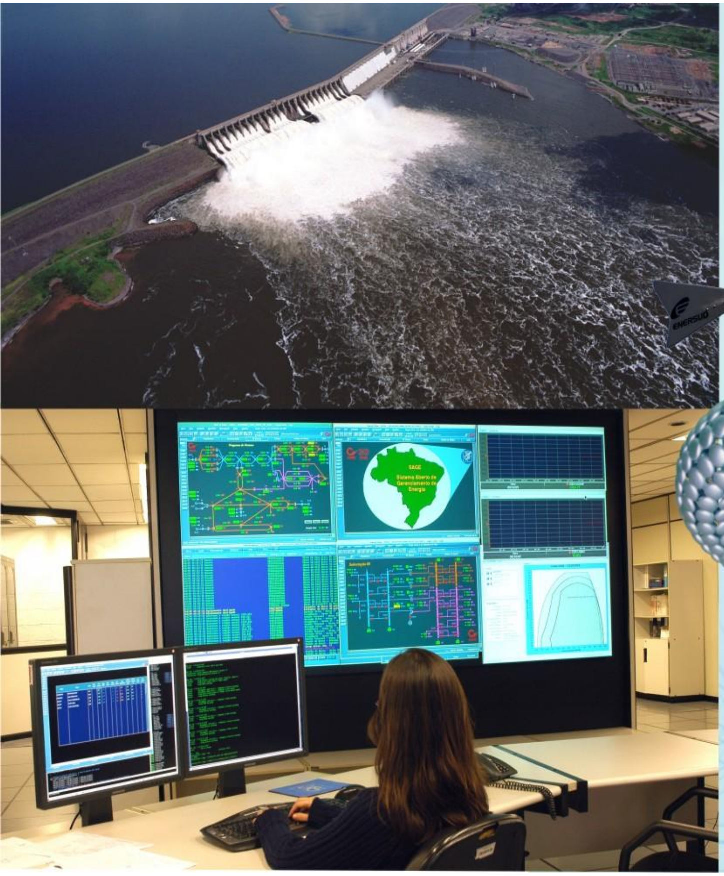
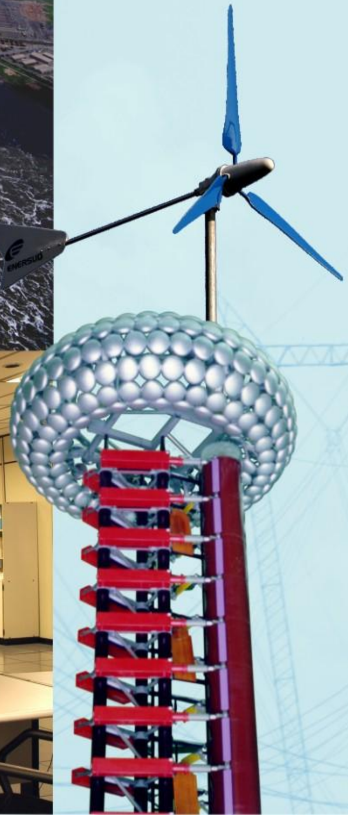
STOCHASTIC PROGRAMMING MODELS
AND ALGORITHMS
FOR ENERGY PLANNING





From theory to practice: challenges in providing stochastic optimization tools for the energy planning of real systems

FGV, July 7th, 2019

André Luiz Diniz
Energy Optimization and Environment Department - DEA

OUTLINE

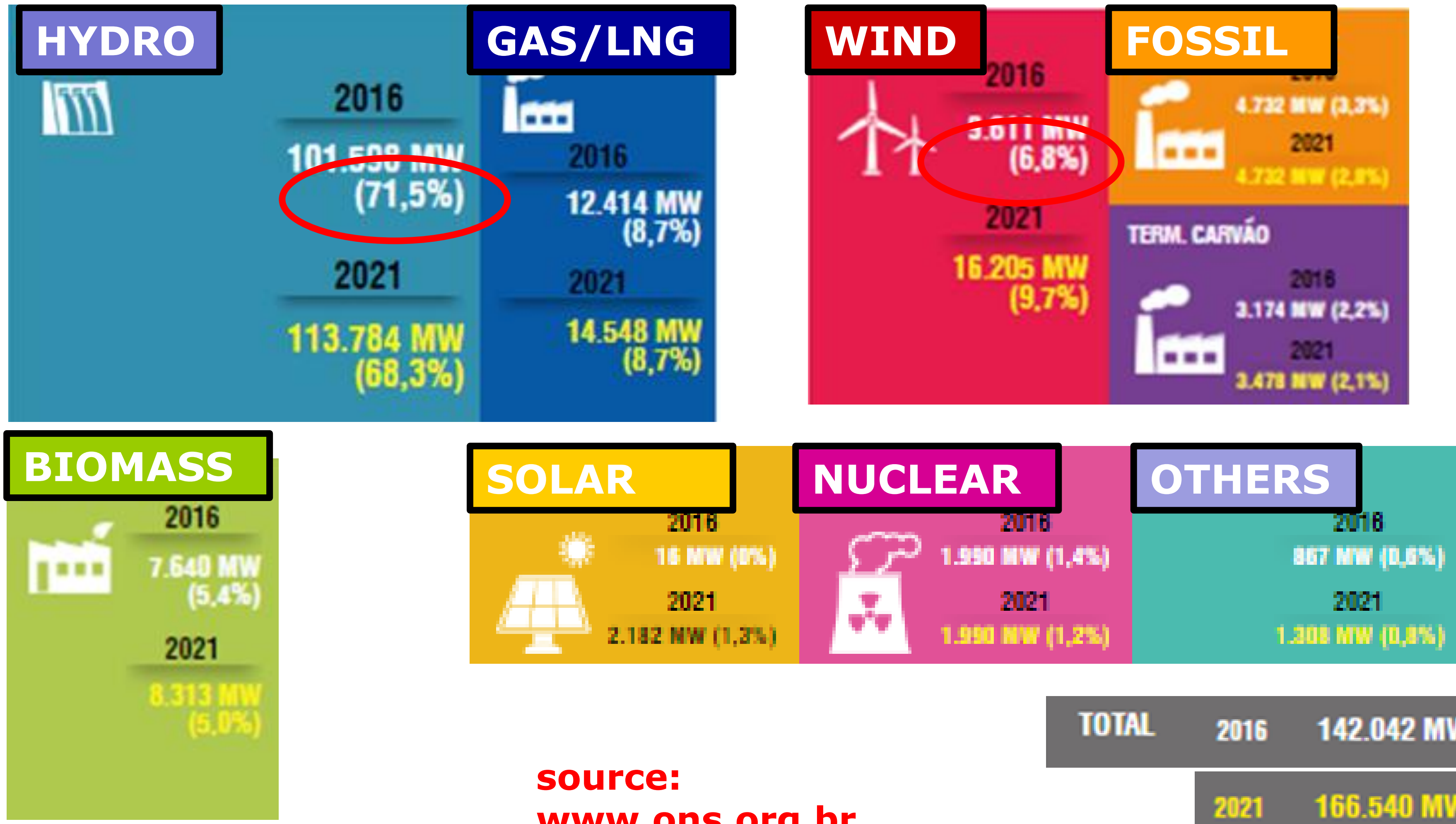
- Stochastic programming/optimization tools for expansion and operation planning of the large-scale Brazilian system
- **Challenge #1:** Handling risk averse problems
- **Challenge #2:** Sampling backward SDDP scenarios
- **Challenge (aspect) #3:** Resampling forward SDDP scenarios
- **Challenge #4:** Trade-off between system Representation and quality of the results
- **Challenge #5:** Performance requirements
- **Challenge #6:** Handling high uncertainty/variability of intermittent sources
- **Bonus:** Validation of DESSEM model for hourly prices in Brazil

Stochastic programming / optimization tools for expansion and operation planning of the large-scale Brazilian system

BRAZILIAN INTERCONNECTED SYSTEM (SIN)

Eletrobras Cepel

GENERATION MIX – 2016 & 2021

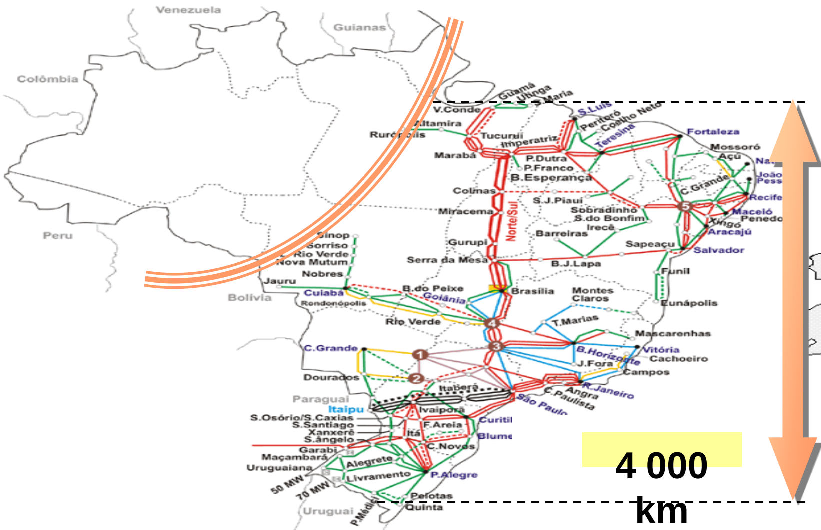


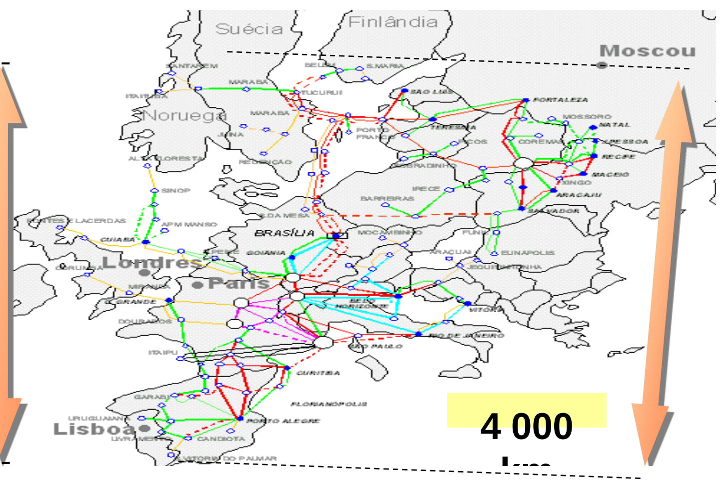
TOTAL	2016	142.042 MW
	2021	166.540 MW

source: www.ons.org.br

MAIN CHARACTERISTICS OF THE BRAZILIAN SYSTEM

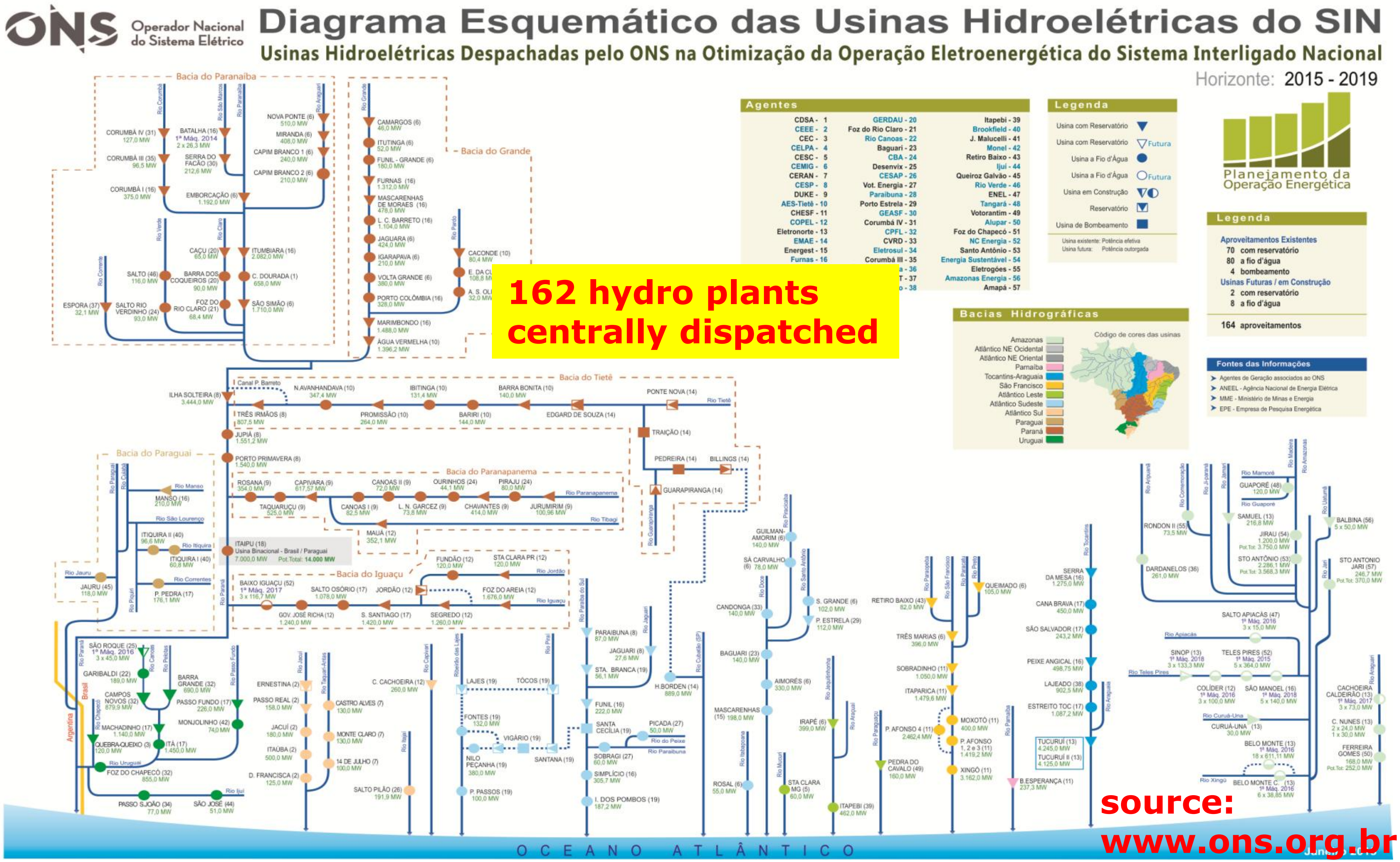
- Large-scale system, predominantly hydro
- Stochastic inflows to reservoirs
- Long distances between generation sources and load
- Many hydro plants in cascade





Coordinated operation is a VERY complex task!

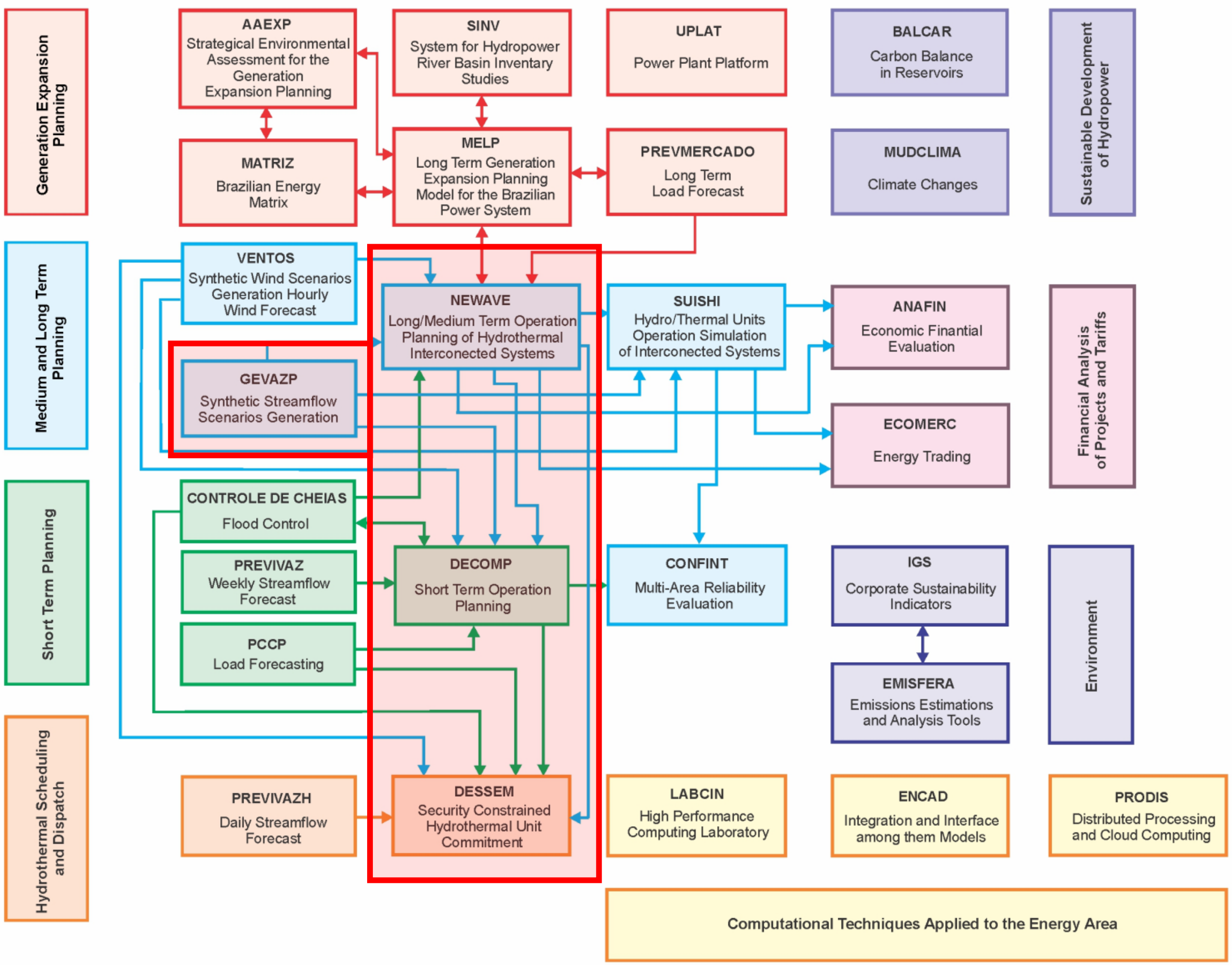
BRAZILIAN INTERCONNECTED SYSTEM (SIN) – HYDRO PLANTS



162 hydro plants centrally dispatched

source: www.ons.org.br

HYDROTHERMAL PLANNING FOR THE BRAZILIAN INTERCONNECTED SYSTEM



Developed by CEPEL, collaborating with scientific comunity

Validated in working groups in by ONS, CCEE, EPE, MME, ANEEL, as well as task forces with most power system utilities

