LABORATORY OF APPLIED MATHEMATICAL PROGRAMMING AND STATISTICS

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The Cost of Time-Inconsistent Long-Term Hydrothermal Operation Policies Induced by Short-Term Modeling Simplifications

Workshop ILAS 2019:

"Stochastic Programming models and algorithms for energy planning"

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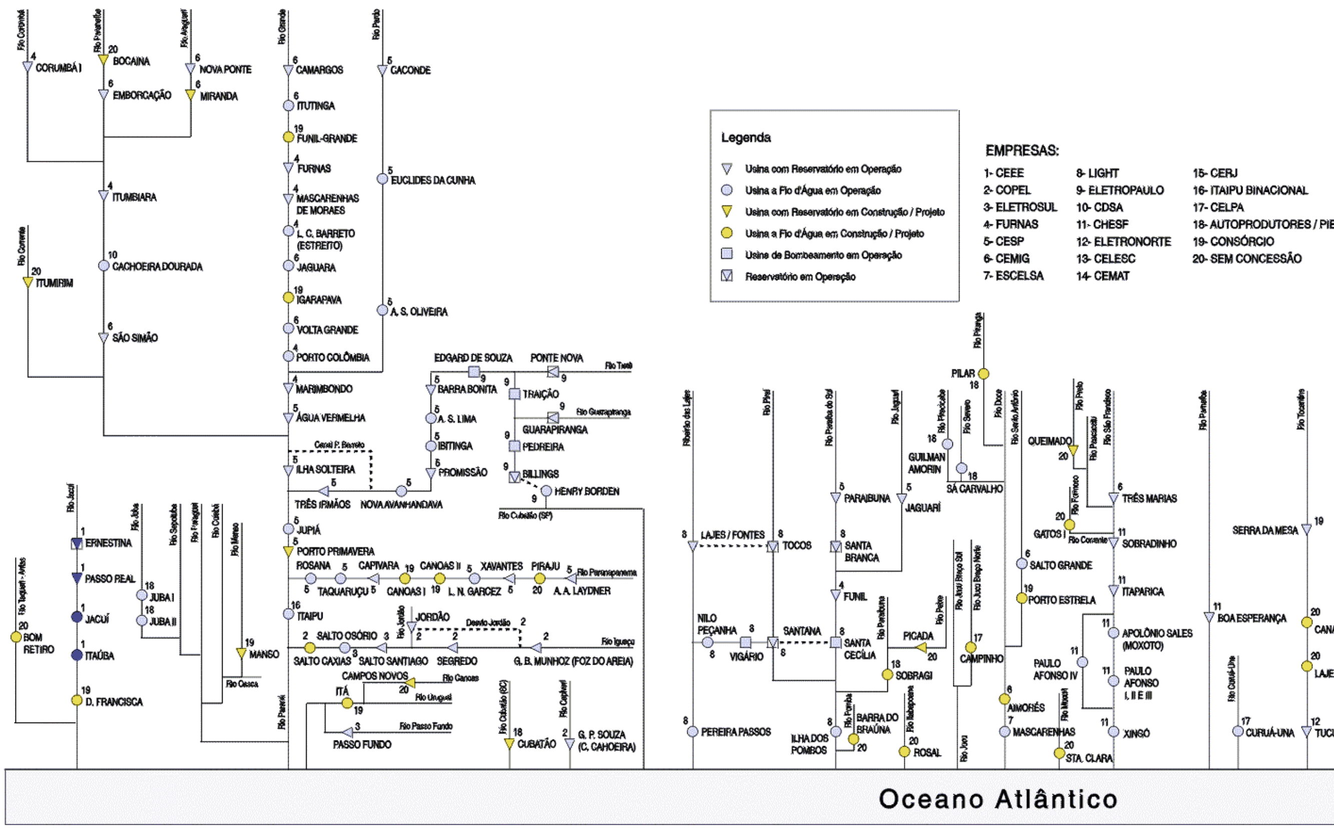
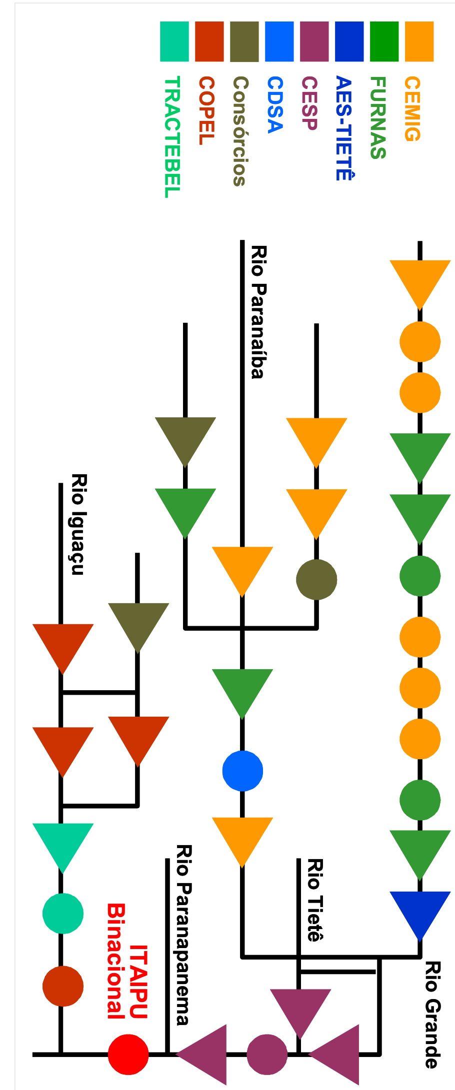
AGENDA

