# Hydro valley chain optimisation at EDF

## Currently used methods, future needs and perspectives

Anes Dallagi, Tomas Simovic
EDF R&D

# Plan

- Large scale energy management: how to match supply to demand?
- Zoom on short term unit commitment
  - Apogee model
  - Hydro representation
  - Past work and perspectives
- River-chain valuation
  - The problem
  - How to solve?
  - Two methods: outer approximation (SDDP) and multi-modeling (sequential relaxation)
- Experiments
  - The models: Vicdessos and Dordogne
  - Basic model
  - Including one type of non-convexities: head effect
- Conclusions and perspectives

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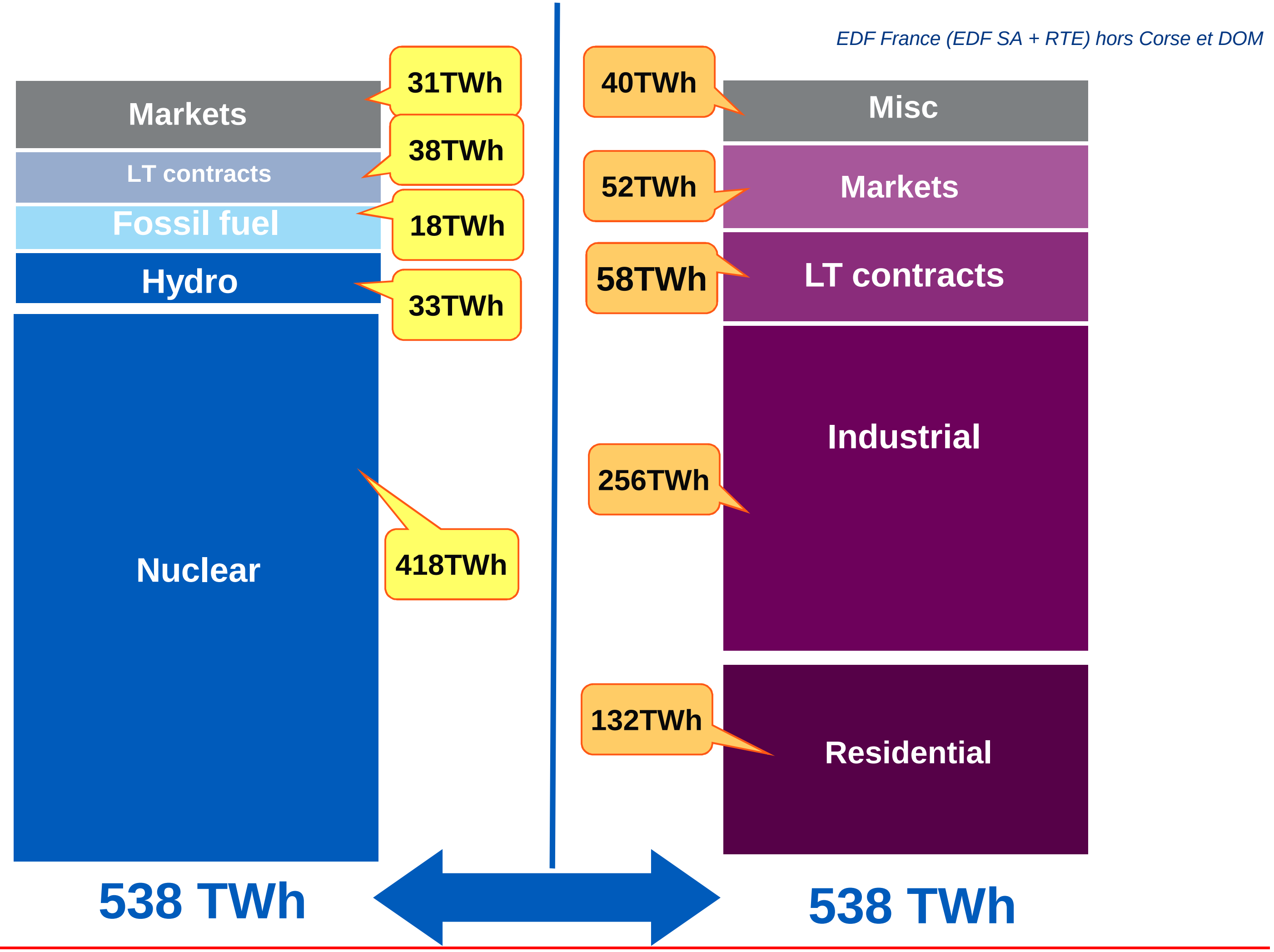
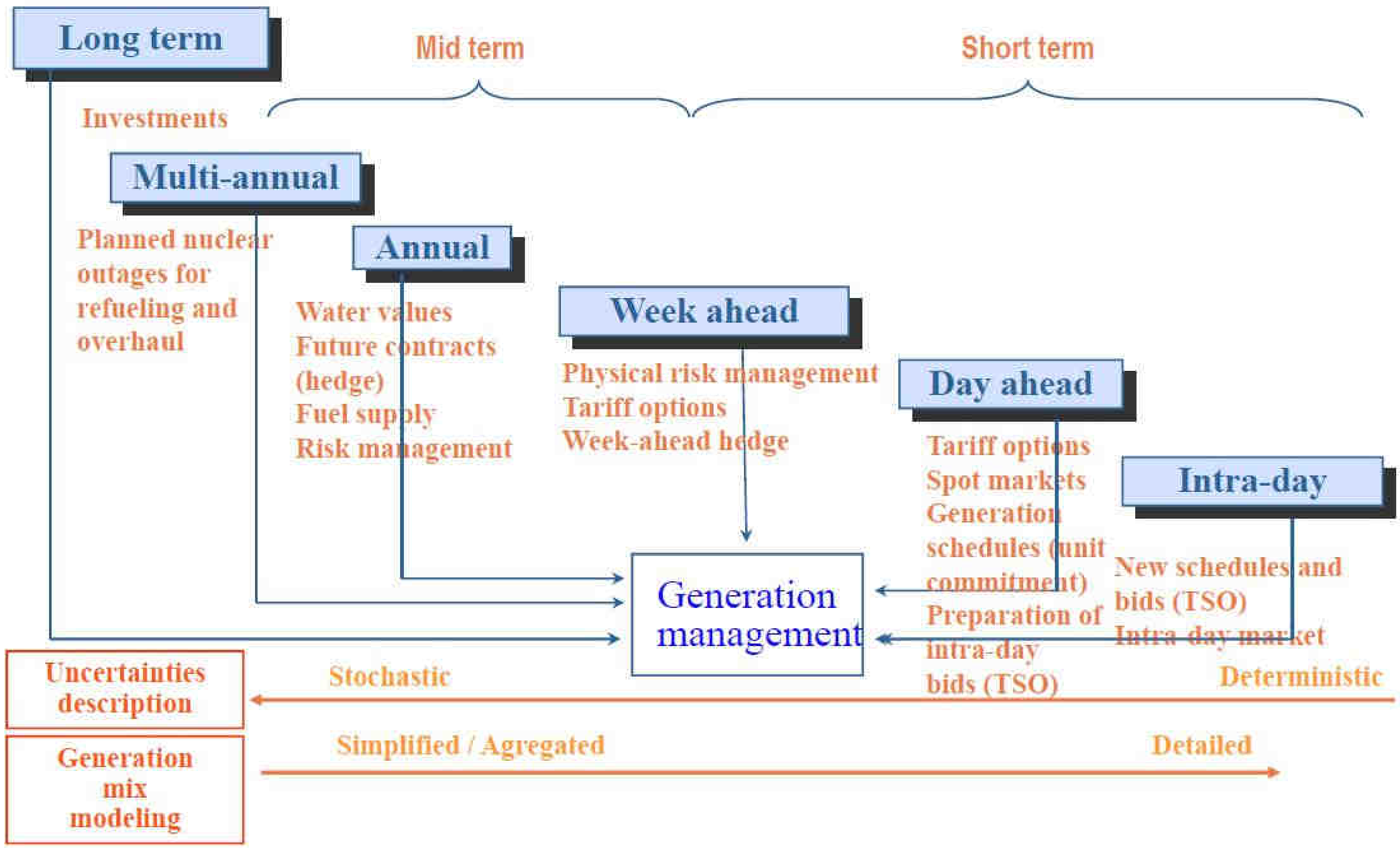
# EDF generation mix