Approved for official use by the regulatory energy

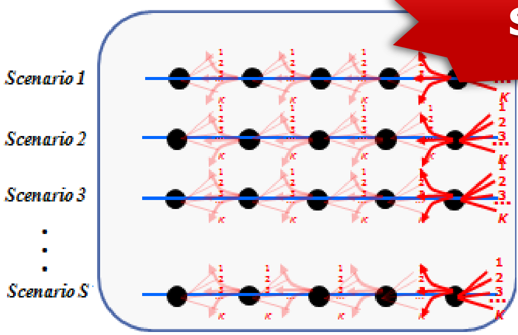
Used by:
- **EPE to plan the system**
- **ONS to dispatch plants**
- **CCEE for market prices**

LONG, MID AND SHORT TERM GENERATION PLANNING

NEWAVE

SDDP

[Pereira,Pinto,91]
[Maceira,93]



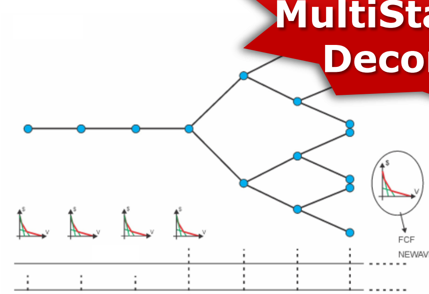
[Maceira,Duarte, Penna,Mor,Mel,08]

[Maceira,Penna, Diniz,Pinto,Melo, Vasconc.,Cruz,18]

DECOMP

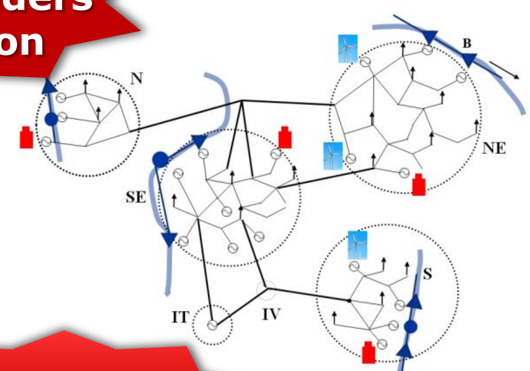
[Birge,85]

DDP
MultiStage Benders Decomposition



[Diniz,Costa,Maceira, Santos,Brandao,Cabral,18]

DESSEM



MILP

[Diniz,Souza, Maceira et al,02]

[Diniz, Santos, Saboia, Maceira,18]

Application of CVaR
Risk Averse Mechanism

[Shapiro,Tekaya, Costa,Soares,12]

[Diniz, Tcheou, Maceira, 12]

LONG TERM MODEL – NEWAVE
Problem Formulation

Eletrobras Cepel

MULTI-STAGE STOCHASTIC LINEAR PROGRAMMING PROBLEM

[Birge,Louveaux,97]

[Kall,Mayer,10]

OBJECTIVE FUNCTION

$$\min\left[\left(\sum_{t=1}^{T}\left(\lambda E_{\omega}+(1-\lambda)CVar_{\omega}\right)\underbrace{\sum_{j=1}^{NT}c_j\left(GT_j^{t,\omega}\right)}_{\text{Thermal generation + load schedding}}\right)+\alpha(v^T)\right]$$

Cvar Criterion

CONSTRAINTS

Demand balance

$$\sum_{i\in H_j} gh_i^{t,\omega}+\sum_{i\in T_j} gt_i^{t,\omega}\pm\sum_{i\in Int_j} Int^{t,\omega}+Defc_j^t=D_j^t,\quad \forall t,\omega,j$$

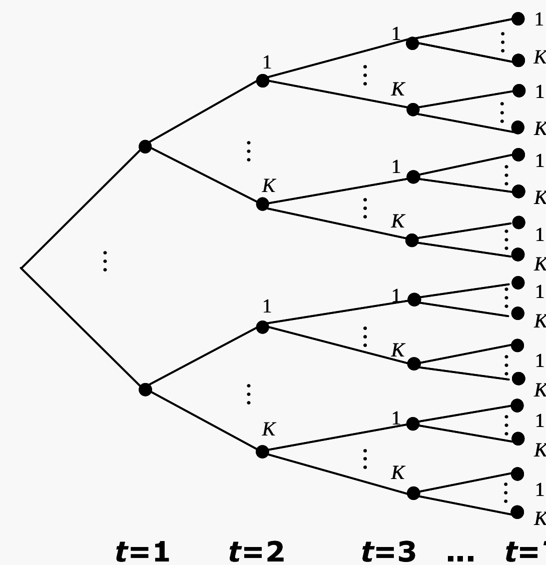
Water conservation

$$v_s^t=v_s^{t-1}-gh_s^{t,\omega}+\underbrace{\xi_s^{t,\omega}\left|\left(\xi_{s,\ p-1,\dots P}^{t-p,\omega},\zeta\right)\right.}_{\text{Par-P model}},\ \forall t,\omega,j$$

[Maceira, Bezerra,97]

+ Many other operation constraints...

SCENARIO TREE



SELECTIVE SAMPLING

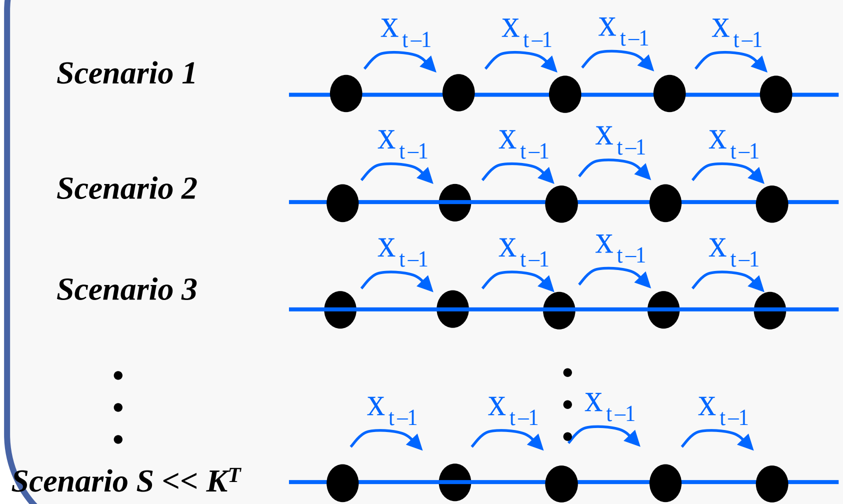
[Penna,Maceira,Damazio,11]

Eletrobras Cepel

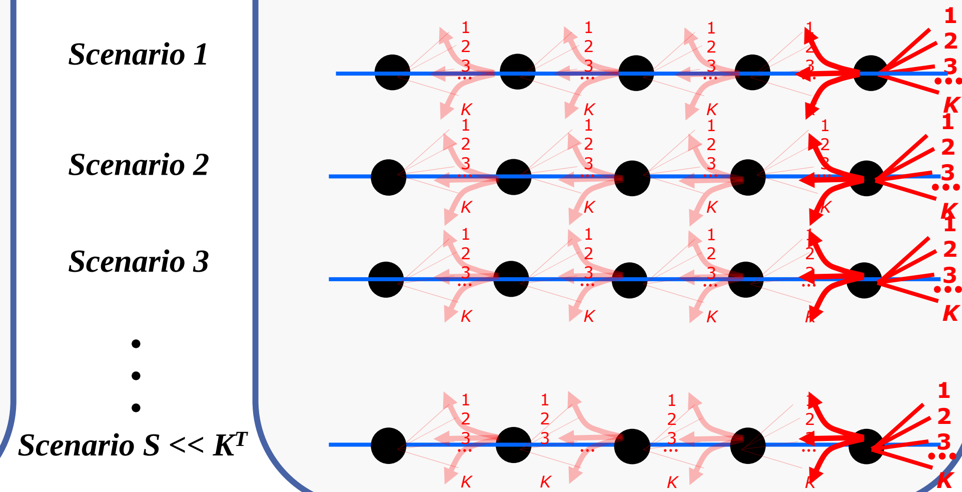
SDDP - STOCHASTIC DUAL DYNAMIC PROGRAMMING

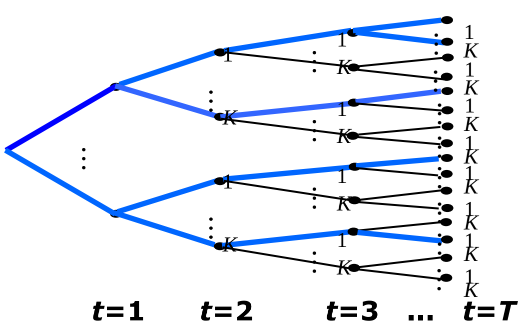
[Pereira,Pinto,91] [Maceira,93]

FORWARD PASS



BACKWARD PASS





Benders cuts:

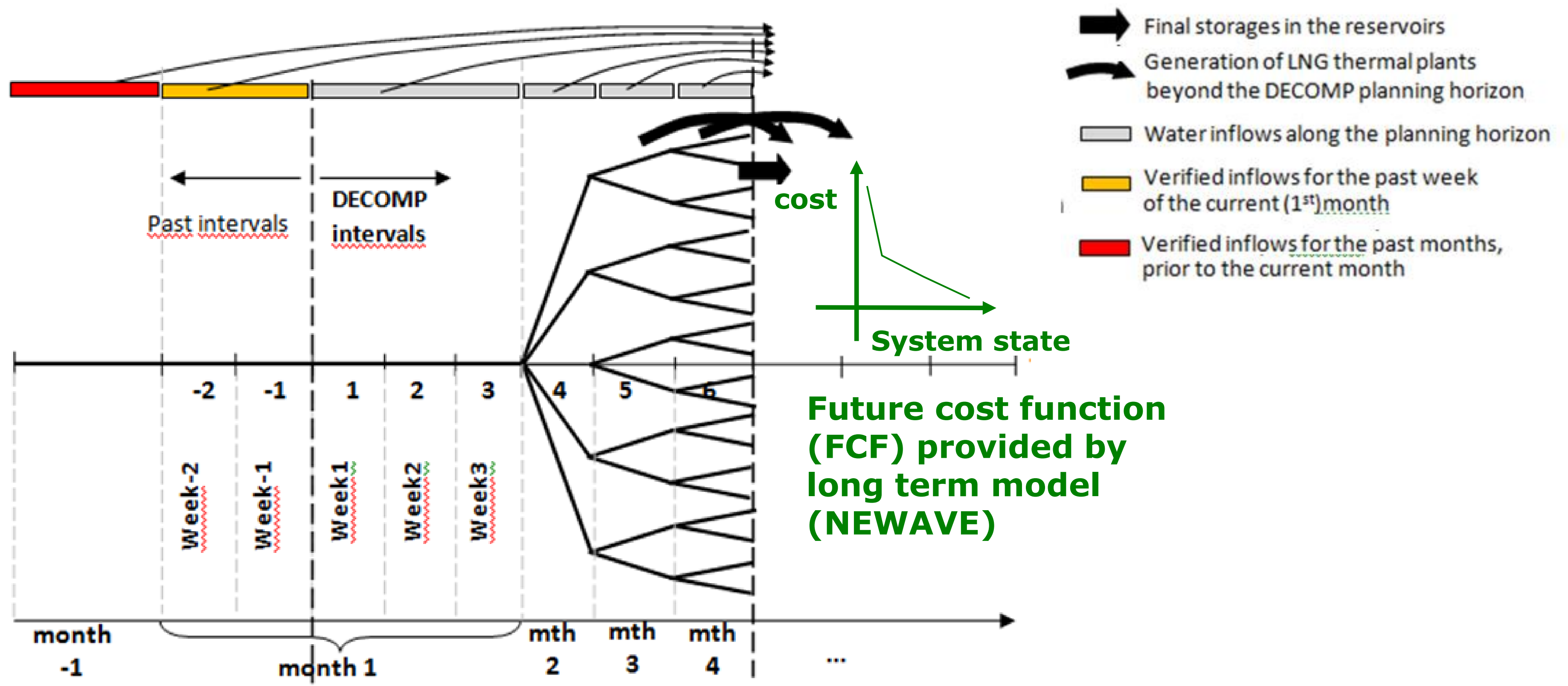
$$\varphi_t(x_{t-1}) \geq \sum_{\omega=1,\dots K} p_\omega \left[z_{t,\omega^*} + \left\langle \frac{\partial z_{t,\omega^*}}{\partial x_{t-1}}(\hat{x}_{t-1,s^*}), x_{t-1} - \hat{x}_{t-1,s^*} \right\rangle \right]$$

OUTPUT:

Optimal Operation Policy

MID-TERM MODEL - DECOMP

- Weekly steps for the 1st month
- Monthly steps for the following months, with several water inflow scenarios
- Several load blocks for each time step
- Coupling with long term model takes into account history of the system



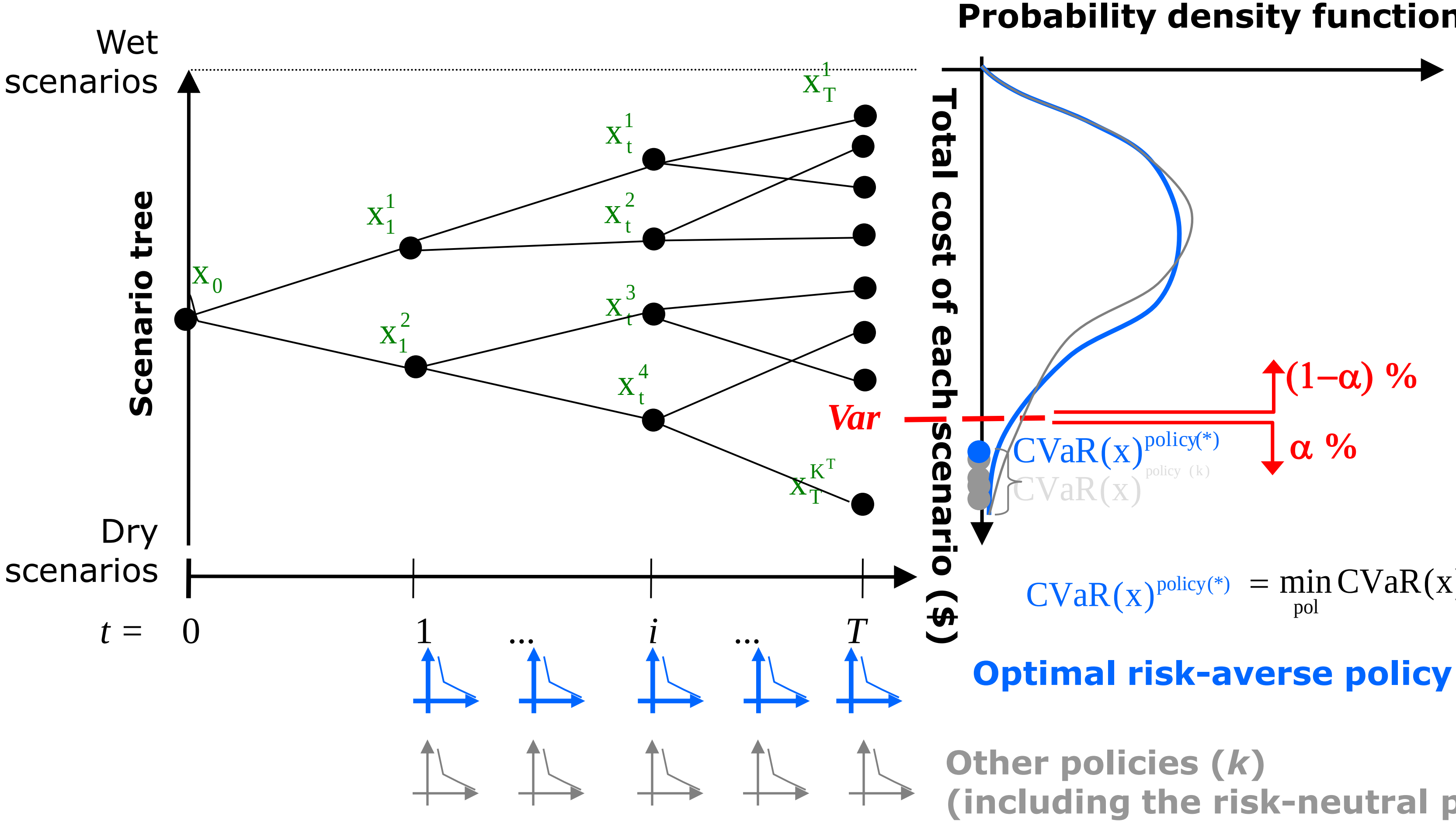
Challenge #1:

Handling risk-averse problems in large-scale systems

APPLICATION TO MULTISTAGE HYDROTHERMAL PLANNING

[Shapiro,10]

[Philpott, de Matos,12]



$$CVaR(x)^{policy(*)} = \min_{pol} CVaR(x)^{pol}$$

Optimal risk-averse policy (*)

Other policies (*k*) (including the risk-neutral policy)

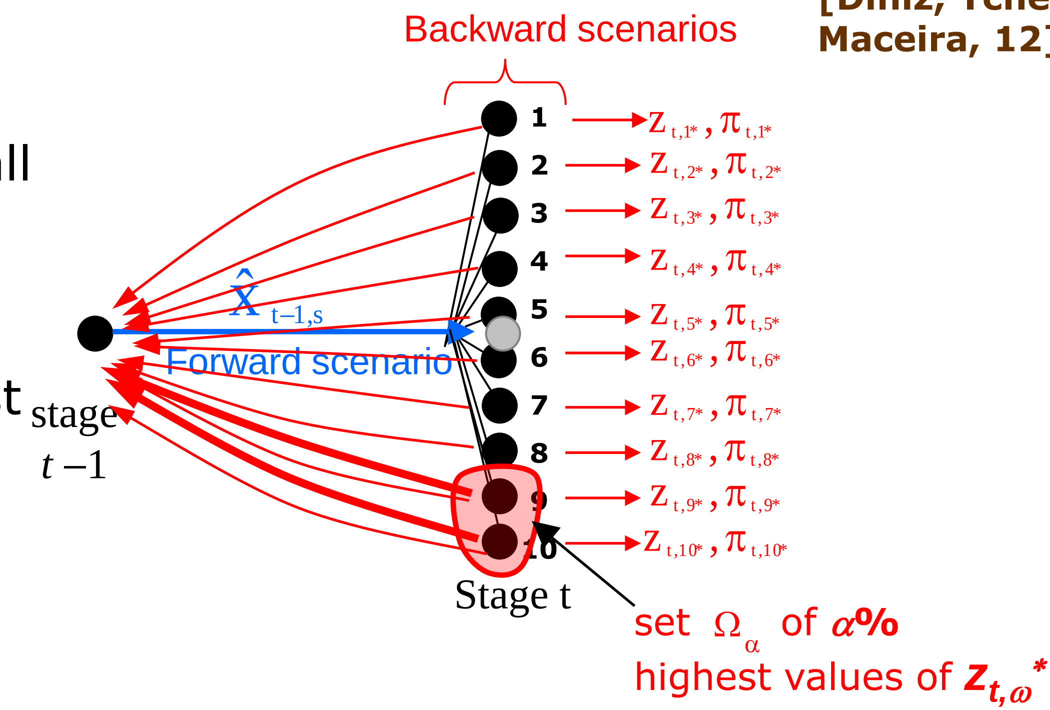
DIRECT APPLICATION OF NESTED CVAR RISK-AVERSE CRITERION

[Shapiro,Tekaya, Costa,Soares,12]