- Hydrothermal operation planning
- Time consistency
- Simplifications in planning models
- n-K security criterion dispatch
- Hybrid SDDP and CCG algorithm

Brazilian power system case

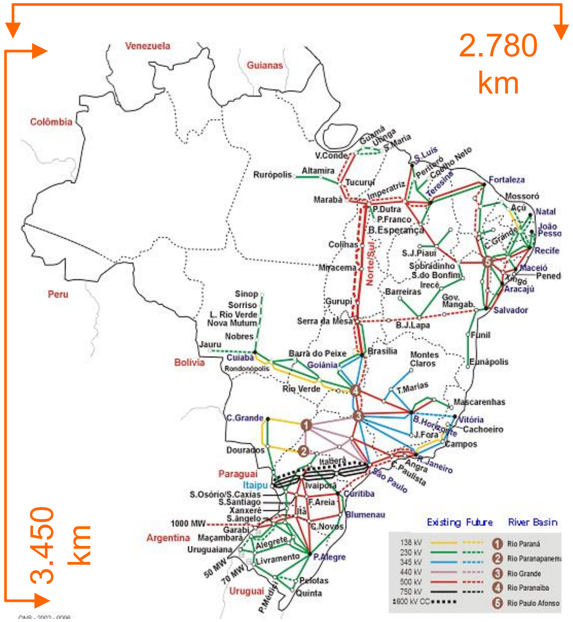
- More than 10 river basins
- Wide variety of weather patterns
- Different ownerships in the same rivers

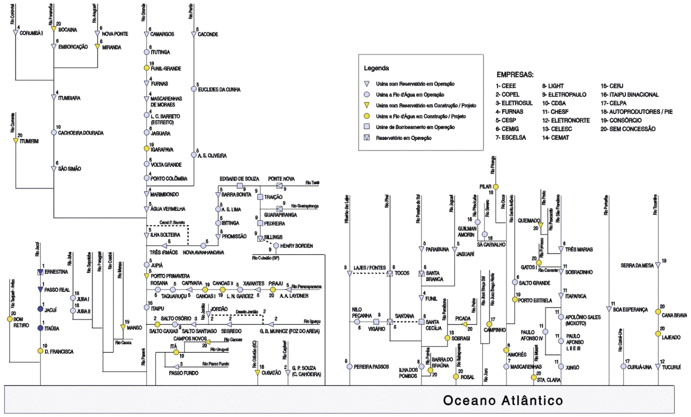




Challenge of operating a integrated hydrothermal system

- An ISO centrally dispatches the system "as a portfolio" to take advantage of the hydrological diversity,
- creating a hedge against dry periods and the waste of fossil fuel.
  - Transferring water from wet to dry basins
  - Transmission network
  - Transferring water from wet to dry periods
  - Large storage capacity





- The "water value" is calculated by an SDDP scheme.
- Spot prices "are" the system demand marginal

Hydrothermal operation planning

- Minimize the expected total thermal cost in a given time horizon
- Subject to
- Demand balance in each stage
- Water balance between stages
- Network constraints
- Bound constraints
- with uncertain inflows
  - w_t is $\mathcal{F}_t - adapted$
  - $\{\mathcal{F}_t\}_{t=1}^{T}$ is a filtration with the structure of how uncertainty is reveled through the time

$$\min_{g_t, y_t, f_t} \mathbb{E}\left[\sum_{t=1}^{T} \frac{c_t^T g_t}{(1+K)^t}\right]$$