- Electricité de France is one of the European leaders in the energy field and the major electricity producer in France
- 58 nuclear units and 47 thermal units (fuel, coal and gas turbine),
- 50 hydro-valleys. Each hydro-valley is a set of interconnected reservoirs (150) and power plants (448). Water stock : 7000hm3
- 25 withdrawal options
- Other : wind, solar, biomass in significant growth

# EDF portfolio



# How to match supply to demand



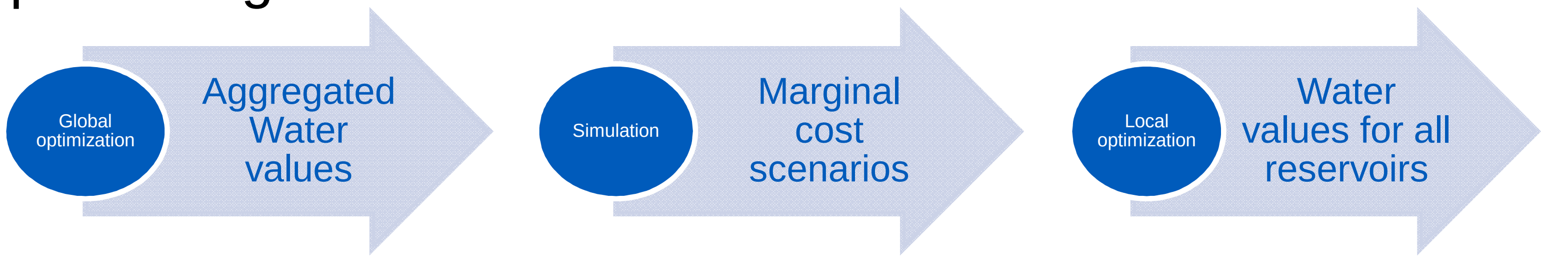
# Optimization process: time decomposition

- The main goal is to make, at all times, the exact balance between electricity consumption and electricity production while minimizing the overall cost.
- Due to storage units, investments, LT contracts etc., the time horizon over which we need to minimize management cost is too large → time decomposition.


- Each optimization problem still too large and we need to separate a global aggregated optimization from a local one

# Optimization process: space decomposition

- The mid-term management process focus on minimizing expected cost over 3 to 5 years.
- It is a large scale stochastic optimization problem:
  - 80 thermal units, 50 hydro-valleys. Each hydro-valley is a set of interconnected reservoirs (150) and power plants (448), 25 withdrawal options, Markets, 60x484 scenarios, etc.
- The hydro-valleys are aggregated into 3 big reservoirs and one withdrawal option → solve the problem using ADP
- Simulating the optimal policies of the aggregated reservoirs, we compute marginal cost scenarios → decentralize decision



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# Short term unit commitment : main characteristics

- A problem of large size
  - EDF production mix :
    - 58 nuclear plants
    - 47 thermal plants
    - 50 hydro-valleys
  - Study performed over 2 days with a 30 minutes step  (96 total time steps)
  - Refined modelling of production units for local dynamic constraints

➔ An optimization model of approximately 1 million variables solved by the daily model Apogee Lissage

# Apogee Lissage daily unit commitment model

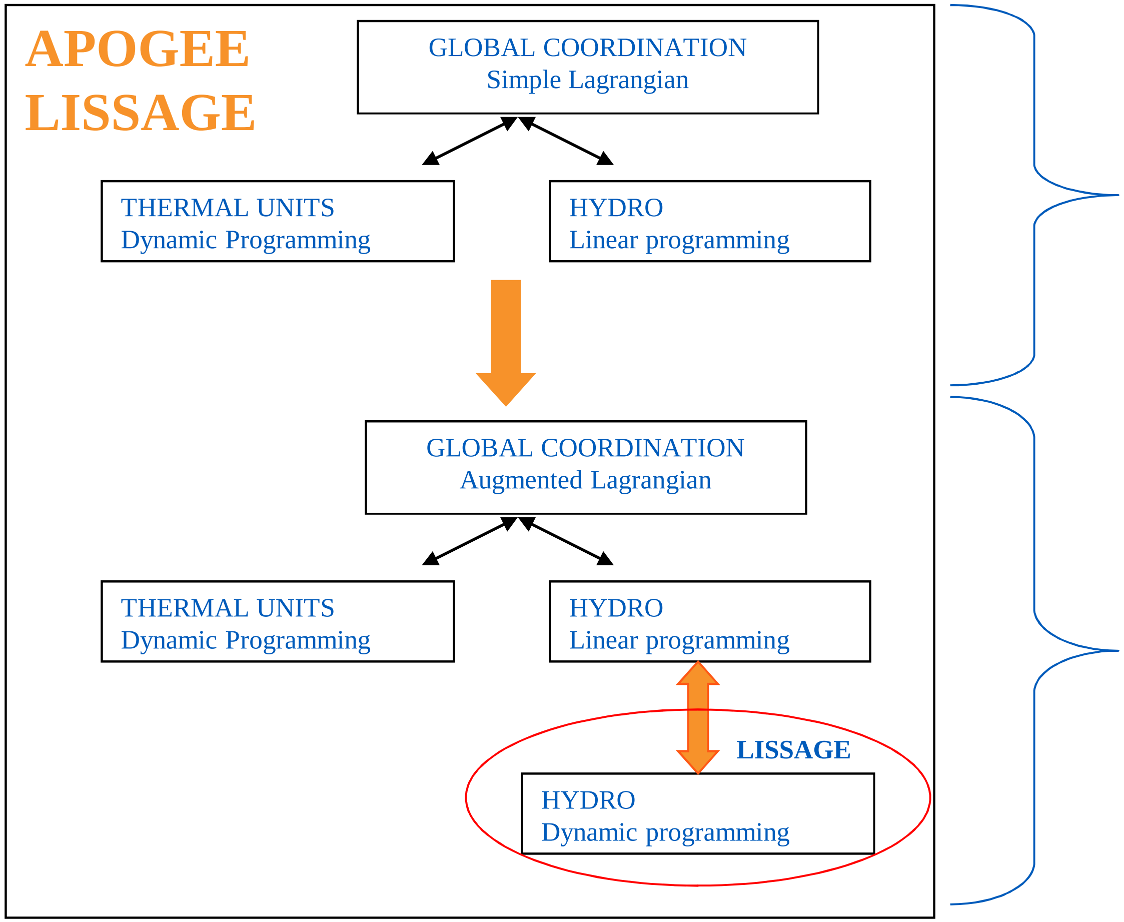
- Input :
  - Demand forecast (power, and ancillary reserves)
  - Technical data for production units
  - Daily data for production units (unavailability, impositions, initial conditions at 0h,…)
  - Economical characteristics (production's costs, water values)
- Output :
  - Feasible production schedules
    - Power
    - Ancillary reserves
  - Marginal cost for each production demand
- Objective function – a minimization of:
  - Thermal unit variable production and start up costs
  - Discharged water quantity x water values
  - Penalties for deviations between demand forecasts and power schedules

# Apogee Lissage daily unit commitment model

- Solved by a price decomposition method :
  - The problem is decomposed into sub problem :
    - Thermal sub problem = a thermal unit
    - Hydro sub problem = a valley chain
  - Allows for parallelisation of the solution process

- Algorithm works in two phases :
  - $1^{st}$ phase : Simple lagrangian provides marginal costs and a lower bound on the solution costs
  - $2^{nd}$ phase : Augmented lagrangian provides feasible production schedules with good supply demand balance