[Diniz, Tcheou, Maceira, 12]

BACKWARD PASS

- solve subproblems for all bacward scenarios ω
- identify the scenarios related to the α% highest values of $z_{t,\omega}$
- Build Benders cut with both expected value and risk averse terms



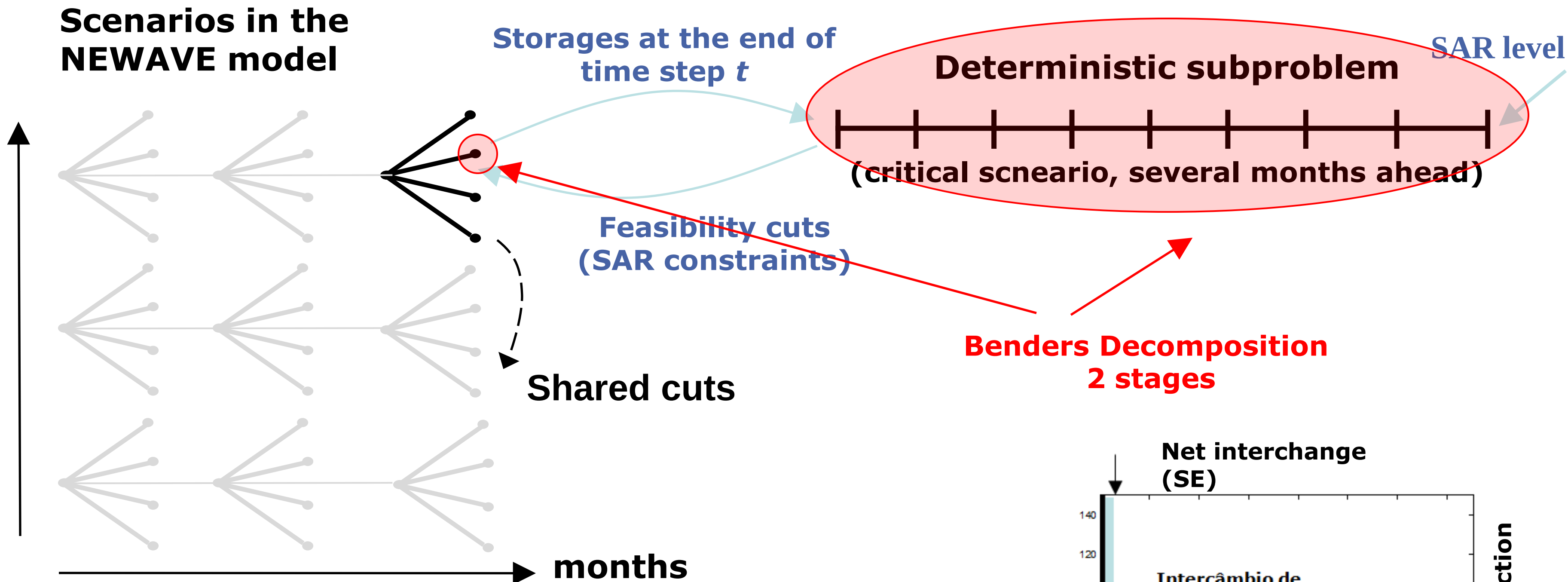
$$\varphi_t(x_{t-1}) \geq (1-\lambda)\sum_{\omega=1}^{K} p_\omega \left[z_{t,\omega^*} + \left\langle \pi_{t,\omega^*}, x_{t-1} - \hat{x}_{t-1,s} \right\rangle\right] + \left(\frac{\lambda}{\alpha}\right)\sum_{\omega\in\Omega_\alpha} p_\omega \left[z_{t,\omega^*} + \left\langle \pi_{t,\omega^*}, x_{t-1} - \hat{x}_{t-1,s} \right\rangle\right] = \boxed{\overline{z}^* + \left\langle \overline{\pi}^*, x_{t-1} - \hat{x}_{t-1,s} \right\rangle}$$

RISK AVERSER SURFACE – SAR (2013)

[PSR,08]

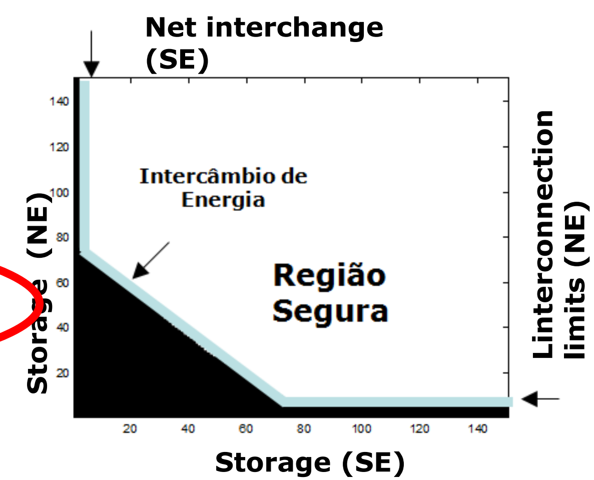
- Explicit protection against critical scenarios

[Diniz, Maceira, Vasconc., Penna,14]



- Novel penalization scheme to avoid a large increase in system marginal costs => Maximum violation along each year

[Diniz, Maceira, Vasconc., Penna,16]



SOME NOTES ON CHOOSING THE BEST POLICY IN RISK AVERSE PROBLEMS

Eletrobras Cepel

- Yielding the **least cost is not anymore a criterion** to select the most suitable policy
- A multiciterion analysis has to be conducted making an out-of-the sample assessment for different hydrological and system conditions of many aspects such as:

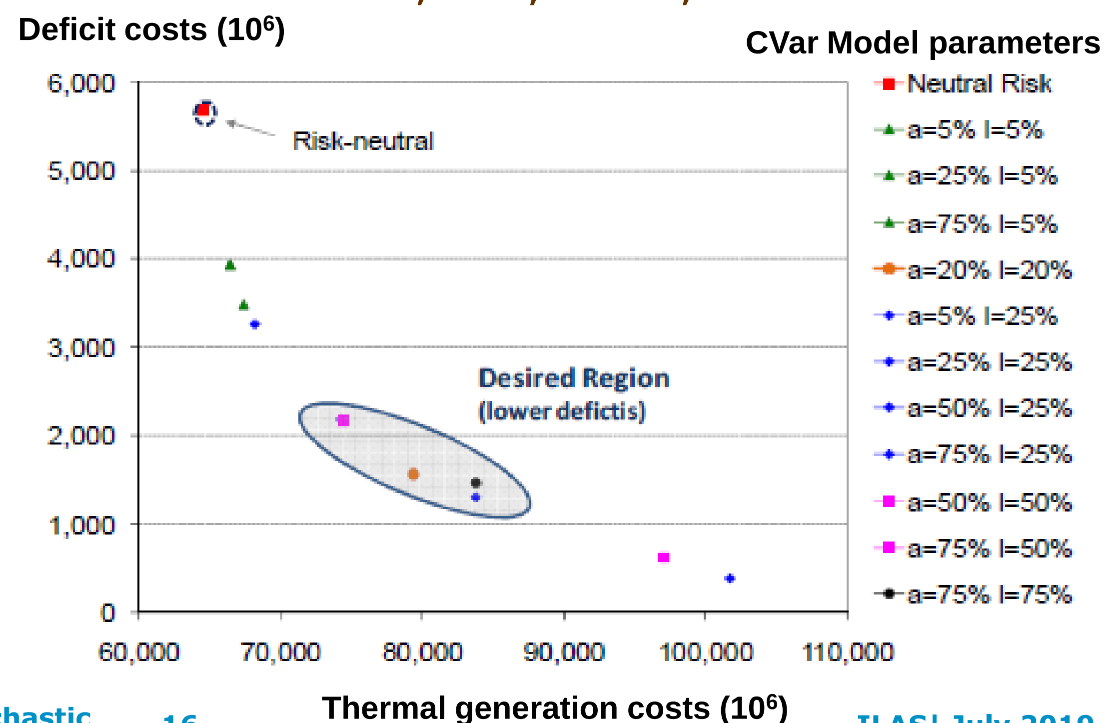
✓ **Thermal generation costs X deficit risk (costs)**

✓ Distribution of energy not served (ENS)

✓ Probability of spillage

✓ Evolution of the storage of the reservoirs

[Maceira, Marzano, Penna, Diniz, Justino,14



Challenge #2:

Sampling backward SDDP scenarios

SOME NOTES ON BACKWARD SCENARIO GENERATION

- In sample average approximation (SAA) algorithms, usually a random (Monte Carlo) sampling is recommended to generate scenarios, in order to have more diversity
  - ✓ Many replications of the sceario tree should be performed
- However, **the problem can only be solved ONCE**
- The use of random sampling in backward scenarios makes the results **very sensitive to the seed** used to generate scenarios

➡ Therefore, it is recommended to use clustering techniques when generating backward scenarios, even though the value of the optimal solution may be (a bit) biased

➡ Also, while clustering, picking the centroid as representative of each cluster (instead of the closest object to the centroid) brings more stable results

SCENARIO GENERATION: MONTE CARLO x CLUSTERING

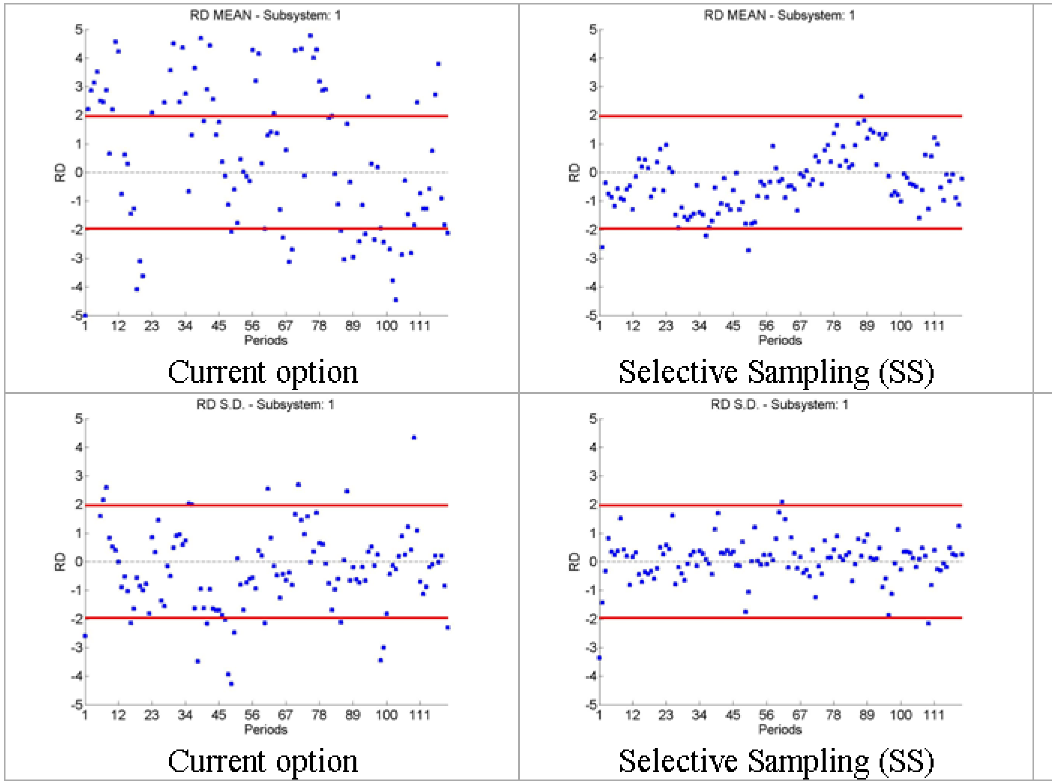
➢ Inflow values at each time step, for different seeds

MONTE CARLO | **SELECTIVE SAMPLING (2009) (K-MEANS)**

[Penna, Maceira, Damazio, 11]

MEAN

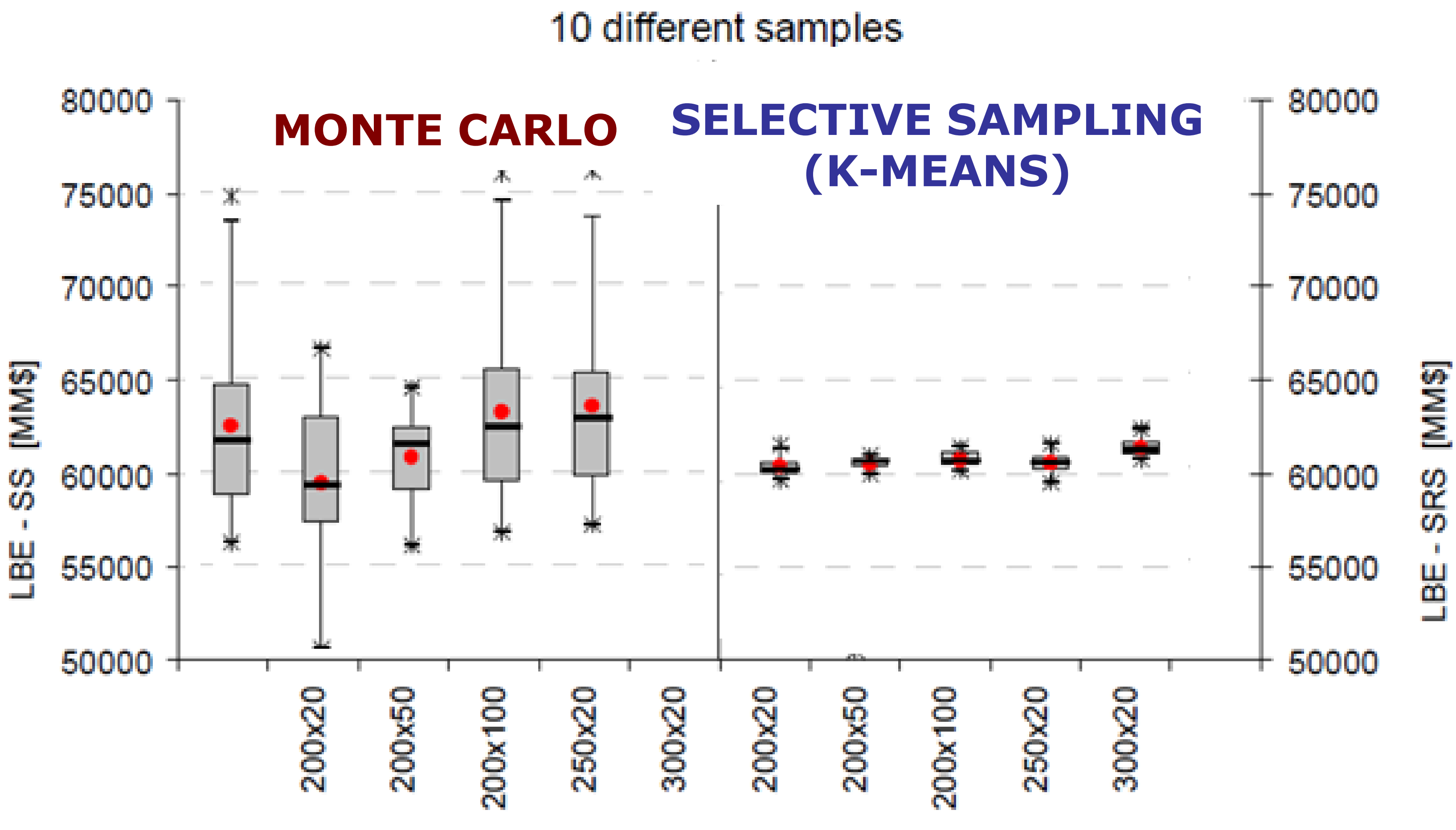
S.D.



SCENARIO GENERATION: MONTE CARLO x CLUSTERING

Eletrobras Cepel

- Lower bound for the optimal solution

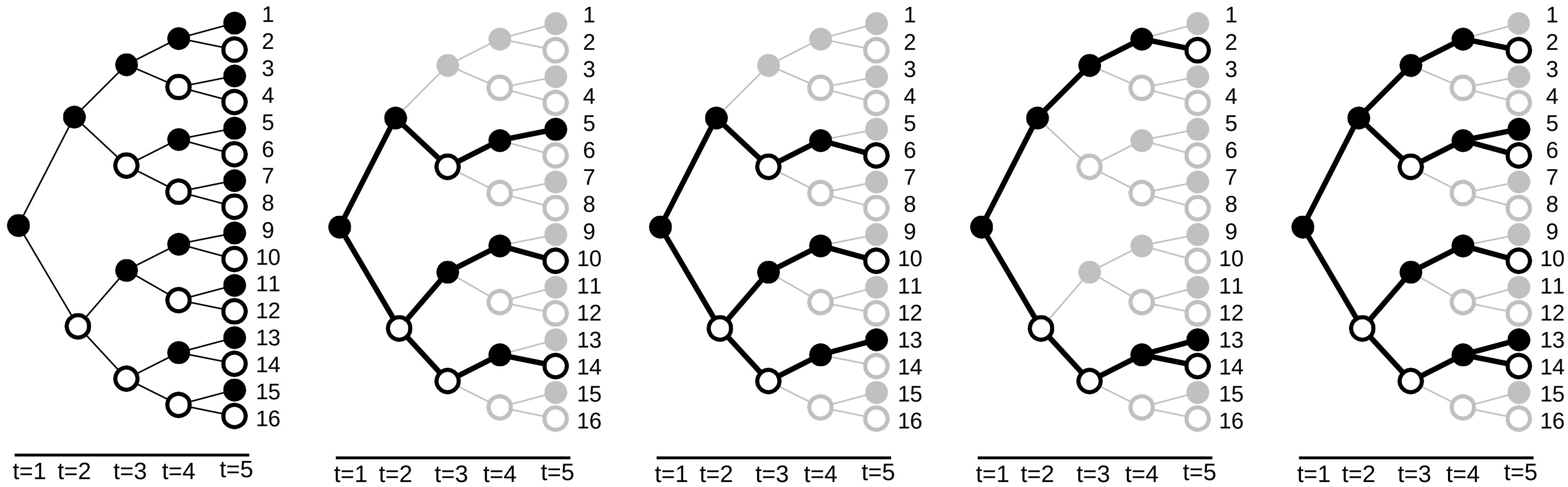


Challenge (aspect) #3:

Resampling Forward SDDP scenarios

FORWARD RESAMPLING

- **OBJECTIVE: To allow a more representative part of the HUGE multi-stage scenario tree to be visited**