Subject to

$$A_t g_t + P_t u_t + C_t f_t = d_t$$
$$v_t + u_t + s_t = v_{t-1} + w_t$$
$$(v_t, u_t, s_t, g_t, f_t) \in \mathcal{X}_t$$
$$(v_t, u_t, s_t, g_t, f_t)\ is\ \mathcal{F}_t - adapted$$

Hydrothermal operation planning

- Dynamic equations

$$\mathcal{Q}_t(v_{t-1}) = \min_{g_t, y_t, f_t} \mathbb{E}[c_t g_t + \beta \mathcal{Q}_{t+1}(v_t)]$$

Sujeito a:

$$A_t g_t + P_t u_t + C_t f_t = d_t$$
$$v_t + u_t + s_t = v_{t-1} + w_{t,\omega}$$
$$(v_t, u_t, s_t, g_t, f_t) \in \mathcal{X}_t$$

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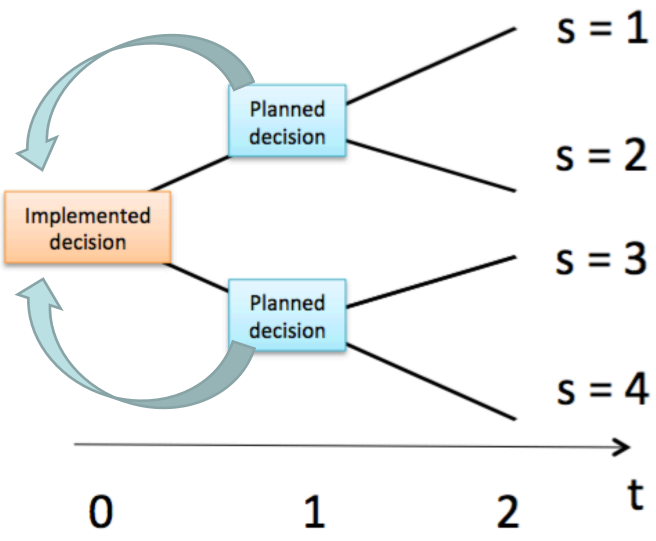
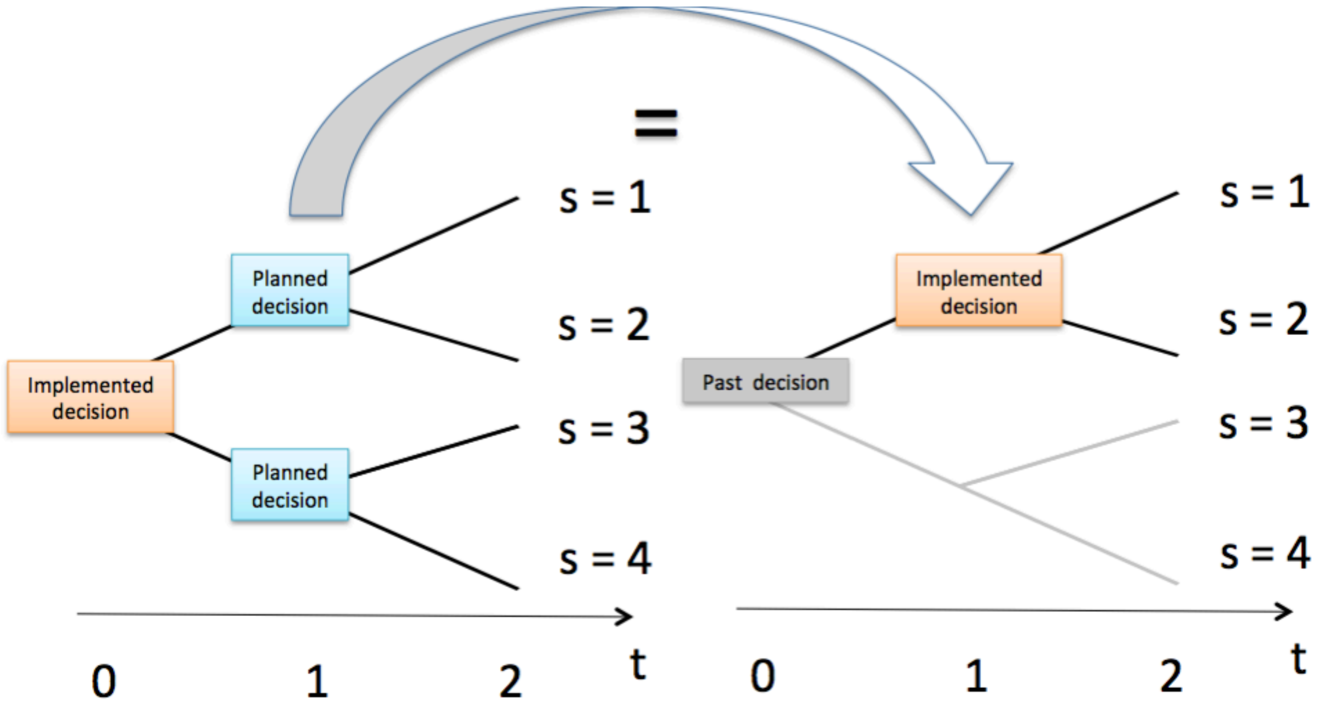
Motivation for the multistage setting