# Apogee Lissage daily unit commitment model




**<u>1st phase</u> :**

- **coordination by bundle method**
- **700 itérations**
- **hydro units without discrete set points**
- **computes marginal costs**

**<u>2nd Phase</u> :**

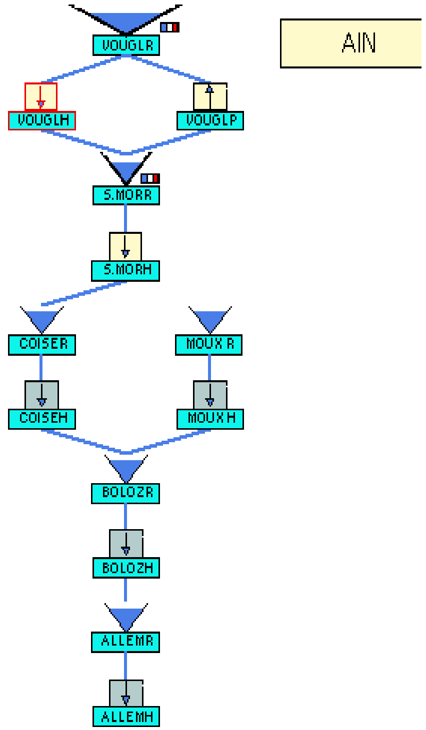
- **coordination by Uzawa**
- **700 iterations**
- **hydro units without discrete set points then projection on discreete set points by « lissage » heuristic**

# Hydro sub problem:

- A hydro valley chain : a set of interconnected reservoirs and power plants
- Flow constraint

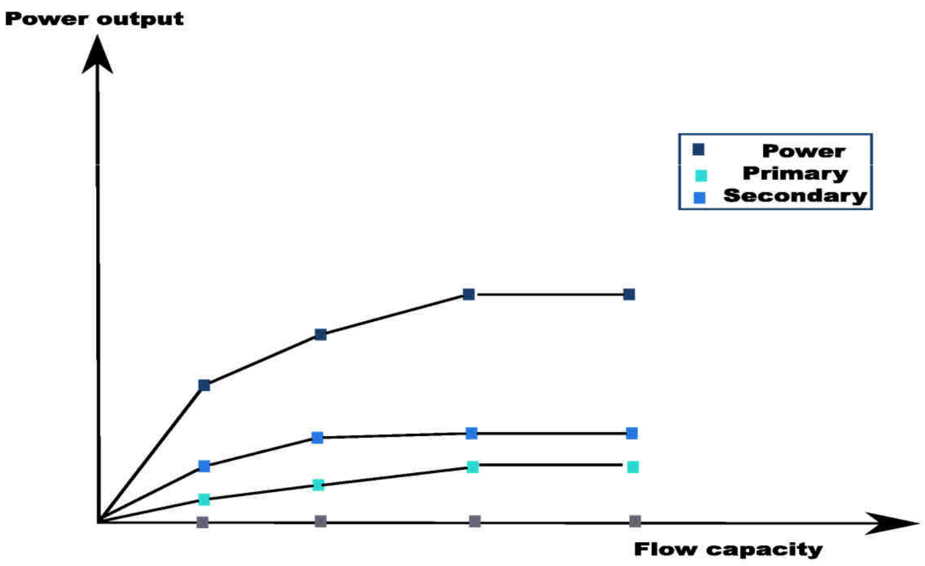
$$V(t,r) = V(t-1,r) + \sum_{u \in up(r)} T_u^{t-d(u,r)} - \sum_{u \in down(r)} T_u^{t+d(r,u)} + O_r^t$$

  - $V(t,r)$ Volume of reservoir r at time step t
  - $T_u^t$ Discharge of plant u at time step t
  - $o_r^t$ Inflows to reservoir r at time step t
  - $d(u,r)$ Travel time of water between unit u and reservoir r



# Hydro sub problem:  hydro unit model (1/2)

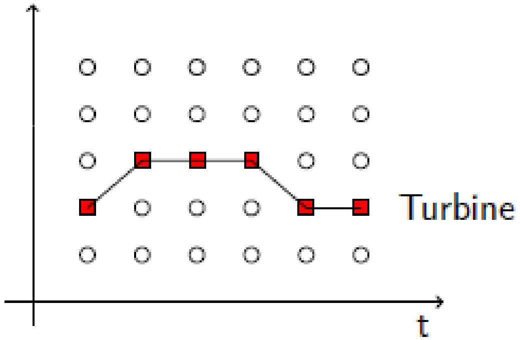
- Power, primary, secondary reserve = piece wise linear functions of flow



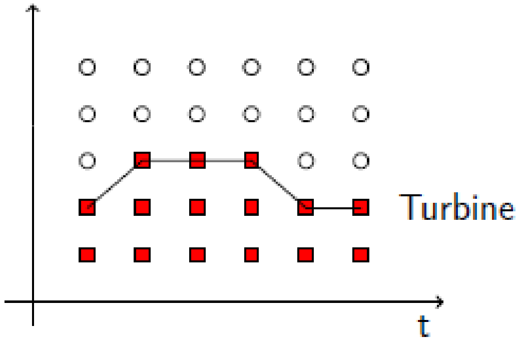
# Hydro sub problem : hydro unit model (2/2)

- Modelling of discrete set points :

multiple choice model




incremental model




■ : $X_{t,u,g} = 1$  ○ : $X_{t,u,g} = 0$

$\sum_g X_{t,u,g} \leqslant 1$  $\forall g, X_{t,u,g+1} \leqslant X_{t,u,g}$

$$\text{Turb}_{t,u} = \sum_g X_{t,u,g} \cdot T_{t,u,g}$$

$T_{t,u} = [60\ 80\ 100\ 115]$  $T_{t,u} = [60\ 20\ 20\ 15]$

# Hydro sub problem : unit constraints

- Bounds constraints on production variation

$$\underline{\delta}(u) \leq Turb\,(t+1,u) - Turb\,(t,u) \leq \overline{\delta}(u)$$

- $\overline{\delta}(u)$ Maximum positive rate of change of production
- $\underline{\delta}(u)$ Maximum negative rate of change of production

- Minimum up time/down time (incremental model)

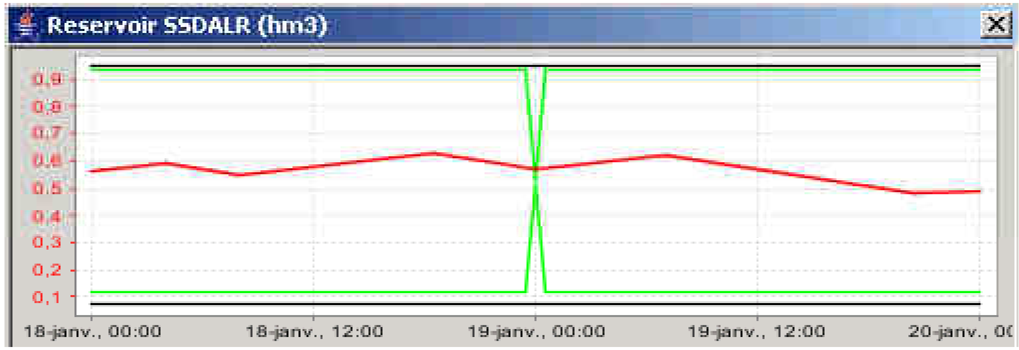
$$-1 \leq X(t,u,g) - X(t-1,u,g) - X(t+1,u,g) \leq 0$$