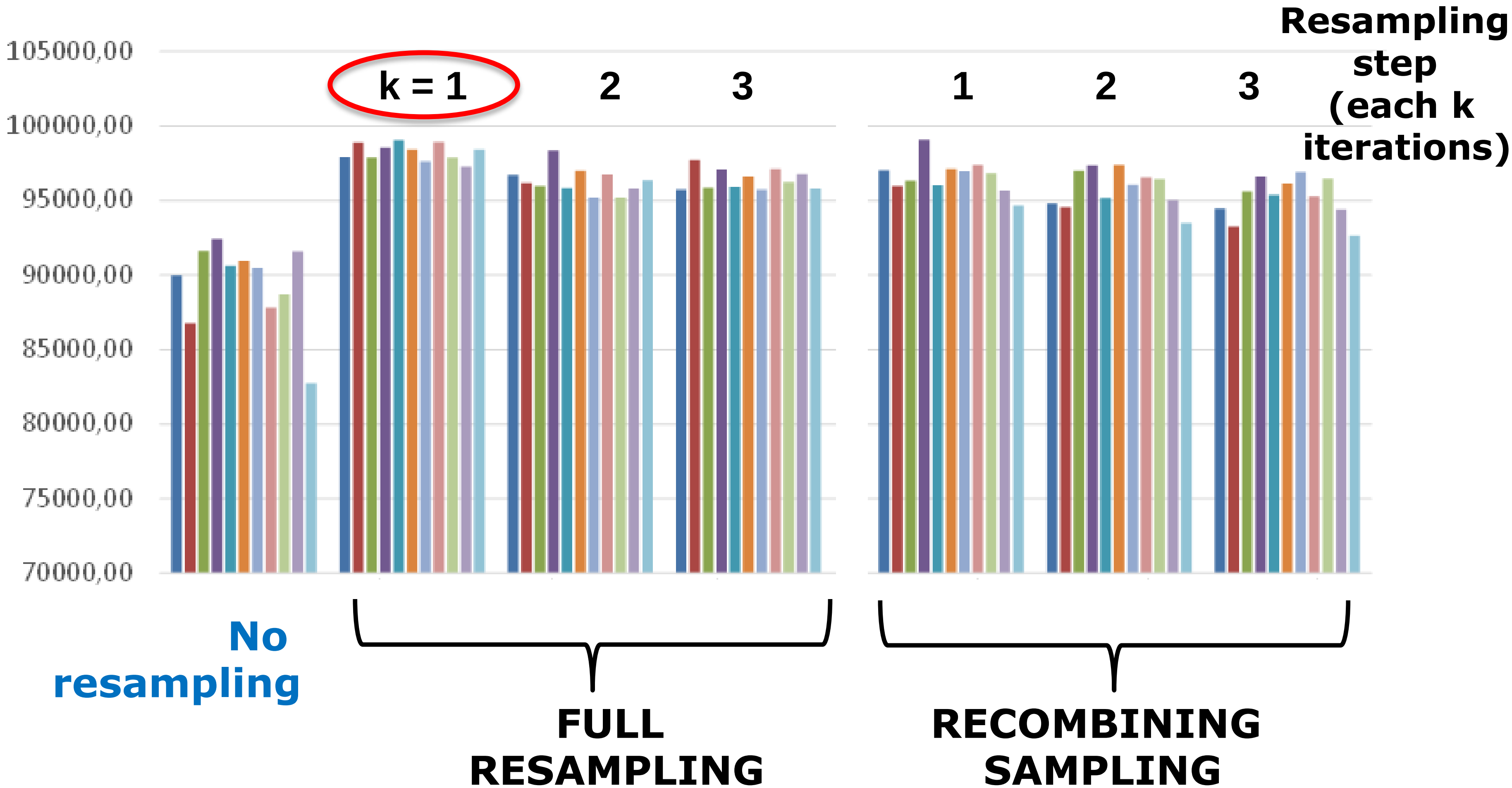


(a) (b) (c) (d) (e)

- **SDDP convergence has been proved once forward resampilng is performed**
  - ✓ **Philpott e Guan [2007] - On the convergence of stochastic dual dynamic programming and related methods. Operation Research Letters 36 (4) – 450-455**

RESAMPLING - RESULTS FOR DIFFERENT SEEDS (1/2)

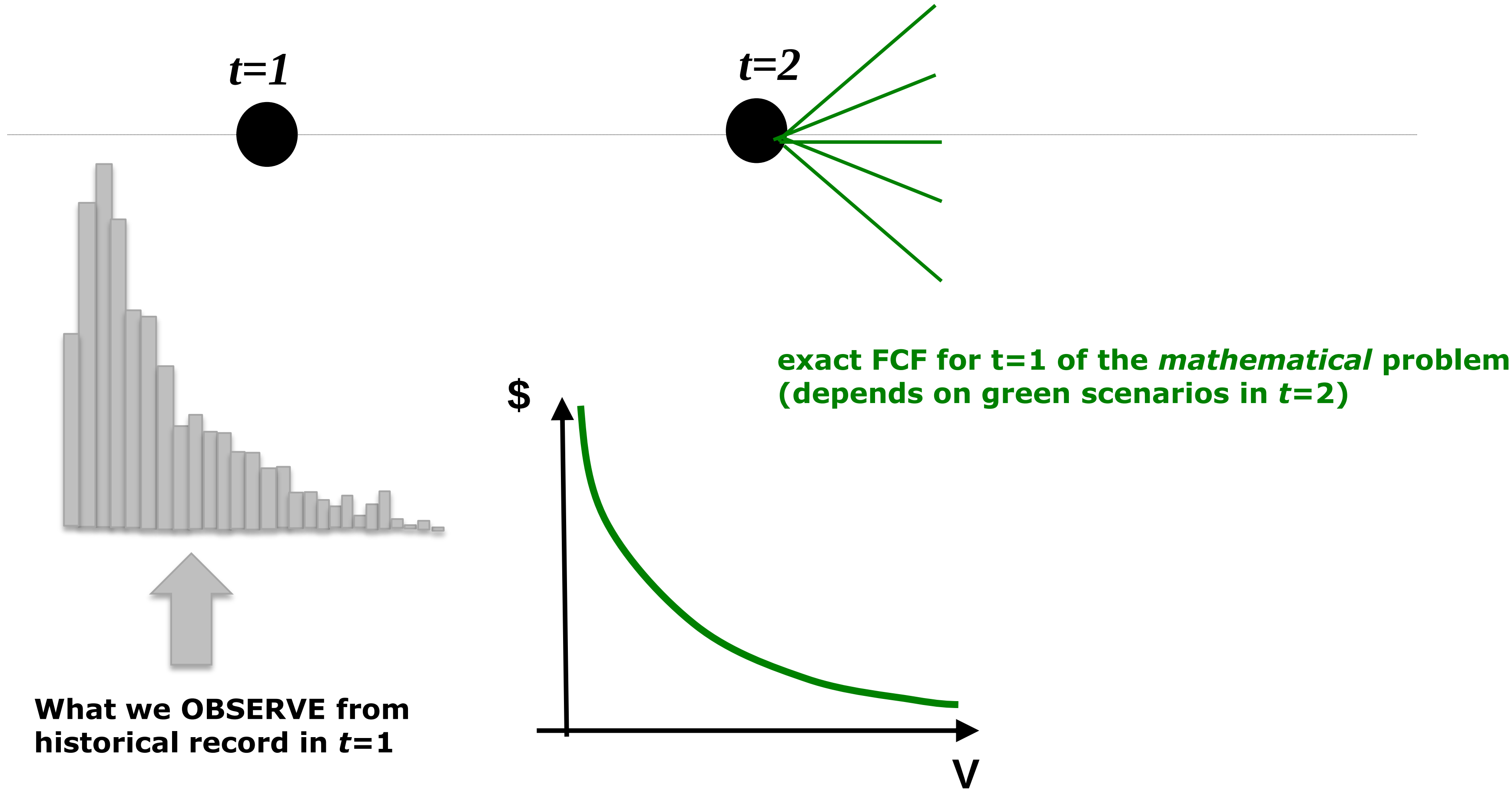
LOWER BOUND FOR EACH SEED



SOME NOTES ON FORWARD RESAMPLING

Eletrobras Cepel

- The main objective of NEWAVE model is **NOT TO SOLVE THE DISCRETE MATHEMATICAL PROBLEM**, but rather to **OBTAIN AN OPERATION POLICY** for the **CONTINUOUS PROBLEM**



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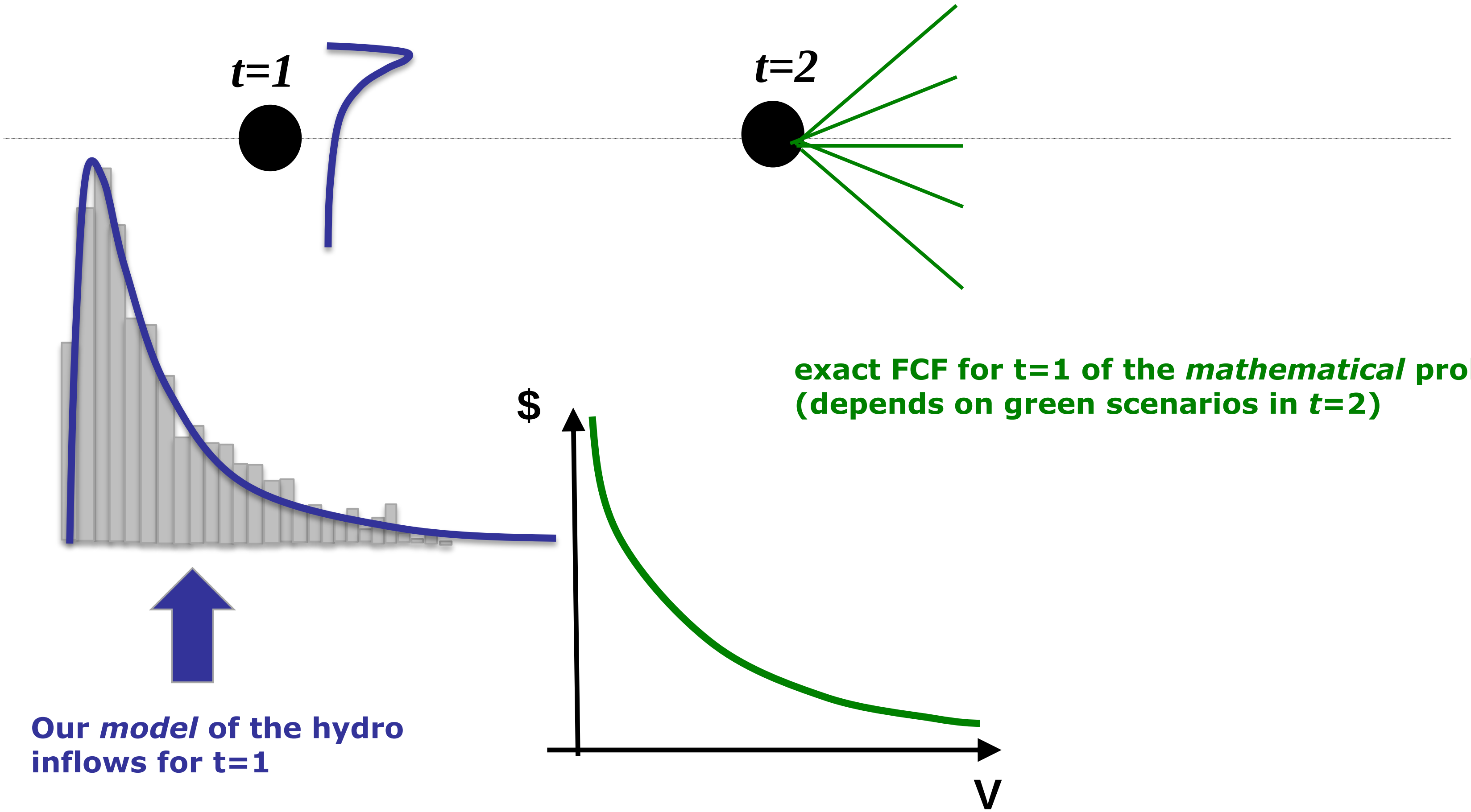
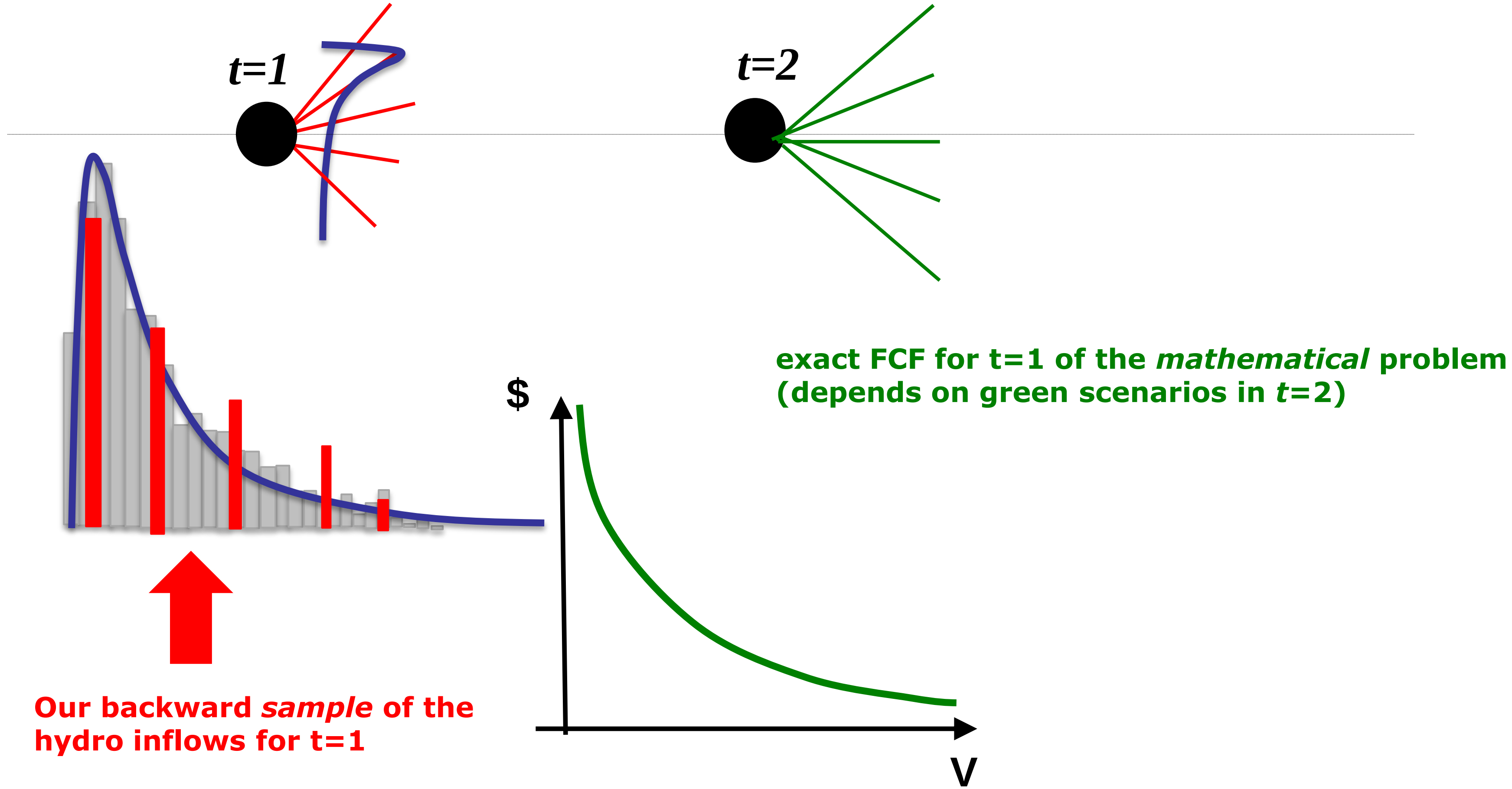


exact FCF for t=1 of the *mathematical* problem (depends on green scenarios in *t*=2)

Our *model* of the hydro inflows for t=1

SOME NOTES ON FORWARD RESAMPLING

- The main objective of NEWAVE model is **NOT TO SOLVE THE DISCRETE MATHEMATICAL PROBLEM**, but rather to **OBTAIN AN OPERATION POLICY** for the **CONTINUOUS PROBLEM**



SOME NOTES ON FORWARD RESAMPLING

Eletrobras Cepel

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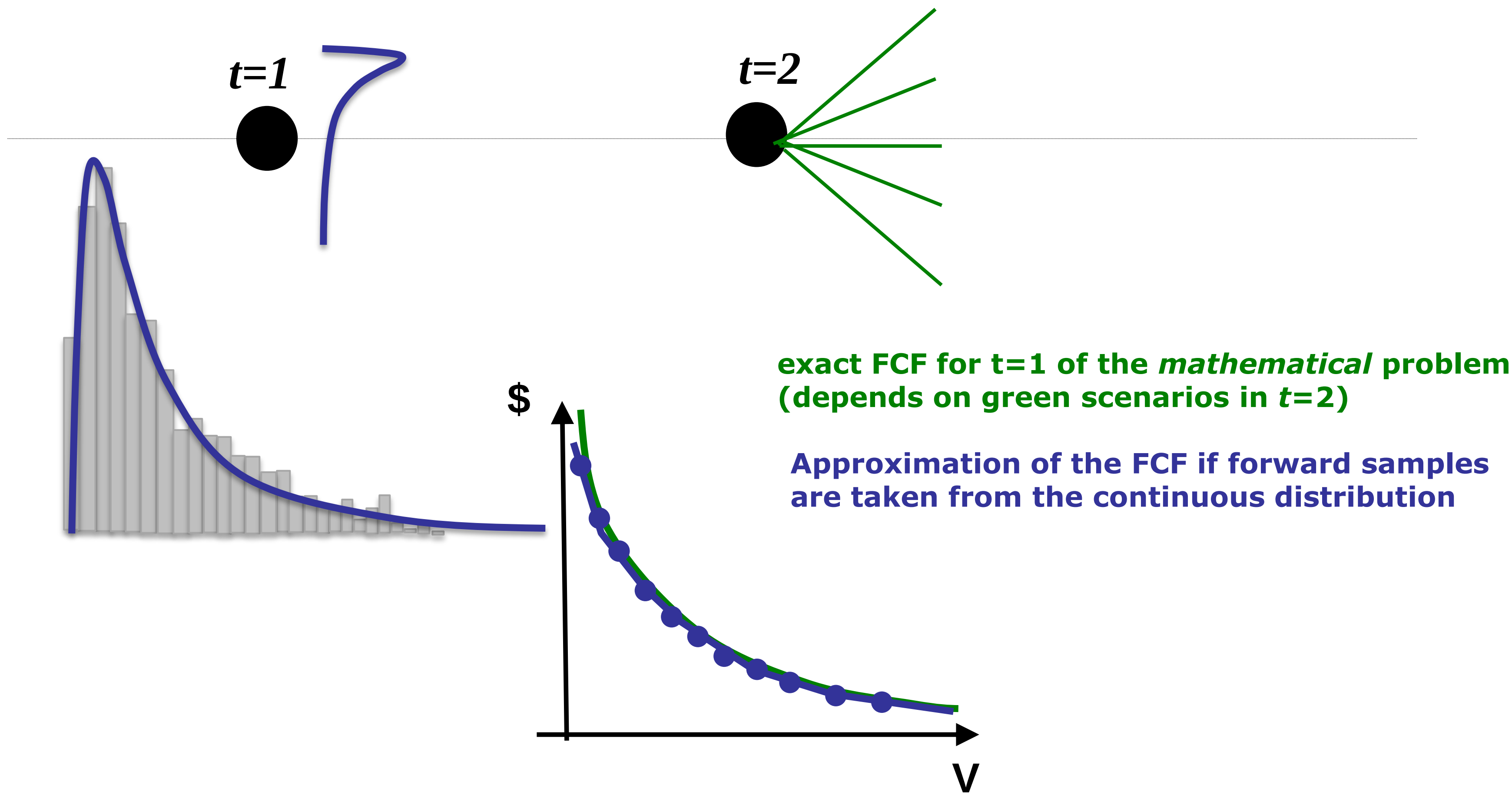