- To incorporate into first-stage decisions (those we actually implement) the flexibility that the dynamics of future decisions might bring
  - Implemented decisions: first-stage decisions of the conditioned multistage problem
  - Planned decisions: those used to model the dynamics of future decisions in the multistage problem



Time consistency definition

- A decision policy is time-consistent if future planned decisions are actually going to be implemented

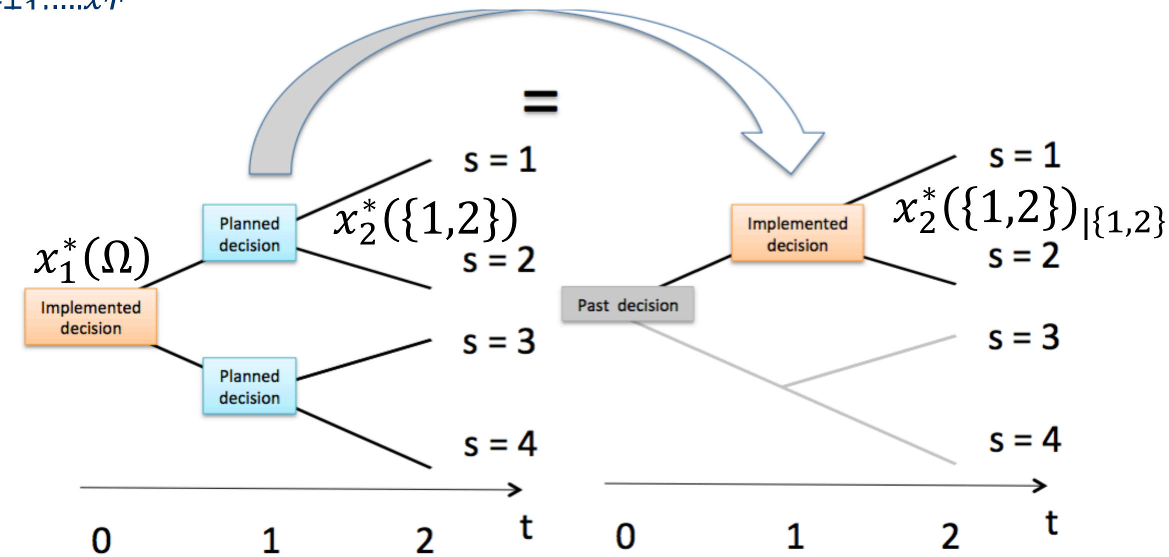


B. Rudloff, A. Street, D. Valladão, "*Time consistency and risk averse dynamic decision models: Definition, interpretation and practical consequences.*" European Journal of Operational Research (EJOR), 2014.

Time consistency definition

- A policy $\{(x_t^*: \Omega \to \mathbb{R}^n)\}_{t=1}^{T}$, devised in a given stage (e.g., t=1), is time consistent if its planned decisions are optimal with respect to the implementation model

$$\{x_t^*\}_{t=\tau}^{T} \in \arg \min_{\substack{x_\tau \\ x_{\tau+1},\dots,x_T}} \left\{ \rho_{\tau,T}[f(x_\tau,\xi_\tau),\dots,f_T(x_T,\xi_T)] \middle| \begin{array}{c} x_\tau \in \mathcal{X}_\tau(x_{\tau-1},\xi_\tau) \\ x_t \in \mathcal{X}_t(x_{t-1},\xi_t), t = \tau+1,\dots,T \end{array} \right\}$$



A. Shapiro, A. Pichler, "Time and Dynamic Consistency of Risk Averse Stochastic Programs". Optimization On-line, 2016.

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How do we operate a real system?