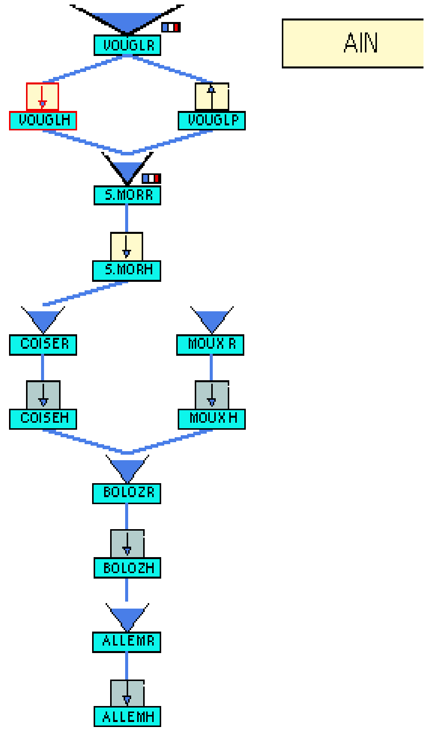
- Simultaneous discharge and pumping prohibited (incremental model)

$$X^{tur}(t,u,1) + X^{pump}(t,u,1) \leq 1$$
$$X^{tur}(t+1,u,1) + X^{pump}(t,u,1) \leq 1$$
$$X^{tur}(t,u,1) + X^{pump}(t+1,u,1) \leq 1$$

# Hydro sub problem: reservoir constraints

- Bound constraints on volumes




$$V^{\min}(t,r) \leq V(t,r) \leq V^{\max}(t,r)$$

- $V^{\min}(t,r)$ Minimum volume of reservoir r at time step t
- $V^{\max}(t,r)$ Maximum volume of reservoir r at time step t
- $V(t,r)$ Volume of reservoir r at time step t

# Hydro sub problem : solution methods

- Apogee Lissage :
  - Linear programming
  - Projection of the continuous solution on discrete set points by a dynamic programming based heuristics (Lissage)
  - Problem :
    - Linear programming violates discrete constraints
    - Dynamic programming heuristic violates continuous constraints (volume bounds)
    - Result is suboptimal

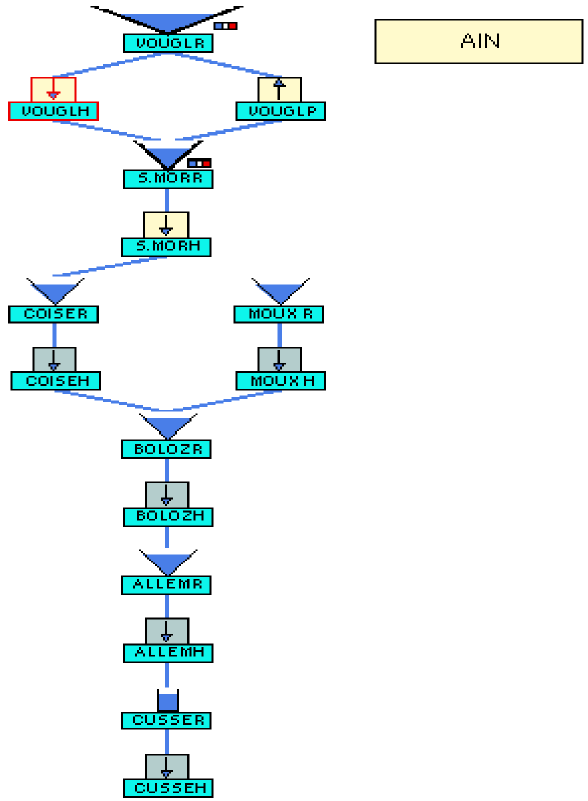
- Apogène :
  - Hydro sub problem modelled as a MILP problem and solved by CPLEX
  - All constraints are satisfied and global optimality guaranteed if enough time to converge
  - MILP well adapted to model constraints that will have to be taken into account in the future
  - However :
    - Longer, data dependent, computing times for some valley chains

## Hydro sub problem : work done in recent years

- Valid inequalities for unit constraints :
  - Minimum up time/down time
  - Gradient constraint
- Modelling of the hydro production function :
  - "Incremental model" gives the best experimental results => an excellent linear relaxation, structure of the model is favourable for clique cuts
- Heuristics :
  - Small number of fractional variables in linear relaxation => neighbourhood search heuristics seem promising (RENS)
  - Rounding the remaining fractional variables does not lead to a feasible solution => feasibility pump based rounding heuristic is not efficient

# Hydro sub problem : perspectives (1/2)

- The hydro model will have to evolve in the coming future :
  - A large number of new constraints will be added :
    - Flexible maintenance outages
    - Imposed production profiles
    - Minimum energy production
    - Maximum flow dependent on head
    - …
  - Including the head effect would be interesting if computationally feasible
  - Improvement in computing times is needed
- New applications based on the the hydro model (not necessarily in a price decomposition context) :
  - Estimation of tertiary reserve
  - Outage scheduling
  - Construction of capacity offers
  - …

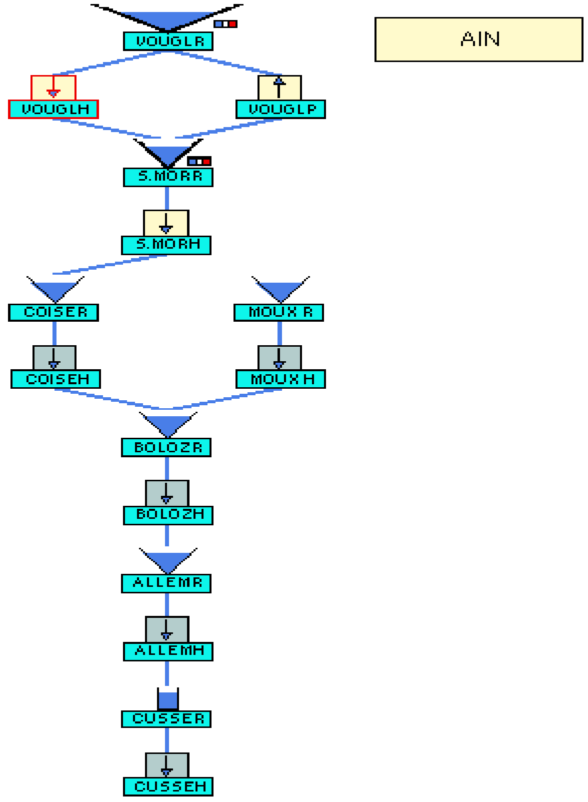




[1]CNRS, Ecole Polytechnique
[2]Electric Power Optimization Center University of Auckland, New Zealand

# Hydro sub problem : perspectives (2/2)

- Future work :
  - with Claudia d'Ambrosio[1] : *Optimality for tough combinatorial hydro-valleys problems* - PhD thesis + postdoc
  - with Andy Philpot[2] : *Hydro-electric scheduling under uncertainty* - PhD thesis
  - with Pascal Côté[3] – internship followed by a PhD thesis

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[3] Rio Tinto Alcan, Canada

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# River-chain valuation: the problem

- We focus on the local optimization process.
  - Input: marginal cost scenarios.
  - Output: water values.
- The problem is to maximize the expected revenue for a hydro river-chain when releases must be made in each hour, over a couple of years.
- The specific features that we shall study are:
  - Modeling the head effects from river heights in the head ponds and tailraces that affect the efficiency of generation;
  - Provision of energy by committing a number of turbines to be running;
  - Provision of spinning reserve by committing turbines to be in synchronized condensing mode;
  - Provision of frequency-keeping services from a selection of turbines;
  - Avoidance of rough running ranges in turbine curves;
  - Uncertainty in both future price, inflows and bounds on flow rate;

# River-chain valuation: how to solve ?

- Solving this problem require optimization methods that can handle non-convexities appearing in the objective (head effects) and constraints (running ranges).
- Stochastic dynamic programming looks at first glance as an appropriate method (solving transition problems as MIPs).

$$V_t(x, w(t)) = \max_{x(t+1), h(t)} p(t)^T q_t(x, f(t)) + E[V_{t+1}(x(t+1), w(t+1)],$$
$$s.t. \quad x(t+1) = x - ADf(t) + w(t),$$
$$0 \le f(t) \le b_t(x), \qquad 0 \le x(t+1) \le r(t+1).$$

- Considering large river-chains (up to 20 reservoirs), we are faced with the curse of dimensionality.
- Then, we use ADP heuristic based on multi-modeling methods (aggregation techniques) → separable policies.
- Questions:
  - Can we use outer approximation techniques?
  - What is the trade-off between non-convexities and multivariate policies?