SOME NOTES ON FORWARD RESAMPLING

Eletrobras Cepel

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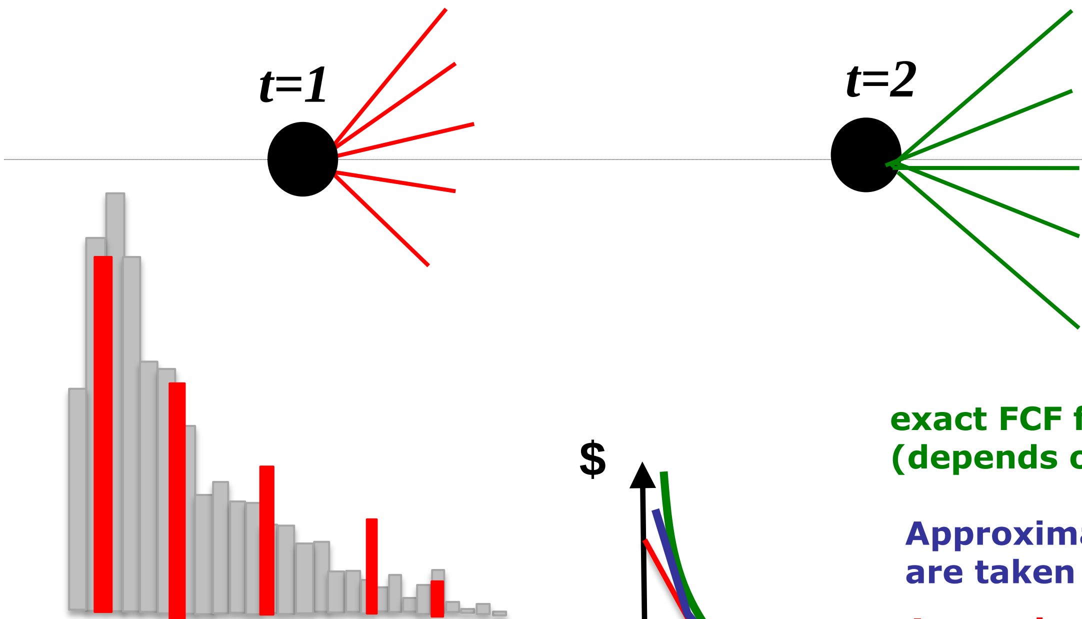
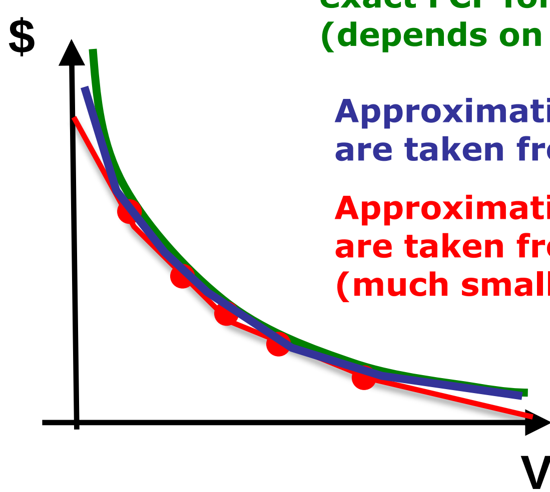




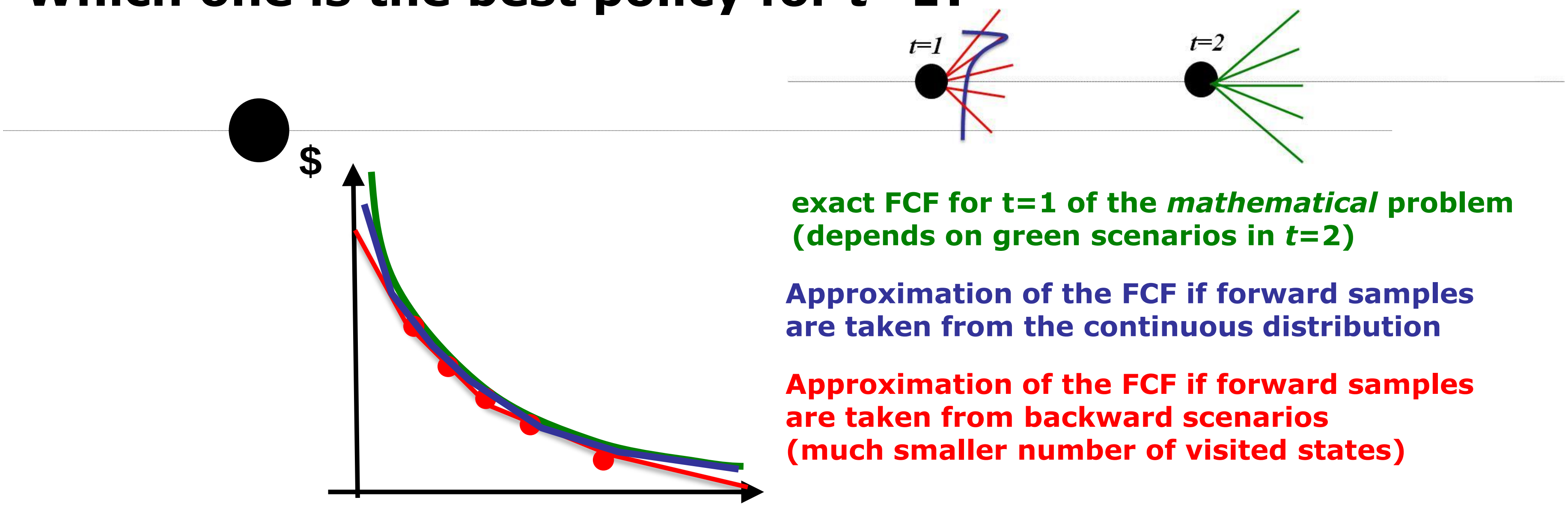
exact FCF for t=1 of the *mathematical* problem (depends on green scenarios in *t*=2)

Approximation of the FCF if forward samples are taken from the continuous distribution

Approximation of the FCF if forward samples are taken from backward scenarios (much smaller number of visited states)

SOME NOTES ON FORWARD RESAMPLING

- **Which one is the best policy for *t*=1?**



- The red points are enough to find the optimal solution for the **mathematical problem** (red + green scenarios)
- However, we know this is NOT the true problem: we should be prepared for the "real" **continuous distribution**
- So, why do we use a discrete backward distribution?
  - ✓ we must set a tractable and exact mathematical problem

SOME NOTES ON FORWARD RESAMPLING

Eletrobras Cepel

The main objective of NEWAVE model is not to solve the problem, but rather to obtain an operation policy

- With such policy it is possible to simulate a large number of scenarios in order to obtain proper statistics for system operation:
  - ✓ Average System Marginal costs
  - ✓ Average thermal generation
  - ✓ Average storage in the reservoirs along time
  - ✓ Deficit risk and average load curtailment
  - ✓ Average spillage
- The policy should be "good" for **ANY SET OF SCENARIOS IN THE CONTINUOUS DISTRIBUTION** of the random variable

Therefore, for practical applications, we **sample the forward scenarios from the continuous distribution**, rather than the set of backward noises, even though this is a theoretical requirement to find the optimal solution of the mathematical problem (**our aim is NOT to find it!!)**

Challenge #4:

Trade-off between system Representation and quality of the results

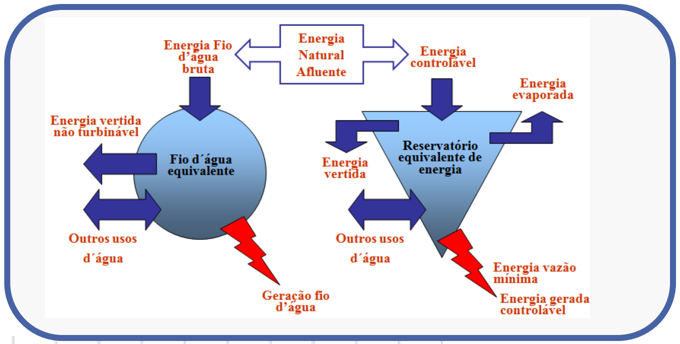
MODELING OF EQUIVALENT RESERVOIRS IN THE LONG TERM

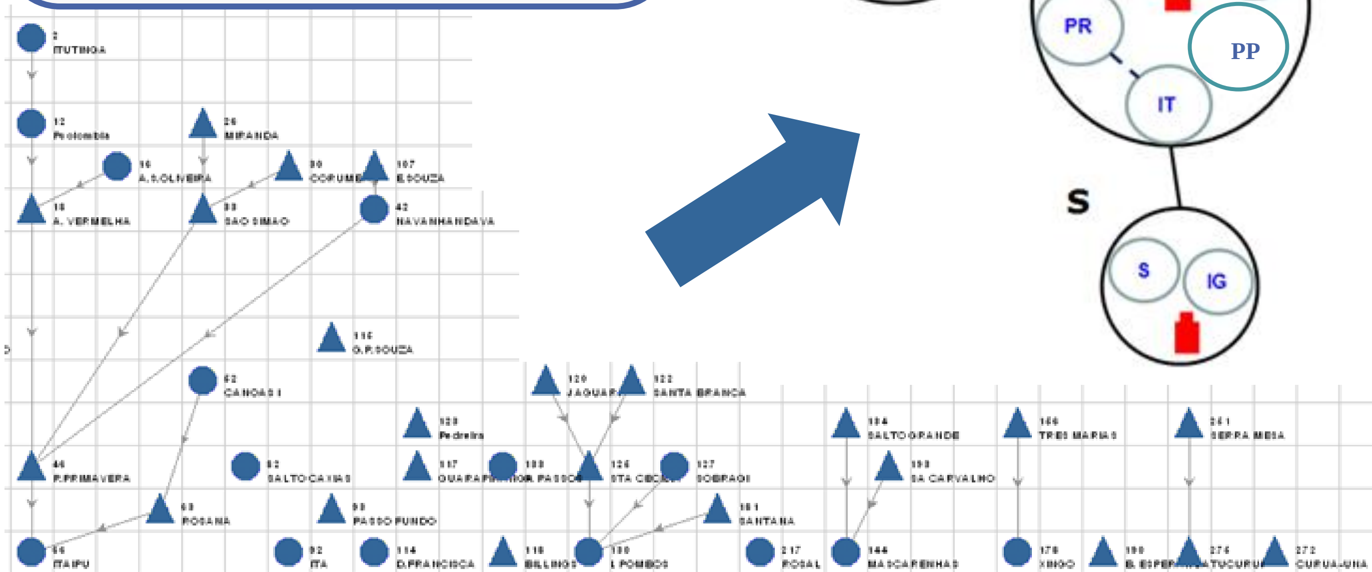
- Individual aspects are modeled as much as possible
  - ✓ Loss of efficieny with the water head
  - ✓ Inflows/spillage in run of the river plants, etc.

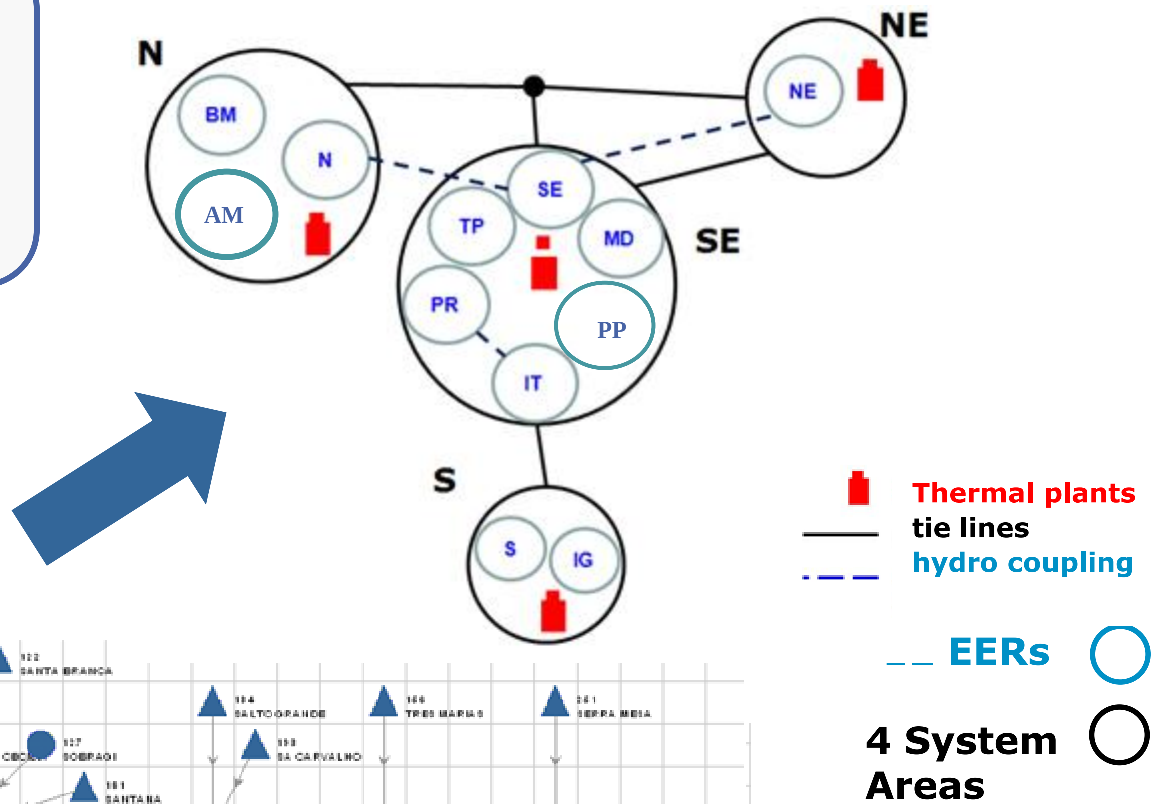
[Arvanitidis, Rosing,70]

[Maceira,Duarte, Penna,Tcheou,11]

[Terry,Maceira, Mercio,Duarte,04]

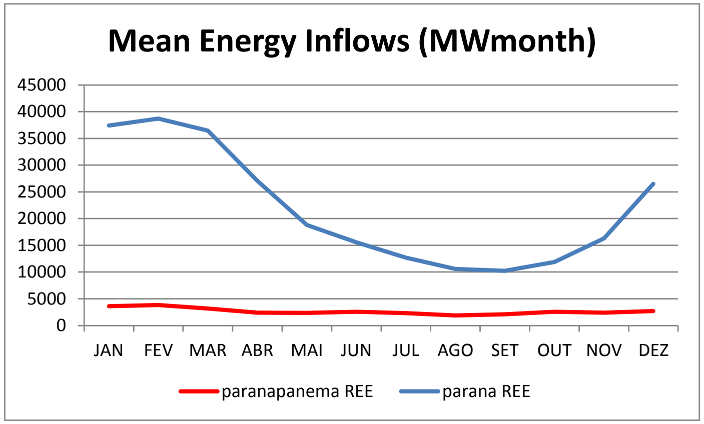






INCREASE IN THE REPRESENTATION OF THE HYDRO SYSTEM ALONG TIME

- The main goal is to capture diversity of the hydrological behaviour, while still keeping a lower state space

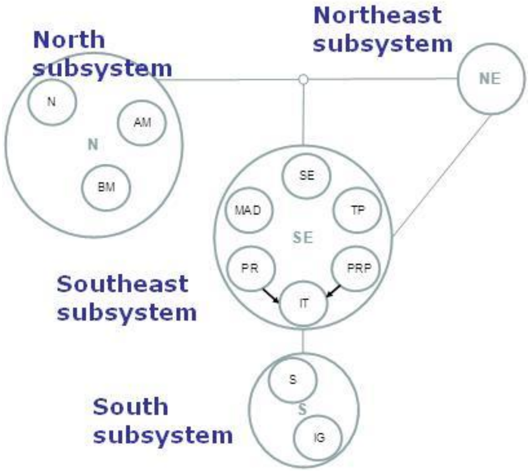


- Due to market aspects, the number of market areas is kept

[de Matos, Finardi, Silva, 08]

[Ennes, Penna, Maceira, Diniz, Vasconcellos,11]

- The increase in the number of EERs is based on comprehensive studies performed by CPAMP (ONS,CCEE,EPE,MME,ANEEL,CEPEL)
  - ✓ until 2015: **4 EERs**
  - ✓ 2016: **9 EERs**
  - ✓ 2018: **12 EERs**

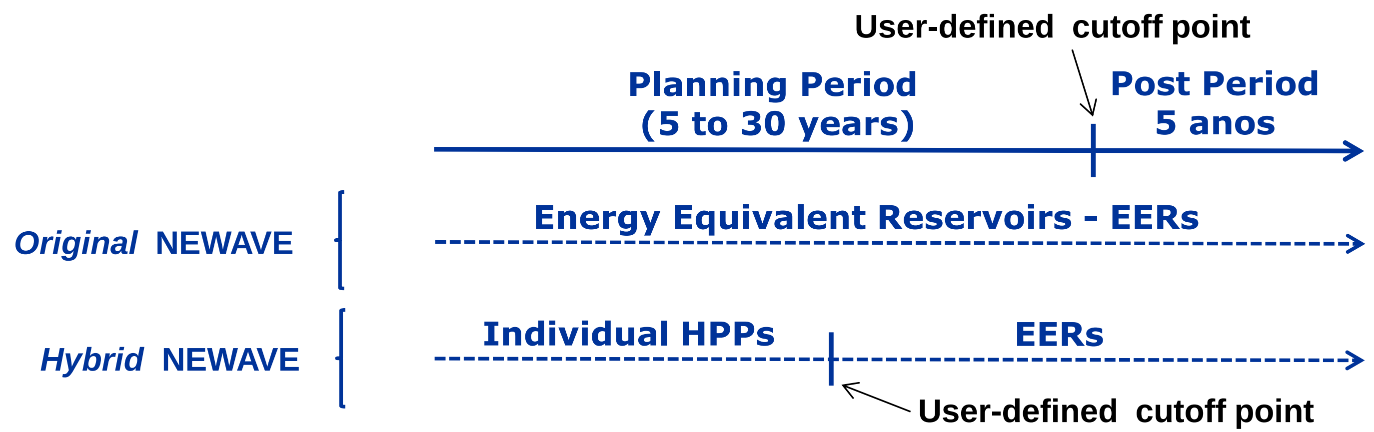


HYBRID INDIVIDUAL / EER REPRESENTATION IN NEWAVE

Eletrobras Cepel

- Allows NEWAVE model to represent the hydropower plants individually in the entire or in part of its planning horizon