- We devise an approximation for the system model, $\mathcal{X}_t^{plan} = \mathcal{X}^S$
- But in the short-term we implement decisions using a detailed version of the model, $\mathcal{X}_t^{imp} = \mathcal{X}^D$

$$\min_{g_t, y_t, f_t} c_t^T g_t + \beta Q_{t+1}^{plan}(v_t)$$

Sujeito a:

$$A_t g_t + P_t u_t + C_t f_t = d_t$$
$$v_t + u_t + s_t = v_{t-1} + w_{t,\omega}$$
$$(u_t, s_t, g_t, f_t) \in \mathcal{X}_t^{plan}$$

Planning model
(Generally simplified)
Model used to assess the cost-to-go function

$$\min_{g_t, y_t, f_t} c_t^T g_t + \beta Q_{t+1}^{plan}(v_t)$$

Sujeito a:

$$A_t g_t + P_t u_t + C_t f_t = d_t$$
$$v_t + u_t + s_t = v_{t-1} + w_{t,\omega}$$
$$(u_t, s_t, g_t, f_t) \in \mathcal{X}_t^{imp}$$

Implementation model
(Generally very accurate)
Model used to make the decision at stage t

Two policies

- Planning policy: makes use of a planning model, $\mathcal{X}_t^{plan} = \mathcal{X}^S$

$$\left(x_\tau^{plan}, \{x_t^{plan}\}_{t=\tau+1}^{T}\right) \in \arg \min_{\substack{x_\tau \\ x_{\tau+1},\dots,x_T}} \left\{ \rho_{\tau,T}[f(x_\tau,\xi_\tau),\dots,f_T(x_T,\xi_T)] \middle| \begin{array}{c} x_\tau \in \mathcal{X}^S(x_{\tau-1},\xi_\tau) \\ x_t \in \mathcal{X}^S(x_{t-1},\xi_t), t = \tau+1,\dots,T \end{array} \right\}$$

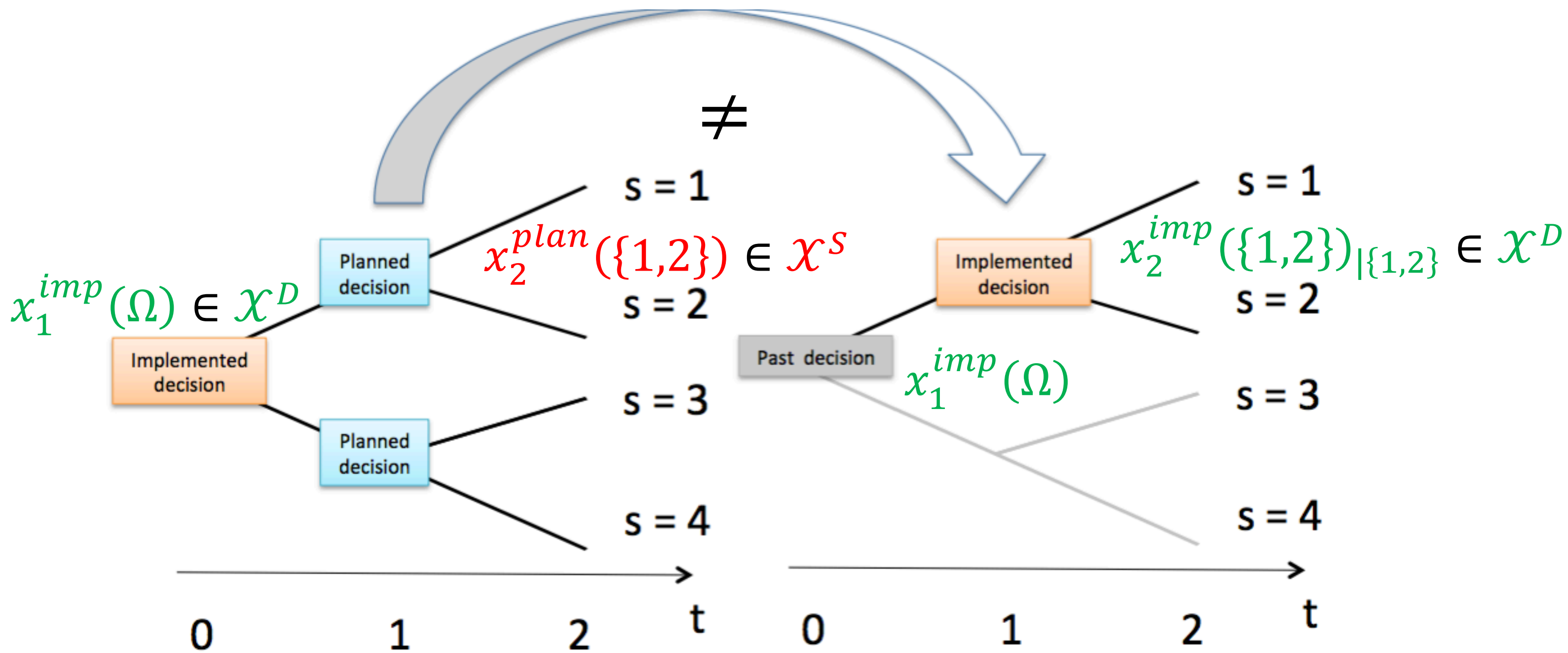
- Implementation policy: makes use of both implementation, $\mathcal{X}_t^{imp} = \mathcal{X}^D$, and planning model, $\mathcal{X}_t^{plan} = \mathcal{X}^S$

