 Perturbations :

- to avoid local minimum ;
  - implementing quasi-random movements, including permutations and winter jumps ;
  - iterating with the gradient descent.

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

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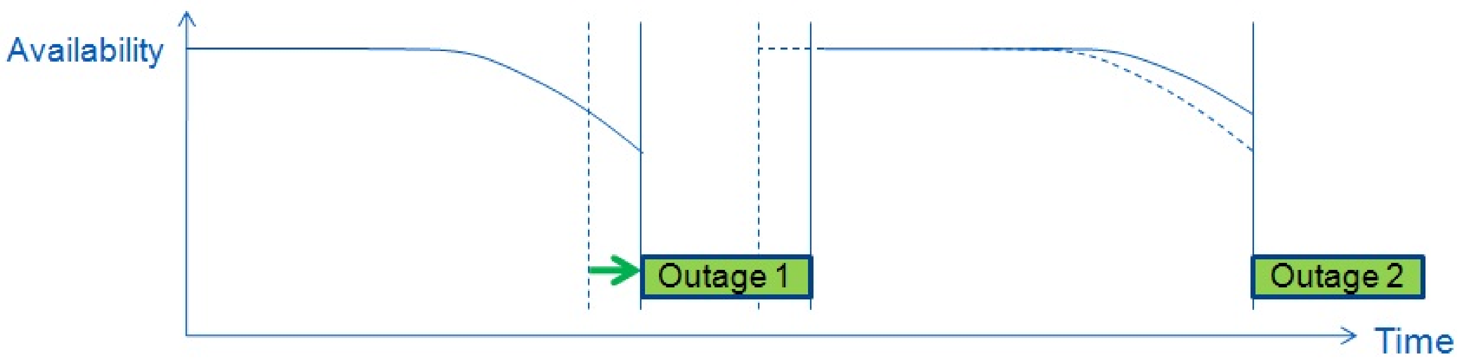
Movement proper cost

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 1.
   - No STOP.

Heuristics (2/2)

Perturbations

1. Calculate :
   - the proper cost of all movements ;
   - all the potential permutations ;
   - all the potential winter jumps.
2. Apply a quasi-random set of movements.
3. Repair violations.
4. Use the gradient descent and **evaluate** the new schedule.
5. Did the cost decrease ?

   Yes All the movements are accepted.

   No Reject all the movements.

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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 advancing forward until the end :
   - given the nuclear availabilty, calculate the nuclear demand ;
   - decide which REP should decrease its production in order to absorb the difference between nuclear availability and demand.
3. If the result is satisfying, STOP. Otherwise go to 2.

Methodology (2/2)

Problem : how to decide which REP should decrease production ?

- 1^{st} priority : satisfy the **constraints**
  - two constraints can be violated because of non-optimal production : **minimum** and **maximum stock** at the end of the production cycle
- 2^{nd} priority : decrease the **total cost**
  - the decrease of production can be used in order to **decrease** the **stretch** $\Longrightarrow$ **decrease total cost**

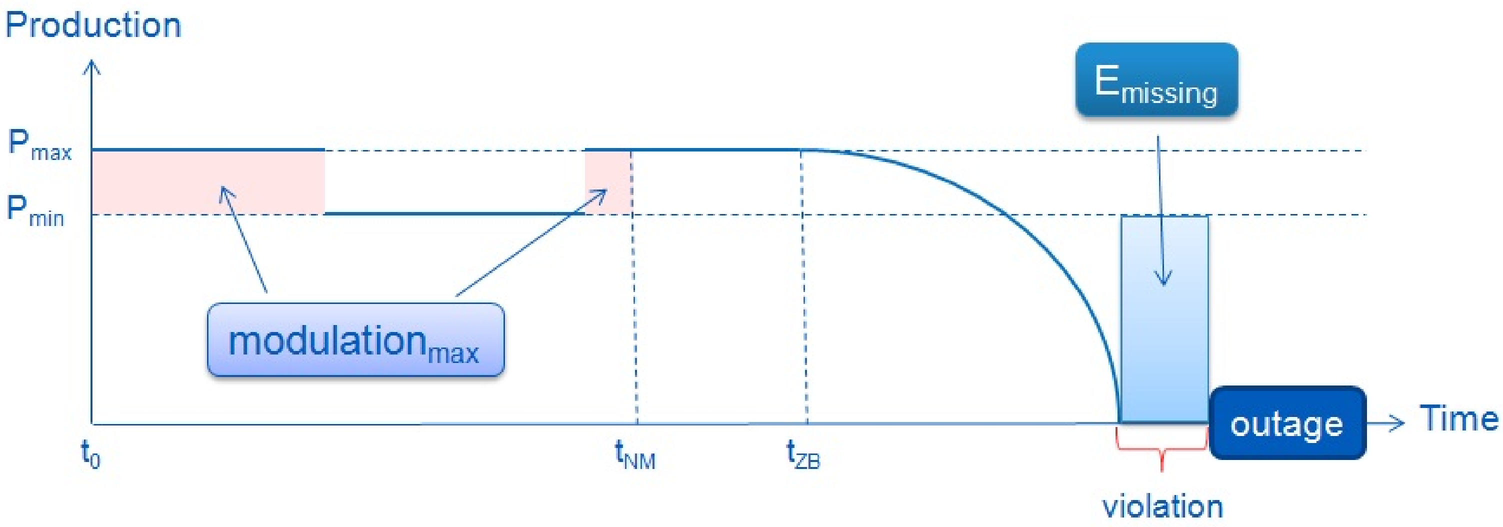
Since there is no proportional cost, *sort* the REPs
in order to represent the above two criterions of *priority*