- Takes advantage of both modellings, without increasing too much the computational effort by considering:
  - ✓ the benefits of an individual representation of HPPs in the horizon closer to the operational decision making
  - ✓ as many EERs as necessary to represent the hydrological diversity among the river basins, in the later stages



SOME NOTES ON SYSTEM REPRESENTATON

Eletrobras Cepel

- From the system modeling point of view, the consideration of individual reservoirs in SDDP itself is not a challenge
  - ✓ Constraints are similar (and simpler) than mid/short term models, and the construction of Benders cut in DDP or SDDP is similar
- Modeling of random variables (e.g. past inflows) for individual plants is more involving, due to its high dimensionality and the statistical model (overparametrization, spatial/serial correlations...)
- One major aspect is the **trade-off between system representation and the quality of the results**
  - ✓ It is not enough to simply run a number of SDDP iterations: it is VERY important to make sensitivity analysis on the final simulation results
- A critical issue is the **quality and impact of the detailed data** related to system components and constraints in the long term
  - ✓ It is not possible to satisfy all constraints in all future scenarios: in practice, some constraints are adjusted according to the system state, and one cannot simply discard violated scenarios
  - ✓ Aggregate constraints may be more effective in the long run

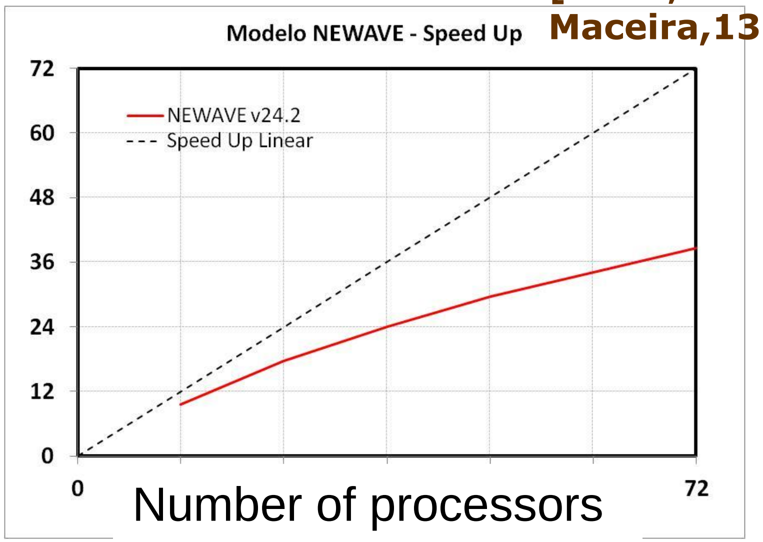
Challenge #5:

Performance Requirements

COMPUTATIONAL EFFICIENCY AND QUALITY OF THE RESULTS

Parallel processing

[Pinto, Borges, Maceira,13]



Reproducibility of the results

- The results should be identical regardless of the machine and number of parallel processors

Solving strategy for economic dispatch subproblems

- warm starts
- optimal simplex basis recovery (LPs)
- dynamic piecewise linear models [Diniz,Ennes, Cabral,12]
- cut selection [Matos, Philpott, Finardi,13]
- MIP: Local branching [Fischetti, Lodi,03]

[Saboia,Lucena,11]

Strict validation process

- CPAMP committee
- Task forces for each model
- + 300 users

Programs are heavily tested

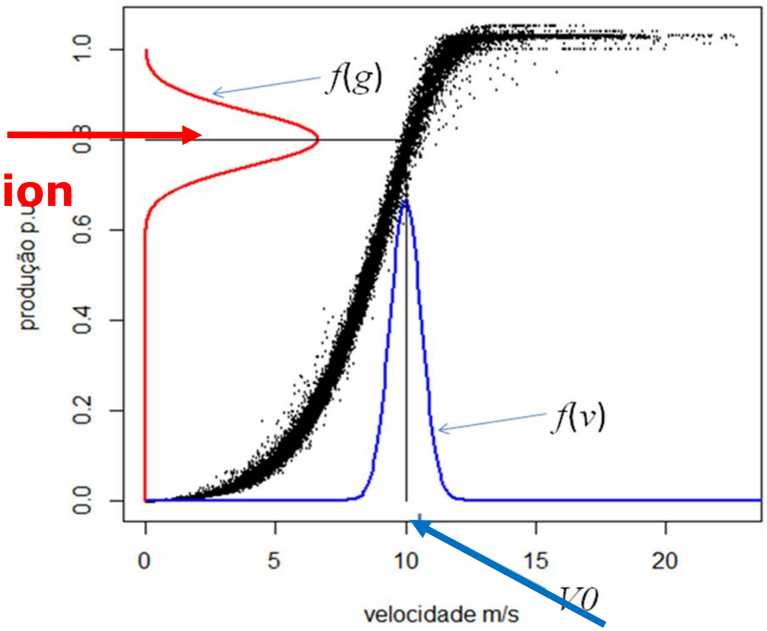
Challenge #6:

Handling high uncertainty/variability of intermittent sources

- Intermittent renewabel generation turns the traditional deterministic unit commitment model into a stochastic unit commitment model
  - ✓ wind generation has to be represented as interruptible generation, for feasible AND economic reasons **[Cotia, Borges,Diniz, 19]**
  - ✓ reliable models for scenario generation of wind production should be developed

[Pessanha et al,18]

Power generation

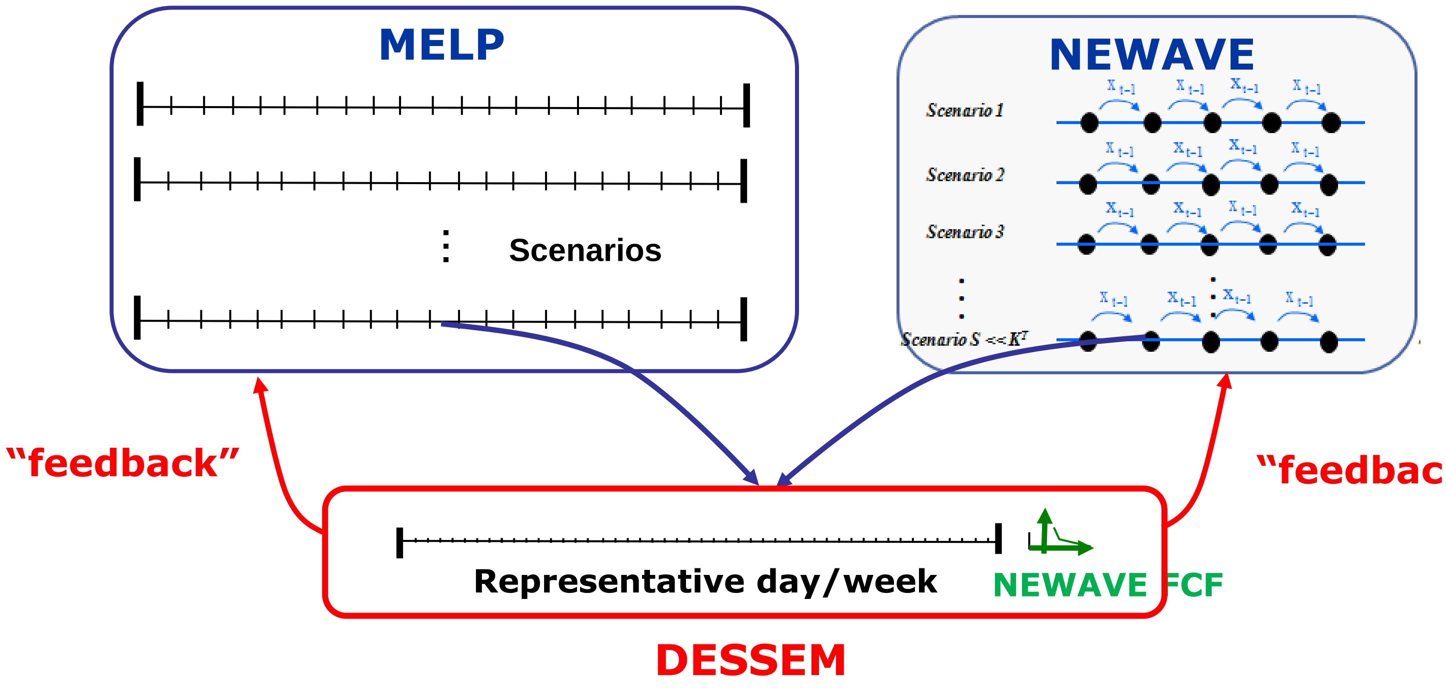


Wind speed

MODELING OF RENEWABLE GENERATION – LONG TERM

"SOFT LINK"

- integration between long term and short term models [Deane, Chiodi, Gargiulo, 12] [Pina, Silva, Ferrão, 13]



"HARD LINK"

- directly represent hourly operation constraints in the long term model [Deane, Chiodi, Gargiulo, 12] [Pina, Silva, Ferrão, 13] [Tejada-arango Domeshek, Wogrin 18]

This list of challenges is BY FAR not exhaustive:

- How to make SDDiP practical?
- How to better handle long tem uncertainties? (e.g. load growth)
- How to better address short range uncertainties on intermittent generation?
- Consideration of climate changes
- etc, etc, etc.

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OBRIGADO!

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Hourly prices with DESSEM model

Eletrobras Cepel

Ministério de
Minas e Energia

Validation of DESSEM model for hourly prices in Brazil

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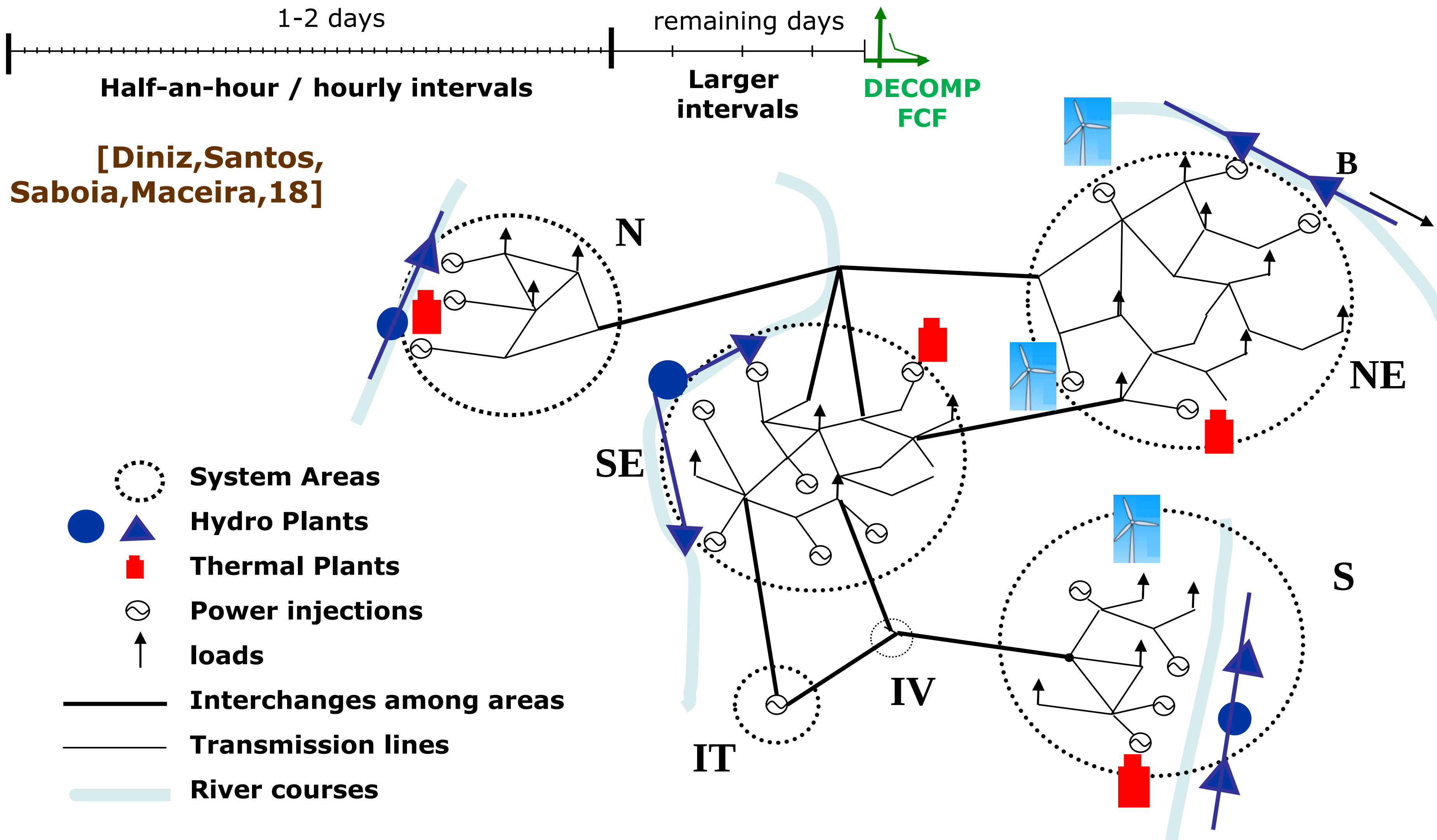
DETAILED REPRESENTATION OF THE ELECTRICAL NETWORK

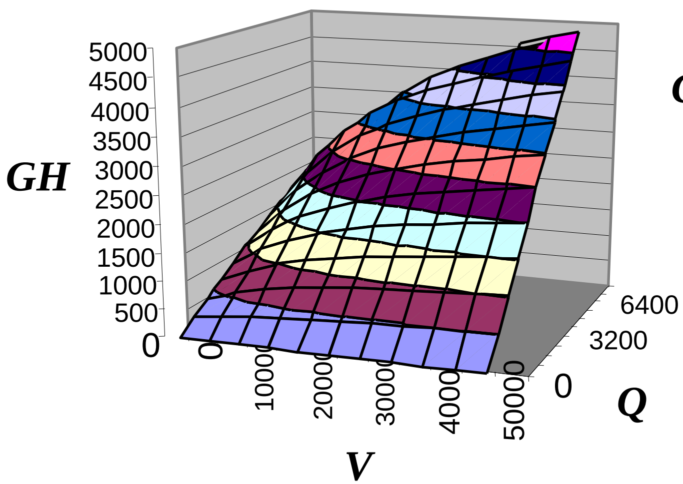
[Diniz,Santos, Saboia,Maceira,18]



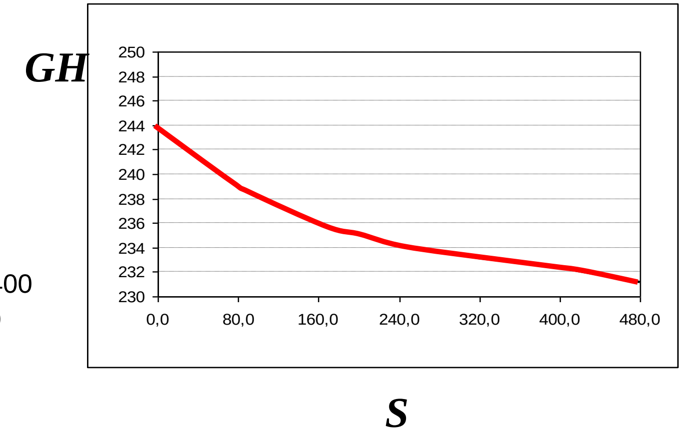
VARIATION OF EFFICIENCY WITH THE WATER HEAD

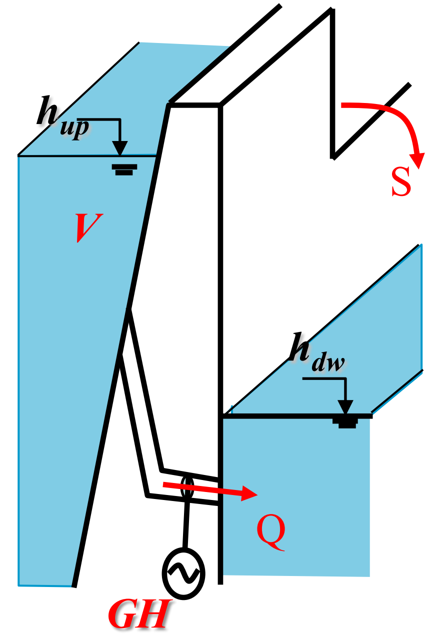
$$GH_i = 9.81 \times 10^{-3}\, \eta Q \left[h_{up}(V) - h_{dn}(Q+S) - h_{loss} \right]$$

Example of HPF as a function of *V* and *Q*



Example of HPF as a function of *S* (fixed values of *V* and *Q*)



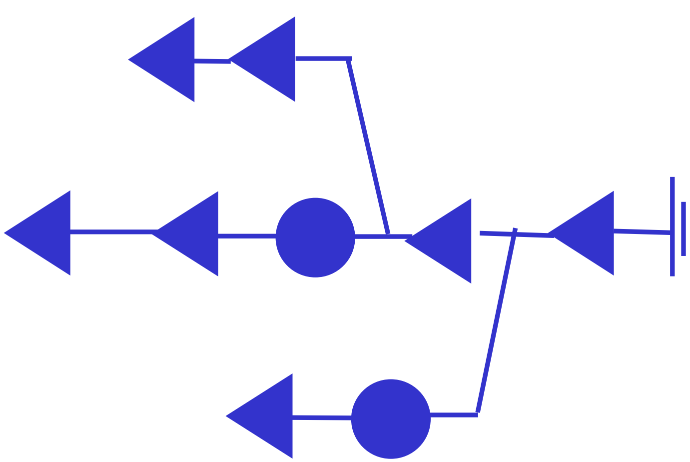


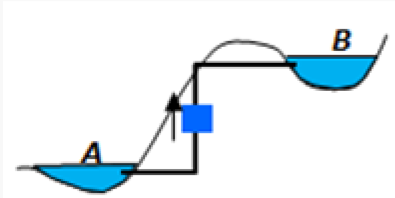
Four-dimensional piecewise linear model

[Diniz,Maceira,08]

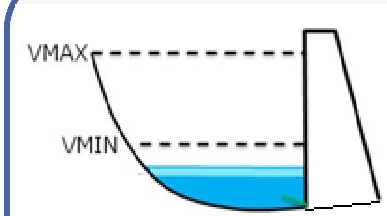
V, Q, S → **AHPF** → *GH*

HYDRO PLANTS IN CASCADE

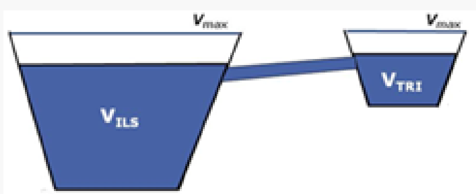




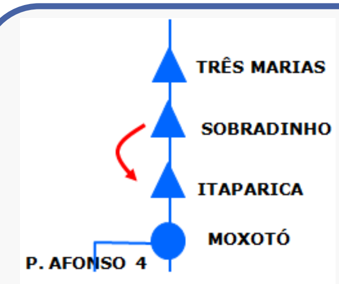
pumping stations



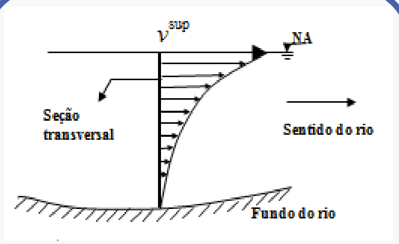
Filling of "dead volumes"