# River-chain valuation: two methods

## Multi-modelling

- The multi-modeling heuristics are close to sequential relaxation techniques.
- They assume separability of the Bellman function → univariate water values.
- They can handale non-convexities → transition are “small” MIPs
- Considering a river chain with *n* reservoirs, in order to compute release policy for reservoir *I, we fix the reservoir level of the others*

## Outer approximation

- The outer approximation method also called SDDP is an iterative algorithm based on dynamic programming, backward passes and simulations
- It is mainly based on the convexity of the Bellman function → the basic method can not handle non-convexities
- It gives multivariate Bellman functions → the policy of one reservoir depend on the others

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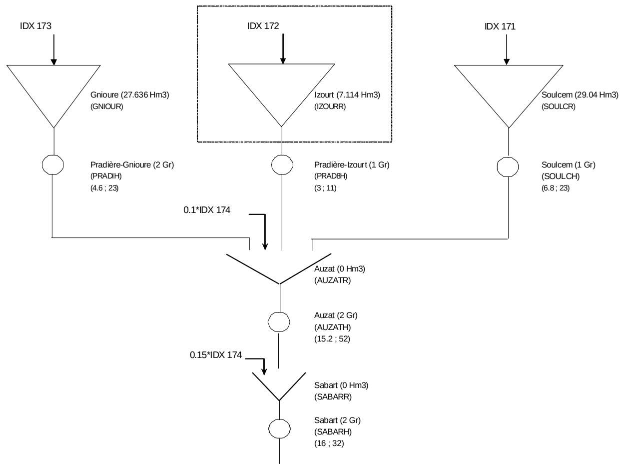
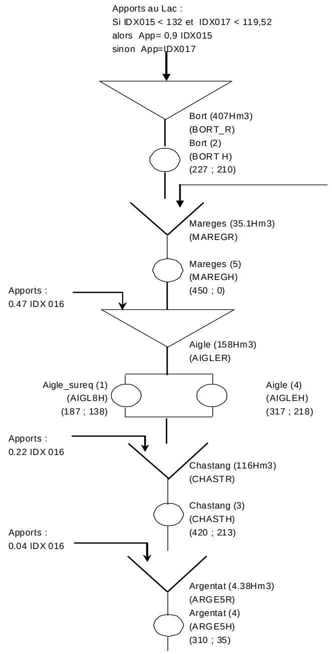
# Experiments: the models

- A first river-chains where the separability of policies (Bellman functions) seems to be a relatively good assumption: $V_t(x,w(t))=\Sigma V^i_t(x^i,w^i(t))$
- *Vicdessos : 141 MW (0.7% of hydro power)*



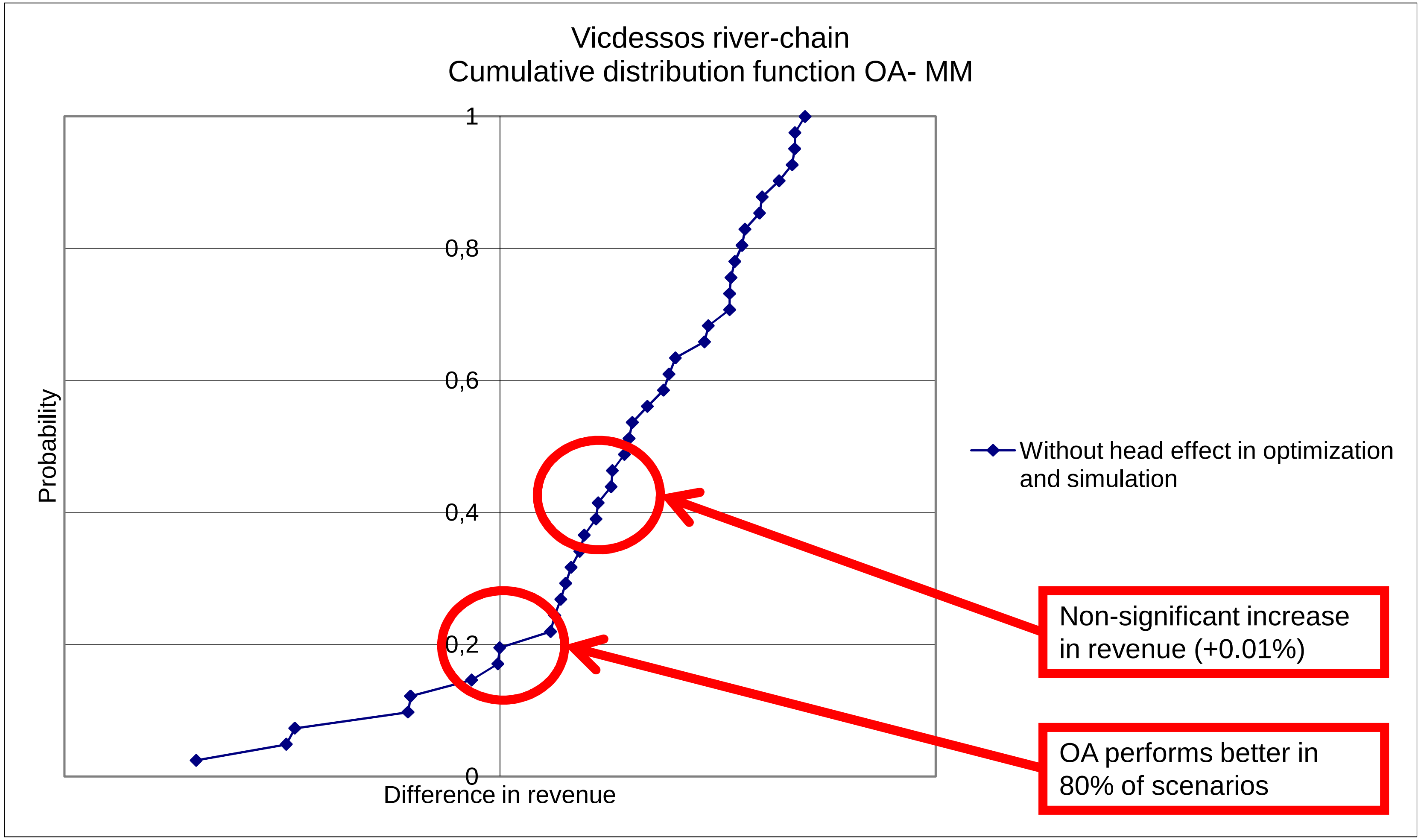

- A second one where the policy of one reservoir depends strongly on the policies of the upstream and downstream reservoirs.
- Dordogne 871 MW (4.4% of hydro power)