Nuclear plants classification : 1^{st} class

Class $REP_{minStock}$ - “high-cost” reactors

- REPs that run out of stock before end of the cycle.
- Inner-class criterion :

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



Nuclear plants classification : 2^{nd} class

Class REP_{cost} - "medium-cost" reactors

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

$$marginalProfit_{modulation} = \frac{cost(P_{max}) - cost(P_{min})}{P_{max} - P_{min}}$$

Remark : by producing less (minimum power) :

$\Rightarrow$ REP stretch decreases ;

$\Rightarrow$ REP availiablity increases ;

$\Rightarrow$ CGs cost decreases.

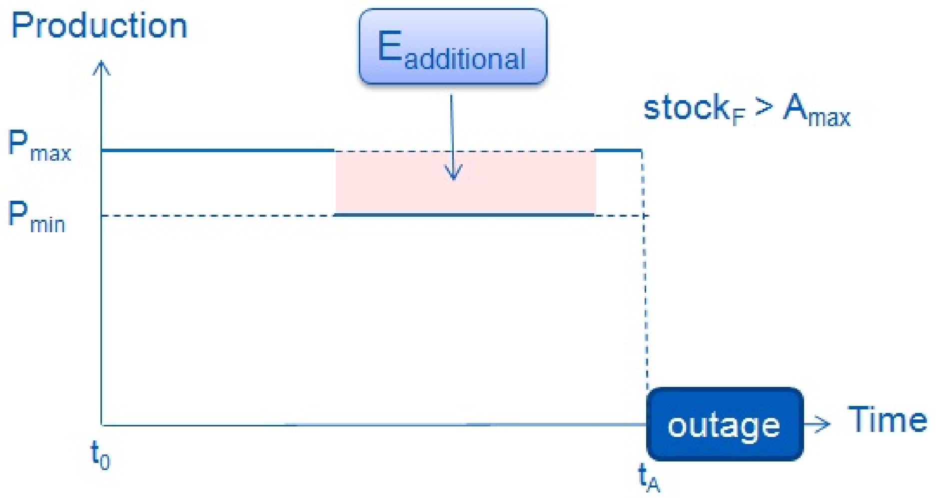
By producing more (maximum power), cost increases.

Nuclear plants classification : 3^{rd} class

Class $REP_{maxStock}$ - “low-cost” reactors

- REPs that violate the maximum stock constraint at the end of the cycle.
- Inner-class criterion :

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



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 advancing forward until the end :
   - given the nuclear availabilty, calculate the nuclear demand ;
   - classify all the REPs ;
   - decide which REP should decrease production in order to absorb the difference between nuclear availability and demand.
3. If the result is stabilizing, STOP. Otherwise go to 2.

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Still, a lot of work remains

Iterated Local Search improvement

- tune heuristics, stabilize the results and the performance ;
- use of *CP* in order to repair explored, but non-feasible solutions.

Parallelism

- to explore multiple neighborhoods in parallel.
- to work with *multiple scenarios* ;

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A first step

1. Implementing robustness of the schedule facing the uncertainty on outage duration
   - Possibly taking advantage of recourse on the reload
2. Investigating the problem of stabilizing the solutions, along the re-optimizations performed bimonthly on a receding horizon.
   - Outage dates are very constrained decisions which cannot easily be changed. Currently 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 current stocks are not taken into account.
4. What about schedule *strategies* ? Necessary to implement a closed-loop process using a simulator to reproduce the bimonthly re-optimization → "the" big challenge.

Contents

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