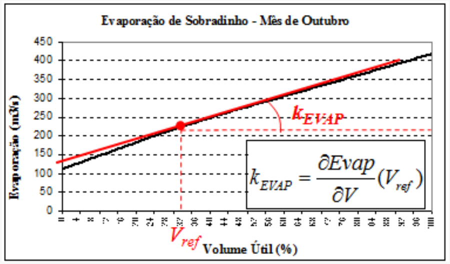
channels between reservoirs



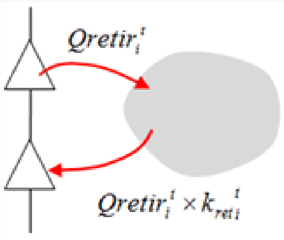
Minimum releases



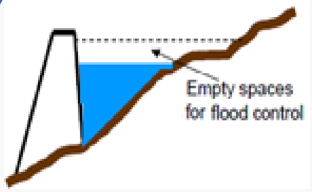
Modeling of river sections



Evaporation in reservoirs



Multiple uses of water

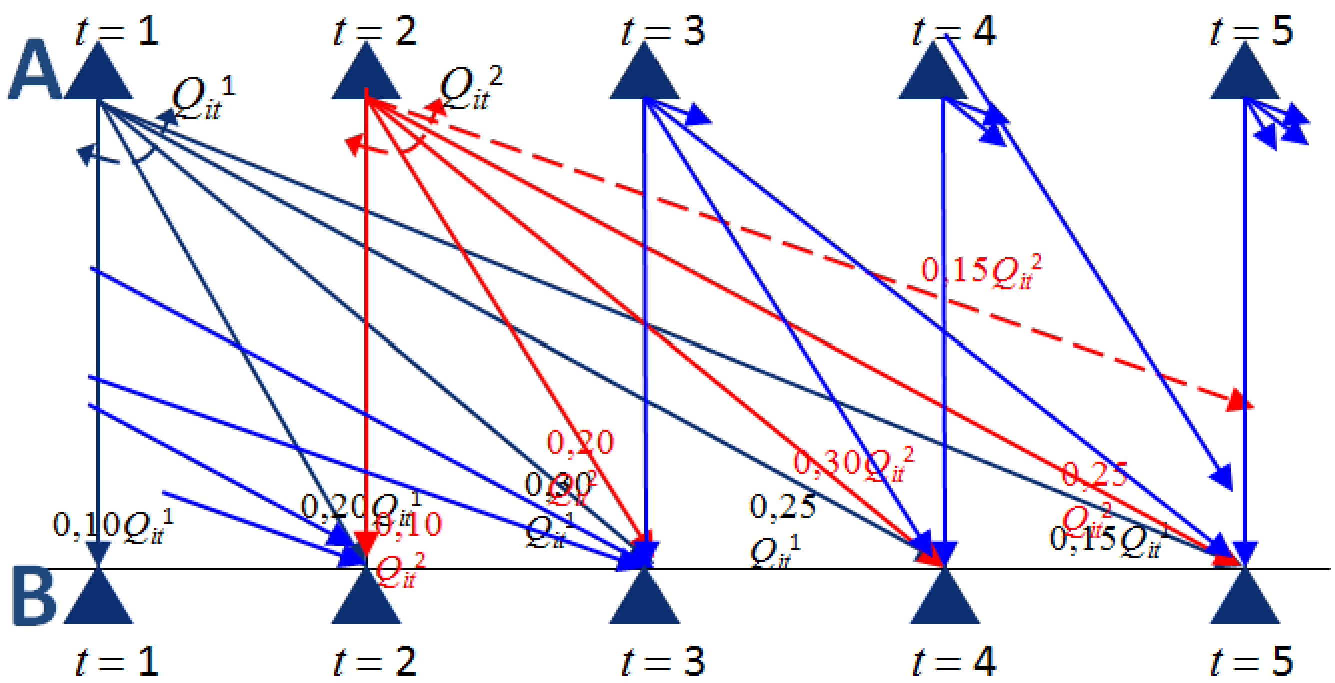


Flood control constraints

RIVER ROUTING

- Representation of water propagation curves along the river courses

[Diniz,Souza,14]



$$V_i^t + \left(Q_i^t + S_i^t\right) - \sum_{j \in M} \boxed{\sum_{k=0}^{\tau_{ij}^t} \kappa_{ij,k}^t} \left(Q_j^{t-\boxed{k}} + S_j^{t-\boxed{k}}\right) = V_i^{t-1} + I_i^t$$

NONCONVEX THERMAL UNIT COMMITMENT CONSTRAINTS (1/2)

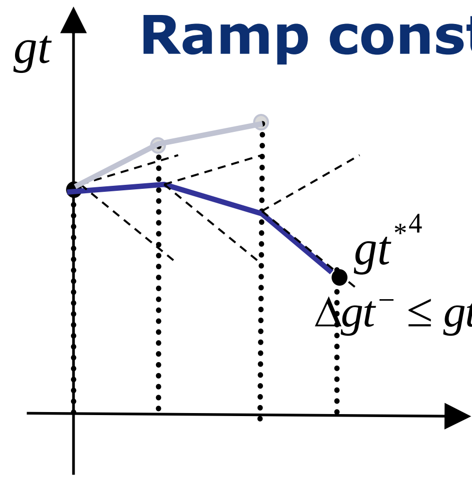
Minimum generation (once ON)

$$u_i^t \in \{0,1\} \qquad \underline{gt_i} \cdot u_i^t \le gt_i^t \le \overline{gt_i} \cdot u_i^t$$

Ramp constraints

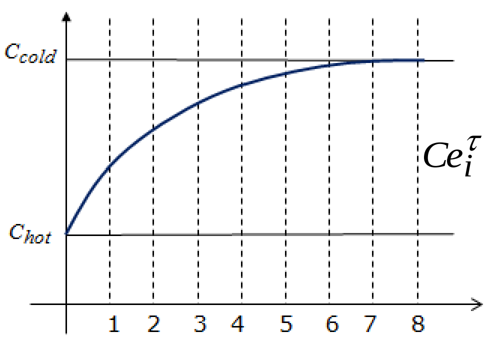
[Carrion, Arroyo,06]

[Saboia, Diniz,16]



$$\Delta gt^- \le gt_i^t - gt_i^{t-1} \le \Delta gt^+$$

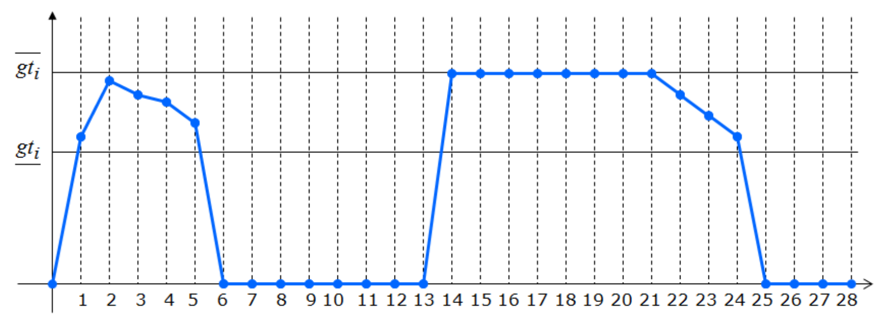
Startup/shutdown costs



$$Ce_i^{\tau}\left(u_i^t - \sum_{k=t-\tau}^{t} u_i^k\right) \le S_i^t$$

$$Cs_i\left(u_i^{t-1} - u_i^t\right) \le S_i^t$$

Minimum up/down times



$$\sum_{k=t}^{t+Ton_i-1} u_i^k \ge Ton_i \cdot (u_i^t - u_i^{t-1})$$

$$\sum_{k=t}^{t+Toff_i-1} (1-u_i^k) \ge Toff_i \cdot (u_i^{t-1} - u_i^t)$$

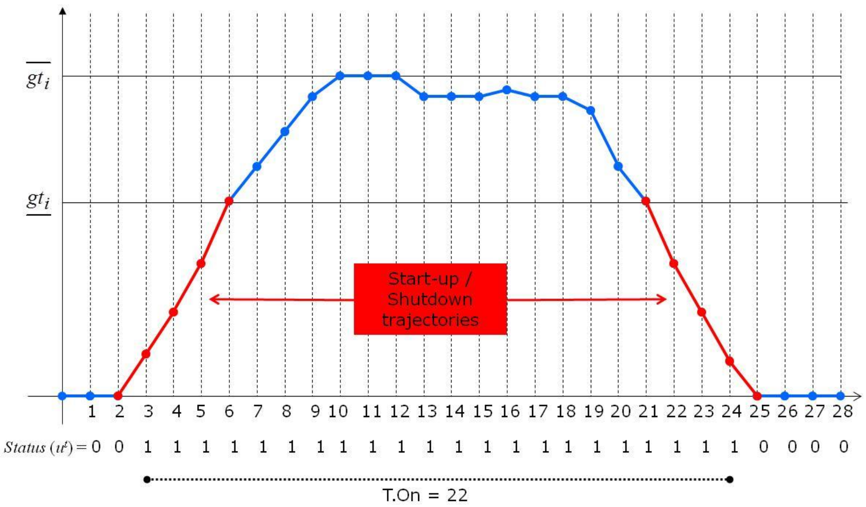
NONCONVEX THERMAL UNIT COMMITMENT CONSTRAINTS (2/2)

Start-up / Shutdown trajectories

$$GT_i^t \geq \underline{GT}_i\left(u_i^t - \sum_{k=1}^{NU_i}\hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i}\tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k)\cdot\hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1)\cdot\tilde{y}_i^{t+k-1}$$

$$GT_i^t \leq \overline{GT}_i\left(u_i^t - \sum_{k=1}^{NU_i}\hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i}\tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k)\cdot\hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1)\cdot\tilde{y}_i^{t+k-1}$$

[Arroyo, Conejo, 04]



Auxiliary variables:

$$\tilde{y}_i^t = \tilde{w}_i^t + \left(u_i^{t-1} - u_i^t\right)$$

$$\tilde{y}_i^t + \tilde{w}_i^t \leq 1$$

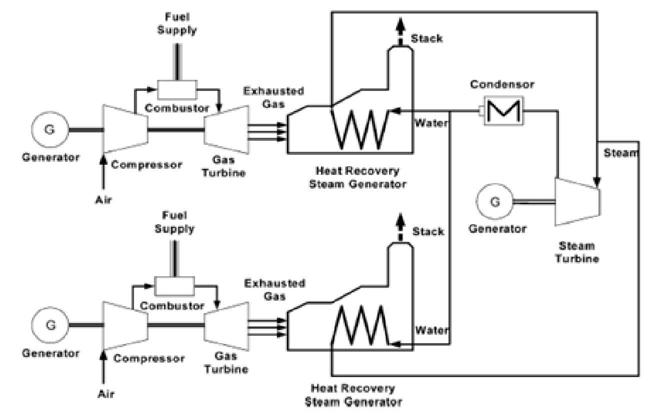
NU_i : length of startup trajectory

ND_i : length of shutdown trajectory

MODELING OF COMBINED –CYCLE PLANTS

Eletrobras Cepel

- Application of a hybrid component/mode model
- Constraints can be individually enforced for the thermal units
- transition requirements between configurations can be included

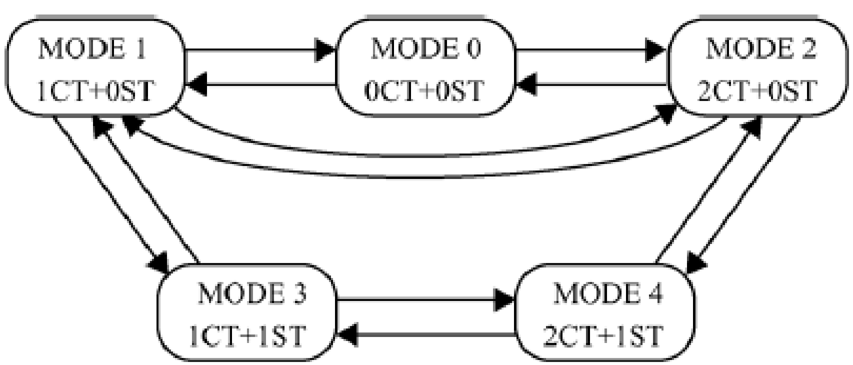


- Linking constraint between units status and configuration modes

[Liu,Shahidehpour, Li,Mahmoud,09] [Morales-Espana, Correa-Posada, Ramod,16]

u_{ij}^{t} x_{ik}^{t}

$$\begin{cases} \sum_{j \in NU_i} P_j u_{ij}^t = \sum_{k \in NC_i} N_k x_{ik}^t \\ \sum_{k \in NC_i} x_{ik}^t = 1 \\ u_{ij}^t, x_{ik}^t \in \{0,1\} \end{cases}$$



DC MODEL OF THE ELECTRICAL NETWORK

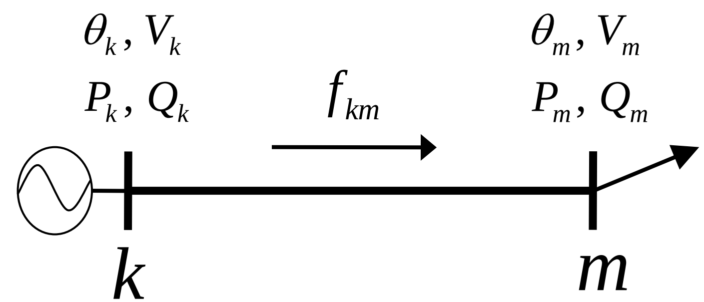
Eletrobras Cepel

Line Flow limit constraints

$$\underline{f_{km}} \le f_{km}^{t} = \frac{\theta_k^t - \theta_m^t}{x_{km}} \le \overline{f_{km}}$$

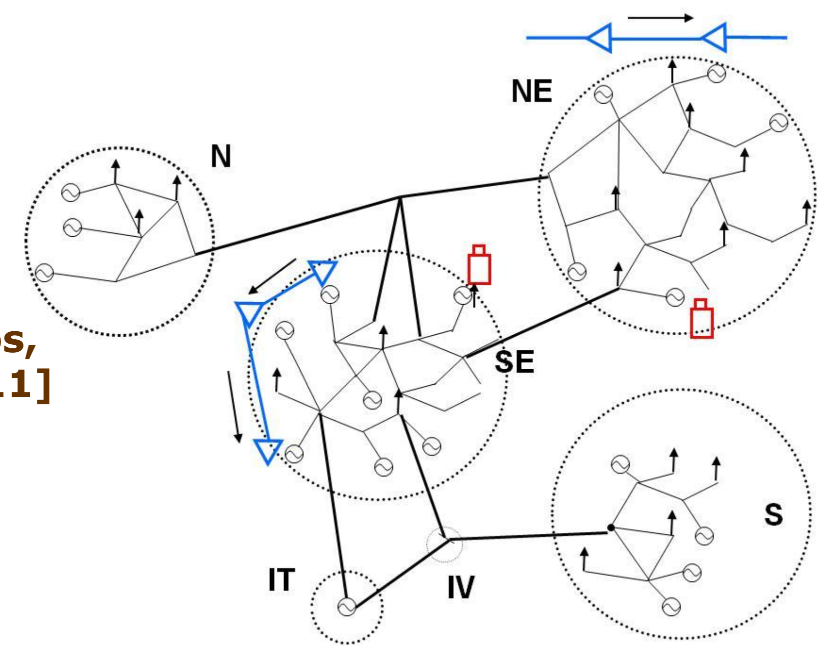
- phase angles are a function of power injections / loads

$$\underbrace{\begin{bmatrix} g \end{bmatrix} - \begin{bmatrix} d \end{bmatrix}}_{gh,\ gt} = \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} \theta \end{bmatrix}$$



Ramp constraint on line flows

$$\left| f_{km}^{t} - f_{km}^{t-1} \right| \le \overline{\Delta f_{km}}$$

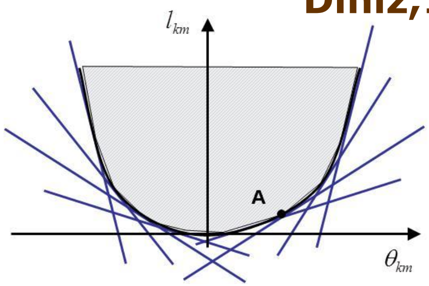


Power transmission losses

[Santos, Diniz,11]

- dynamic piecewise linear approximations

$$l_i \cong g_i \Delta\theta_i^{(k)^2}$$

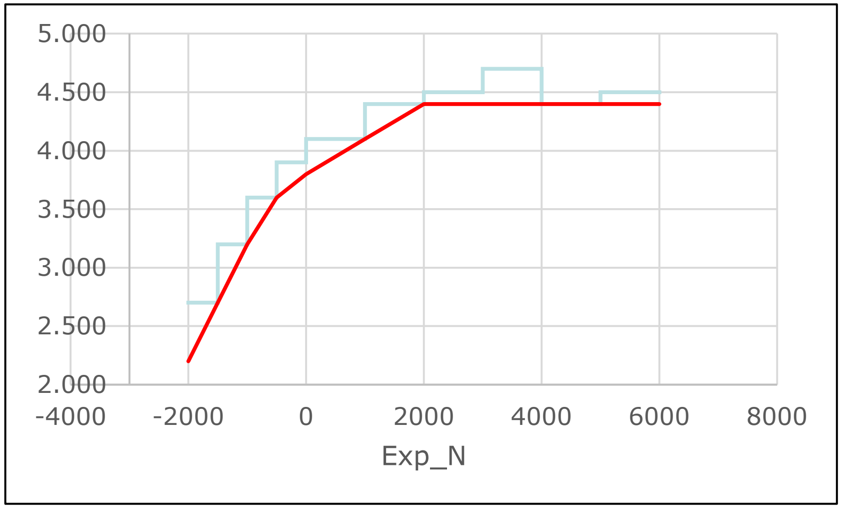


- Line flow limits and approximations for losses are iteratively included

ADDITIONAL SECURITY CONSTRAINTS

- constraints on the relation of flows in given lines of the system for security purposes

PIECEWISE LINEAR CONSTRAINTS



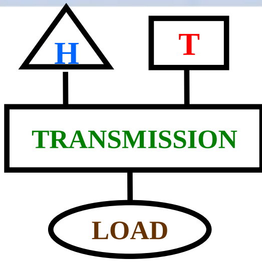
- some constraints are given by tables

HEURISTIC ITERATIVE APPROACH

LIMITES DE RNE (MW)						
	Carga NE < 10.500		10.500 ≤ Carga NE < 12.000		Carga NE ≥ 12.000	
Faixa de Recebimento / Exportação Norte (RN / Exp_N)	(F) = Somatório do fluxo na transformação 500/230 kV de Igaporã III, no sentido de 230 kV para o 500 kV e do fluxo na LT 230 kV Igaporã II / Bom Jesus da Lapa II, no sentido de Igaporã II para Bom Jesus da Lapa II.					
	0 < F ≤ 600	600 < F ≤ 1.050	0 < F ≤ 600	600 < F ≤ 1.050	0 < F ≤ 600	600 < F ≤ 1.050
Exp_N ≥ 5.000	Limite = 40% da carga NE	Limite = 40% da carga NE	4.400 (1)	4.300 (1)	4.400	4.300
4.000 ≤Exp_N< 5.000			4.300 (1)	4.300 (1)	4.300	4.300
3.000 ≤Exp_N< 4.000		4.200 (1)	4.200 (1)	4.200 (1)	4.200	4.200
2.000 ≤Exp_N< 3.000		4.100 (1)	4.100	4.100	4.100	4.100
1.000 ≤Exp_N< 2.000		3.900 (1)	4.000	3.900	4.000	3.900
0 ≤Exp_N< 1.000	4.100 (1)	3.600 (1)	4.000	3.700	4.000	3.500
0 < RN ≤ 500	3.900 (1)	3.300 (1)	4.000	3.500	4.000	3.500
500 < RN ≤ 1.000	3.600 (1)	3.000 (1)	3.800	3.200	4.000	3.300
1.000 < RN ≤ 1.500	3.200 (1)	2.700 (1)	3.400	2.900	3.600	2.900

OVERALL PROBLEM FORMULATION

MIXED INTEGER (PIECEWISE) LINEAR PROGRAMMING



$$\min \sum_{t=1}^{T} \sum_{i=1}^{NUT} c_i(gt_i^t) + S_i^t + \alpha^T \left(V^T\right)$$

s.a.