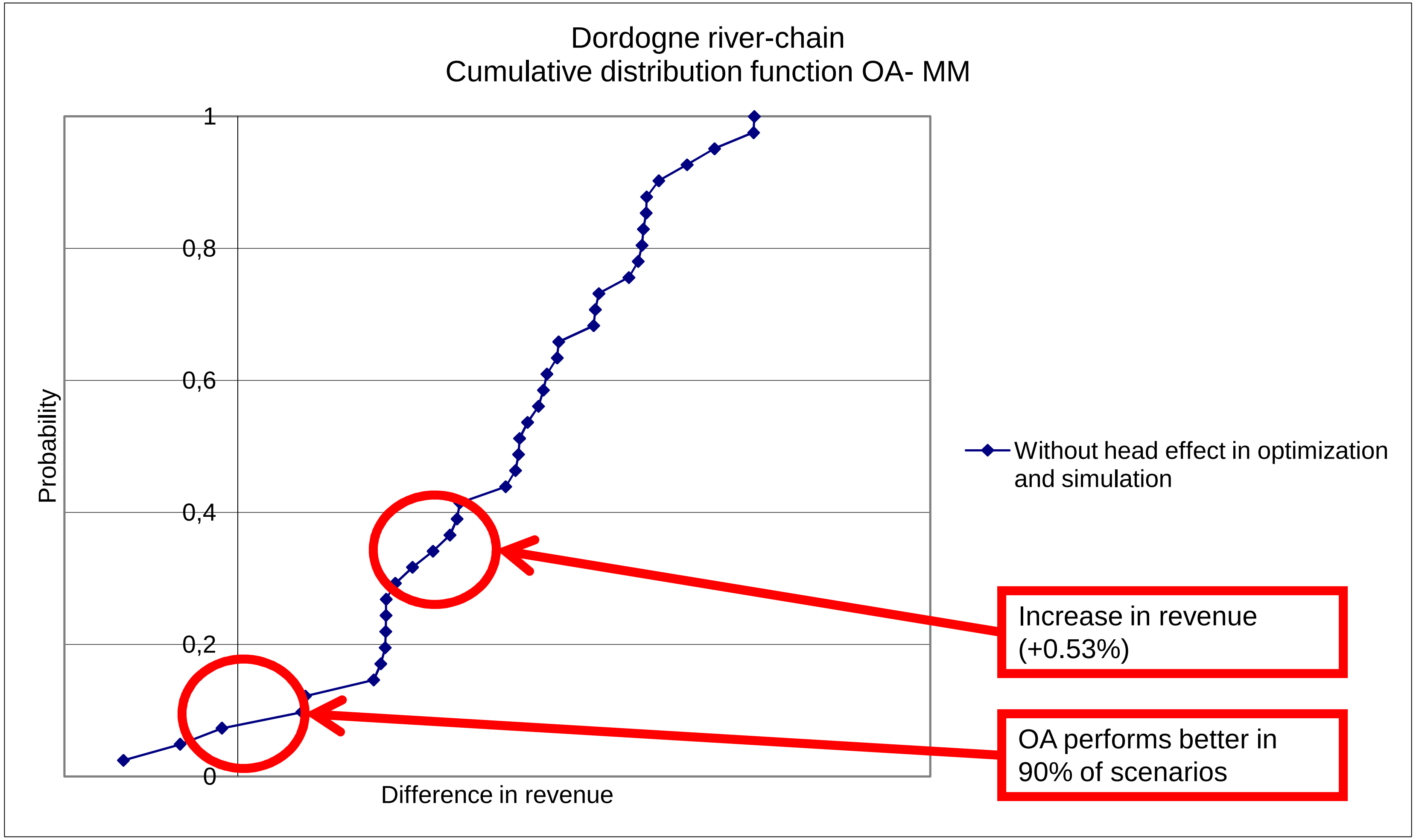
# Experiments: the basic model assumptions

- Weekly stages
- No head effects
- Linear turbine curves
- Reservoir bounds are 0 and capacity
- Full plant availability
- Known price sequence, 21 per stage
- stagewise independent inflows
- 41 inflow outcomes per stage

# Experiments: the basic model results (1/2)



# Experiments: the basic model results (2/2)



# Experiments: Including head effect (1/3)

- Power output *q* depends on net head level *h* which is the difference in headwater and tailwater heights.
- Here *v* is an effciency factor that varies with *h* and flow rate *f*.
- Assuming a fixed tailwater height, we have that *h* is a concave function of reservoir volume x, so

$$q(f,x) = \nu(f,x)\rho g h(x) f$$

- Approximate this by a piecewise linear function:

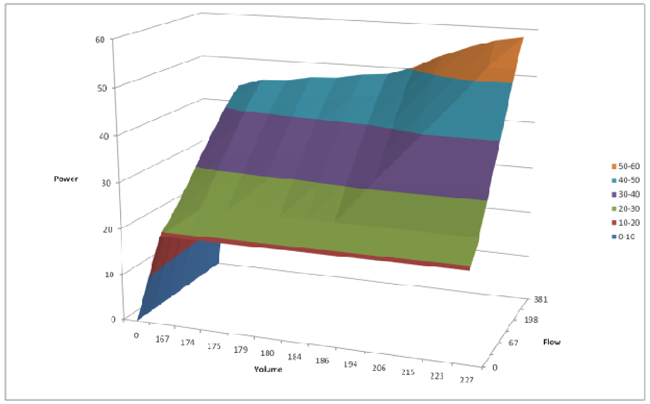
$$\begin{aligned} q(f,x) = \quad & \max_{f_1,f_2} \quad \eta_e(x) f_1 + \eta_m(x) f_2, \\ & s.t. \quad f_1 + f_2 = f, \\ & \qquad f_1 \le f_e(x), \qquad f_2 \le f_m(x) - f_e(x). \end{aligned}$$

- *Where:*

$$\begin{aligned} & f_e(x) = \arg\max_f \nu(f,x), \\ & f_m(x) = \text{maximum flow rate when reservoir level is } x, \\ & \eta_e(x) = \nu(f_e(x),x)\rho g h(x), \\ & \eta_m(x) = \nu(f_m(x),x)\rho g h(x), \end{aligned}$$

# Experiments: Including head effect (2/3)

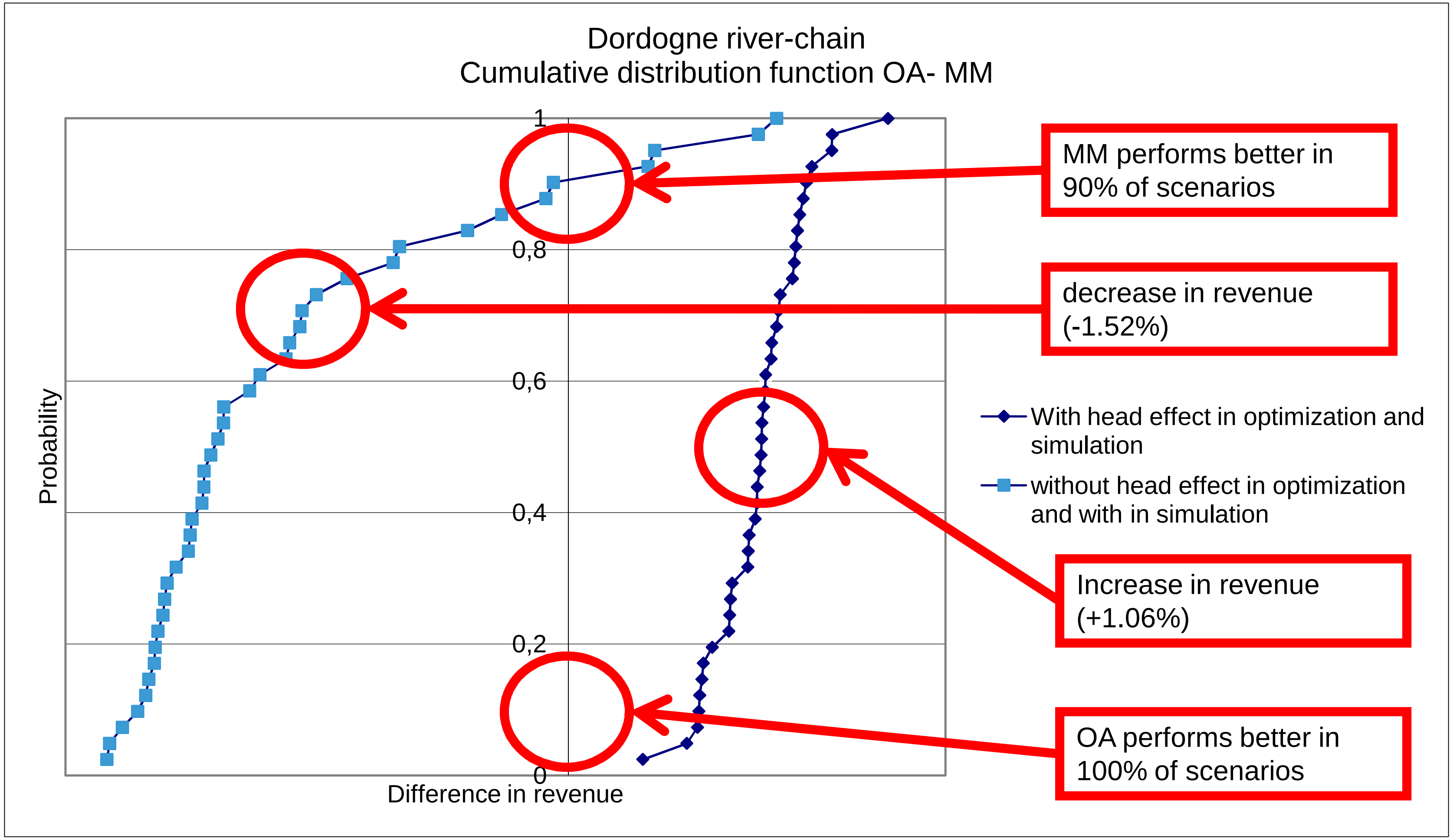
- Power output for a given flow rate assumed to increase linearly with volume stored:




- The problem to solve is concave for all given *x*. But the Bellman function is not concave → discretize *the storage level* → *approximation+increase in computation time*:

$$
\begin{aligned}
V_t(x, w(t)) = & \max_{x(t+1), q, f_1, f_1, f} \quad p(t)^T q(x,t) + E[V_{t+1}(x(t+1), w(t+1)], \\
s.t. \quad & x(t+1) = x - ADf(t) + w(t), \\
& 0 \le f(t) \le b, \quad 0 \le x(t+1) \le r, \\
& q(x,t) = \eta_e(x) f_1 + \eta_m(x) f_2, \\
& f_1 + f_2 = f(t), \\
& f_1 \le f_e(x), \\
& f_2 \le f_m(x) - f_e(x),
\end{aligned}
$$

# Experiments: Including head effect (3/3)



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# Future works

- Outer approximation methods needs further approximation steps to handle non-convexities.
- The trade-off between the increase in computational time and the increase in revenue has to be studied.
- How to include further constraints such:
  - Provision of energy by committing a number of turbines to be running;
  - Provision of spinning reserve by committing turbines to be in synchronized condensing mode;
  - Provision of frequency-keeping services from a selection of turbines;
- How to include other non convexities such:
  - Avoidance of rough running ranges in turbine curves;
  - Uncertainty in both future price, inflows and bounds on flow rate;
- …. To be continued

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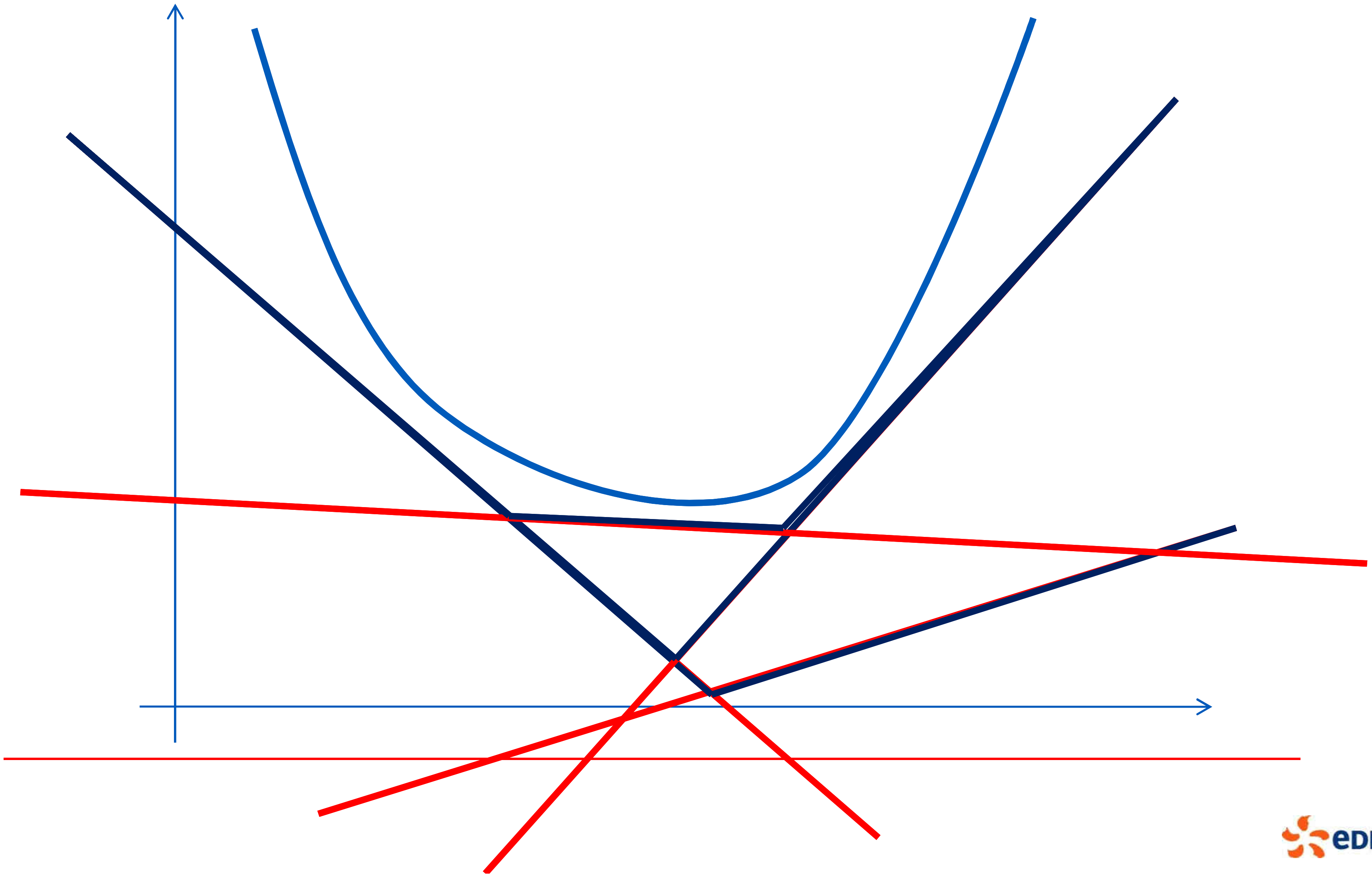
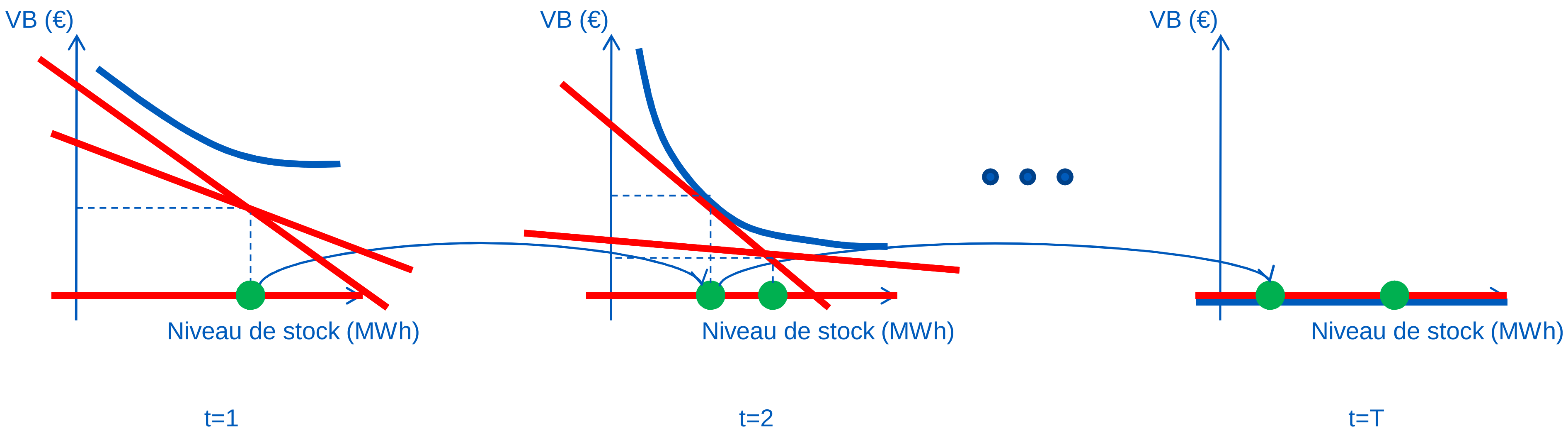
# APPENDIX