Demand / **Electrical network** — E

$$\sum_{j \in \Phi_i} gt_j^t + \sum_{j \in \Psi_i} gh_j^t + \sum_{j \in \Omega_i} \left(Int_{j\to i}^t - Int_{i \to j}^t\right) = D_i^t \qquad i = 1,\ldots,NS,\ t = 1,\ldots,T,$$

$$\sum_{i=1}^{NB} \kappa_{i,l}(g_i - d_i) \le \overline{f_l} \ ;\ p_i - \sum_{i=1}^{NB} \kappa_{i,l}(g_i - d_i) \le rhs \qquad i, j = 1,\ldots,NL\ ,\ t = 1,\ldots,T$$

Water balance / **AHPF** / **Operative constraints** — H

$$\left.\begin{aligned} & V_i^t = V_i^{t-1} + I_i^t - (Q_i^t + S_i^t) + \sum_{j \in M_i} (Q_j^t + S_j^t) \\ & gh_i^t = FPH(V_i^t, Q_i^t, S_i^t) \\ & \underline{V_i^t} \le V_i^t \le \overline{V_i^t},\ \underline{Q_i^t} \le Q_i^t \le \overline{Q_i^t},\ \underline{gh_i^t} \le gh_i^t \le \overline{gh_i^t}, \end{aligned}\right\} \quad i = 1,\ldots,NH,\ t = 1,\ldots,T,$$

Termal constraints / ***Unit Commitment*** — T

$$\underline{gt_i} \cdot u_i^t \le gt_i^t \le \overline{gt_i} \cdot u_i^t$$

$$\sum_{k=t}^{t+Ton_i-1} u_i^k \ge Ton_i \cdot (u_i^t - u_i^{t-1})$$

$$\sum_{k=t}^{t+Toff_i-1} (1 - u_i^k) \ge Toff_i \cdot (u_i^{t-1} - u_i^t)$$

$$u_i^t \in \{0,1\} \qquad \tilde{y}_i^t = \tilde{w}_i^t + \left(u_i^{t-1} - u_i^t\right)$$

$$\tilde{y}_i^t + \tilde{w}_i^t \le 1$$

$$Ce_i^\tau \left(u_i^t - \sum_{k=t-\tau}^{t} u_i^k\right) \le S_i^t \qquad Cs_i\left(u_i^{t-1} - u_i^t\right) \le S_i^t$$

$$\underline{GT}_i \left(u_i^t - \sum_{k=1}^{NU_i} \hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i} \tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k) \cdot \hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1) \cdot \tilde{y}_i^{t+k-1} \le GT_i^t$$

$$GT_i^t \le \overline{GT}_i \left(u_i^t - \sum_{k=1}^{NU_i} \hat{y}_i^{t-k+1} - \sum_{k=1}^{ND_i} \tilde{y}_i^{t+k-1}\right) + \sum_{k=1}^{NU_i} TrUp_i(k) \cdot \hat{y}_i^{t-k+1} + \sum_{k=1}^{ND_i} TrDn_i(ND_i - k + 1) \cdot \tilde{y}_i^{t+k-1}$$

$$i = 1,\ldots,NUT,\ t = 1,\ldots,T,$$

+ MANY more constraints...

Solving Strategy: MILP (1/3)

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ITERATIVE LP APPROACH TO FIND MAJOR / POTENTIAL BINDING CONSTRAINTS IN THE ELECTRICAL NETWORK

Set the Multistage MILP Problem

Solve Linear Relaxation (LP)

Obtain a lower bound

solve a DC load flow compute line flows

[Stott, Marinho, 79

[Diniz,Souza, Maceira et al,02]

[Santos, Diniz, 11]

Insert line flow limits constraints

Satisfy Network constraints?

No

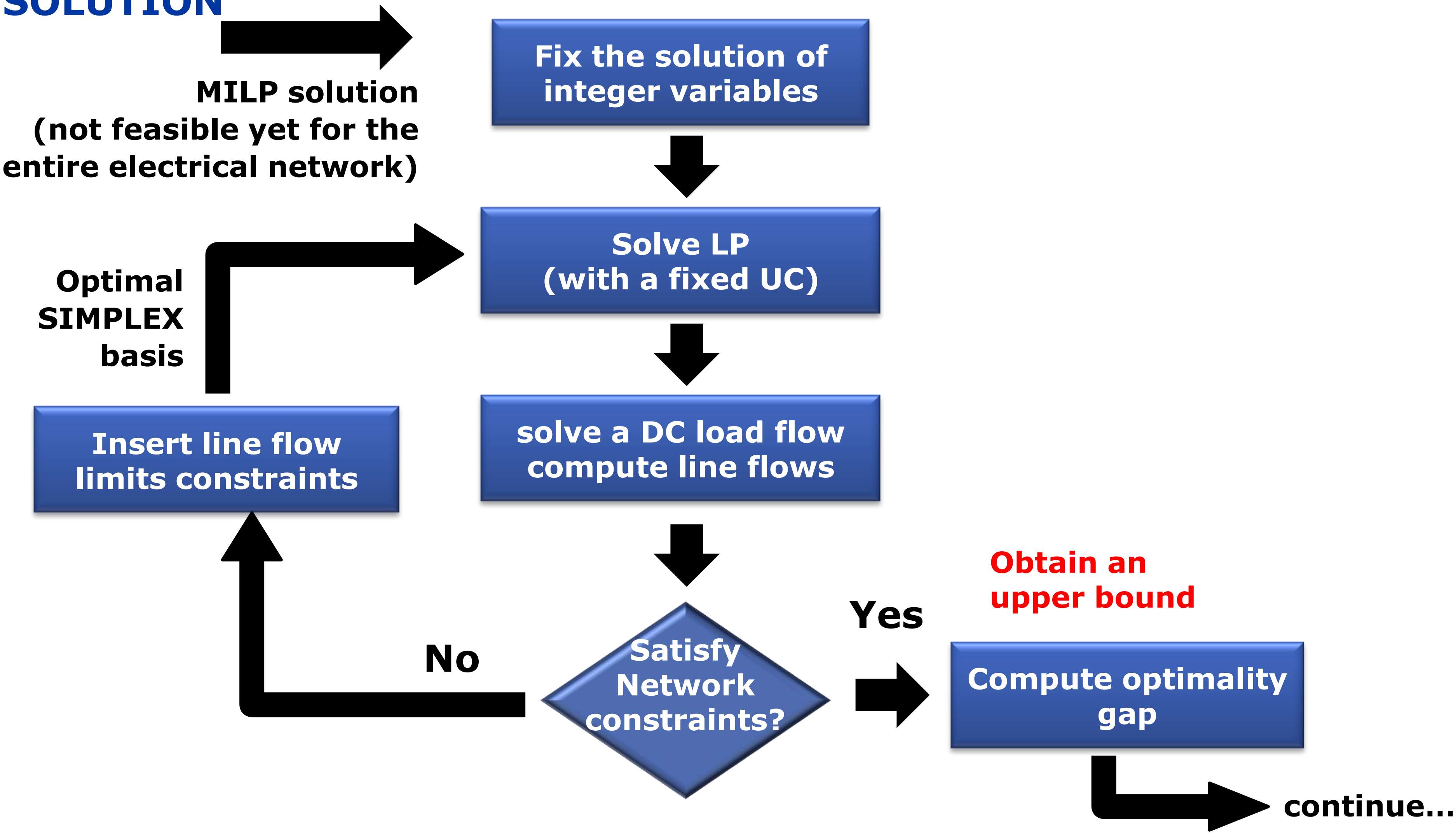
Yes

Solve the MILP problem

continue...

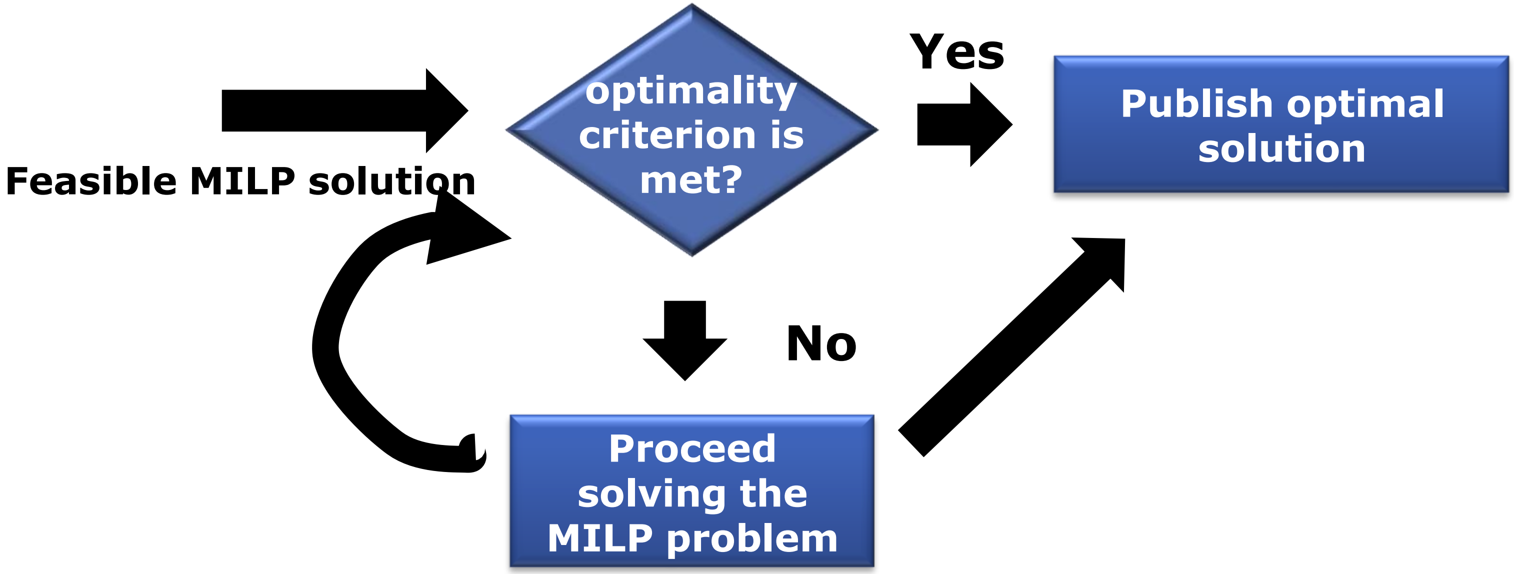
Solving Strategy: MILP (2/3)

ITERATIVE LP WITH FIXED UC TO OBTAIN A GOOD (?) FEASIBLE SOLUTION



Solving Strategy: MILP (3/3)

FINDING AN OPTIMAL SOLUTION WITH THE DESIRED ACCURACY



RECENT DEVELOPMENTS: REDUCTION OF CPU TIMES

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- Use of tighter/more compact unit commitment formulations

[Ostrowsku, Anjos,Vanneli, 13]

[Dam, Kucuk, Rajan, Atam, 13]

[Morales-Espana, Latorre, Ramos, 13]

- Taking into account optimal basis informationwhile adding new constraints to the problem **<u>in a MILP setting</u>**

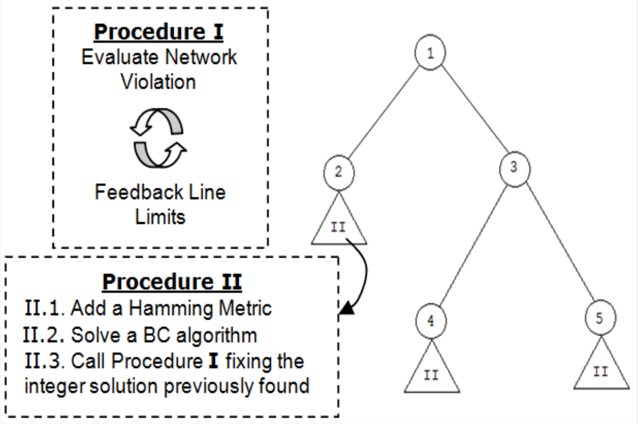
- Alternative (better) interaction between MILP and LP solving procedures
  - ✓ Application of local branching

[Fischetti, Lodi,03]

[Saboia, Diniz,16]

Hamming Metric

$$\Delta(u,\bar{u}) = \sum_{\{v:(\bar{u})^v=1\}} [1-(u)^v] + \sum_{\{v:(\bar{u})^v=0\}} (u)^v$$



DETERMINATION OF MARKET PRICES

Obtain nodal prices for all buses of the system

"Optimal "solution has been reached → Fix commitent status of the units → Solve a continuous hydrothermal scheduling problem → Obtain multipliers for system area and line flow limits constraints

System are price as weighted average in all buses

Multipliers of demand balance in each area

$$\sum_{\substack{i=1 \\ i\in k}}^{NH,NT} g_i \pm \sum_{j\in\Omega_k} Int_{j\rightarrow i} = \sum_{i\in Area\ k} d_i \ , \ k=1,\ldots NS \longleftarrow \lambda_k^d$$

Multipliers of line flow limits constraints

$$\sum_{i=1}^{NB} \kappa_{il} g_i \le f_{l\max} + \sum_{i=1}^{NB} \kappa_{il} d_i \ , \ \ l=1,\ldots NL_{adic}, \longleftarrow \lambda_l^f$$

Nodal price:

$$CMB_i = \lambda_{a(i)}^d + \sum_{l=1}^{NL_{adic}} \kappa_{il} \ \lambda_l^f$$

System Area price:

$$CMO_k = \frac{\sum_{\substack{i=1 \\ i\in k}}^{NB} CMB_i d_i}{\sum_{\substack{i=1 \\ i\in k}}^{NB} d_i}$$

PERFORMANCE RESULTS "shadow" operation – ONS

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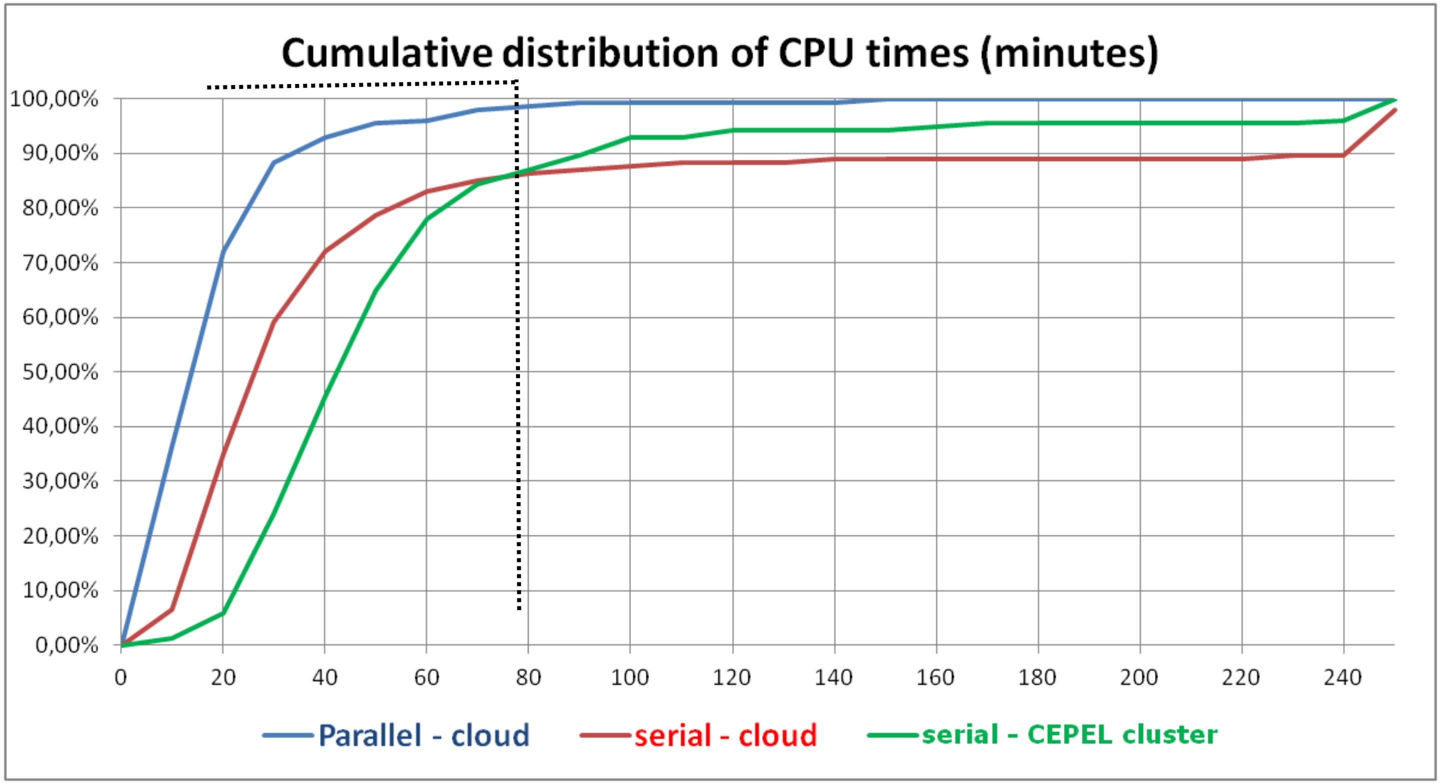
Presentation

154 REAL CASES FROM Jan 1st to Jun 13th



Average CPU time: 18.2min
< 1 hour: ~ 96%

#Hydro Plants:	**158**
#Thermal Plants:	**109**
#Network Buses:	**6,800**
#Transmission Lines:	**9,800**