# River-chain valuation: outer approximation (2/4)

- A convex function can be approximated by the superior envelop of affine functions



# River-chain valuation: outer approximation (3/4)




We need to approximate the real Bellman function / water value

We start with given water values (nill ?)

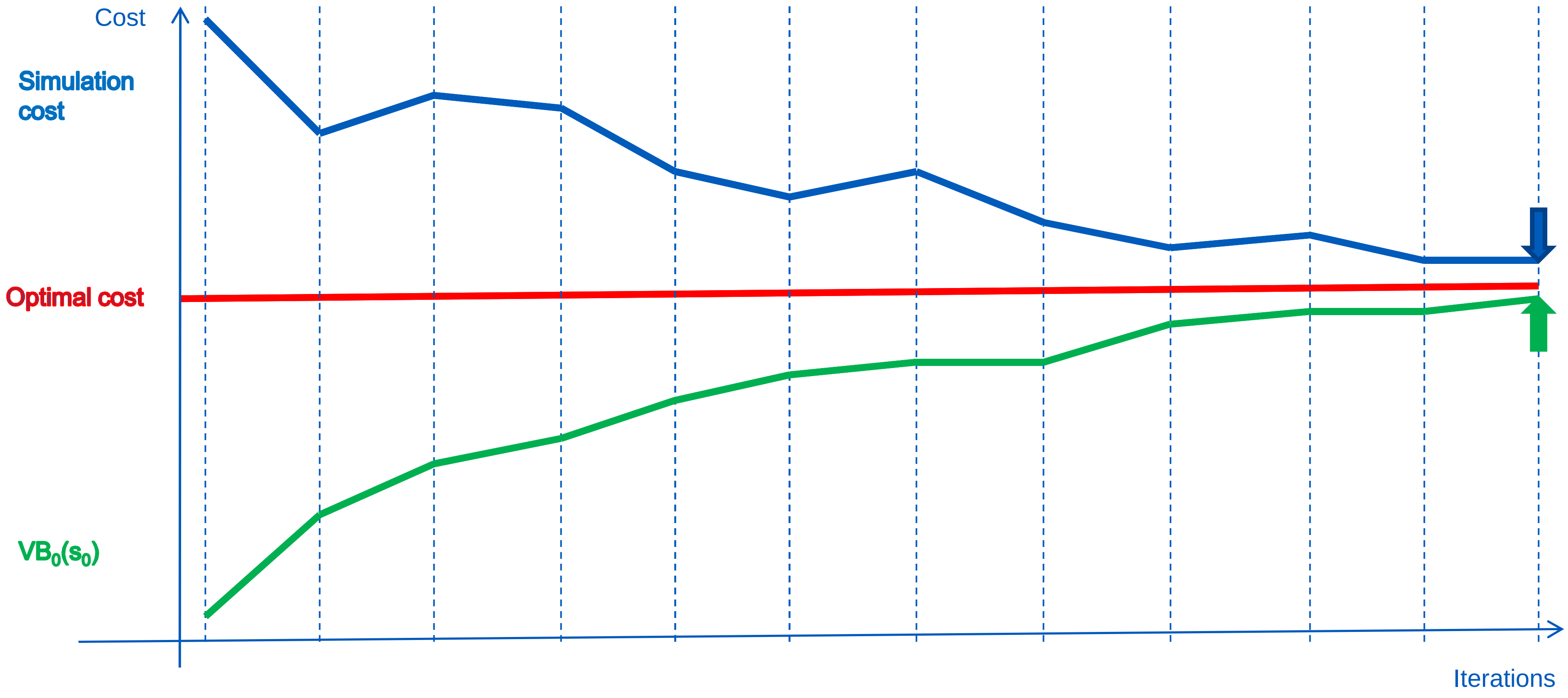
We simulate 1 (or several) scenarios → reservoirs levels trajectories

We compute the water values and Bellman functions on the obtained trajectories

We re-simulate to obtain new trajectories

We iterate this process

# River-chain valuation: outer approximation (4/4)



# River-chain valuation: the model

- We consider a river-chain represented by a network of $n$ nodes (reservoirs and junctions) and $m$ arcs (canals or river reaches). The topology of the network can be represented by the $n$ x $m$ incidence matrix $A$, where:

$$a_{ij} = \begin{cases} 1, \text{ if node } i \text{ is the tail of arc } j, \\ -1, \text{ if node } i \text{ is the head of arc } j, \\ 0, \text{ otherwise.} \end{cases}$$

- Let $x(t)$ denotes a vector of reservoir storages in each node at the beginning of each week.
- Let $w(t)$ denotes a vector of reservoir inflows in each node at the beginning of each week.
- Let $h(t)$ denotes a vector of flow rates in the arcs at each week.
- Let $p(t)$ denotes a vector of prices in each arc at the beginning of each week. These prices are adjusted to account of converting factors $\eta_j$.
- Each week is split into $K=21$ blocks each of duration $d_k$.

$$D = \begin{bmatrix} d_1 & \cdots & d_K & 0 & \cdots & 0 & \cdots & \cdots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & d_1 & \cdots & d_K & \cdots & \cdots & \vdots & & \vdots \\ \vdots & & & & & & \ddots & \ddots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \cdots & & & \cdots & 0 & d_1 & \cdots & d_K \end{bmatrix}$$

- The total quantity of flow through arc $j$ in week $t$ is $Dh(t)$, and the revenue earned is $p(t)^T h(t)$, where component $K(j-1)+k$ of $p(t)$ now equals the electricity price $\pi_k(t)$ (€/MWh) in block $k$ in week $t$ multiplied by both $d_k$ and $\eta_j$: $p_{K(j-1)+k}(t) = \pi_k(t)\, d_k\, \eta_j$

# River-chain valuation: the model

- The hydro-electric river-chain problem we wish to solve seeks to construct a policy for generating electricity from the river-chain so as to maximize the expected revenue.

$$
\begin{aligned}
V_t(x, w(t)) = \quad & \max \quad p(t)^T h(t) + E[V_{t+1}(x(t+1), w(t+1))], \\
& s.t. \quad x(t+1) = x - ADh(t) + w(t), \\
& \qquad\quad 0 \le h(t) \le b, \quad 0 \le x(t+1) \le r.
\end{aligned}
$$

- The relationship between conversion factor and head is expressed using a finite set of hydro production functions that depend on reservoir level *x*. Each production function is modeled using two linear pieces defined by the most efficient flow rate $h_e$ and the maximum flow rate $h_m$, both of which depend on *x*.
- When the reservoir volume is *x*, the power generated by flow rate *h* is:

$$
\begin{aligned}
E(h, x) = \quad & \max_{h_1, h_2} \quad \eta_e(x) h_1 + \eta_m(x) h_2, \\
& s.t. \quad h_1 + h_2 = h, \\
& \qquad\quad h_1 \le h_e(x), \quad h_2 \le h_m(x) - h_e(x).
\end{aligned}
$$