$$\left(x_\tau^{imp}, \{x_t^{plan}\}_{t=\tau+1}^{T}\right) \in \arg \min_{\substack{x_\tau \\ x_{\tau+1},\dots,x_T}} \left\{ \rho_{\tau,T}[f(x_\tau,\xi_\tau),\dots,f_T(x_T,\xi_T)] \middle| \begin{array}{c} x_\tau \in \mathcal{X}^D(x_{\tau-1},\xi_\tau) \\ x_t \in \mathcal{X}^S(x_{t-1},\xi_t), t = \tau+1,\dots,T \end{array} \right\}$$

Implemented policy is time inconsistent

- $\left\{\left(x_t^{imp}: \Omega \rightarrow \mathbb{R}^n\right)\right\}_{t=1}^{T}$, adapted to $\{\mathcal{F}_t\}_{t=1}^{T}$, obtained for each τ with

$$\left(x_\tau^{imp}, \{x_t^{plan}\}_{t=\tau+1}^{T}\right) \in \arg \min_{\substack{x_\tau \\ x_{\tau+1},\ldots,x_T}} \left\{\rho_{\tau,T}[f(x_\tau,\xi_\tau),\ldots,f_T(x_T,\xi_T)] \middle| \begin{array}{l} x_\tau \in \mathcal{X}^D(x_{\tau-1},\xi_\tau) \\ x_t \in \mathcal{X}^S(x_{t-1},\xi_t), t=\tau+1,\ldots,T \end{array}\right\}$$



The implemented rolling horizon hybrid policy is not optimal either for the simplified multistage model or for the detailed one

Time inconsistency due to simplifications

- Example: Two types of simplification
  - Network constraints (Voltage Kirchhoff law)

$$\mathcal{X}_t^{KVL} = \left\{ (v_t, \ , y_t, \ g_t, \ f_t) \in \mathcal{X}_t^{box} \mid f_t = R\theta_t \right\}.$$

  - Security constraints (n-K security criterion)

$$\mathcal{X}_t^{D}(v_{t-1}, w_{t\omega}) = \Bigg\{ (v_t, \ y_t, \ g_t, \ f_t) \in \mathcal{X}_t^{KVL} \ \Bigg| \ \exists \ (v_t^c, \ y_t^c, \ g_t^c, \ f_t^c) \in \mathcal{X}_{tc}^{KVL} : \\ A^c g_t^c + B^c y_t^c + C^c f_t^c = d_t; \ \forall c \in \mathcal{C} \\ v_t^c + H_t^c y_t^c = v_{t-1} + w_{t\omega} \ \ \forall c \in \mathcal{C} \\ -R^{dn} \le g_t^c - g_t \le R^{up}; \forall c \in \mathcal{C} \Bigg\}.$$

Time inconsistency due to simplifications

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- To measure the impact
  - A. Brigatto, A. Street, D. Valladão, ”Assessing the Cost of Time-Inconsistent Operation Policies in Hydrothermal Power Systems.” IEEE Transactions on Power Systems, 2017.

$$GAP = \frac{1}{M}\sum_{t=1}^{T}\sum_{\omega=1}^{M} c_t^{\top} g_{t,\omega}^{Imp} - \frac{1}{M}\sum_{t=1}^{T}\sum_{\omega=1}^{M} c_t^{\top} g_{t,\omega}^{Plan}$$

  - Final forward simulation of both policies
  - GAP is a measure to rank the impact of simplifications

Simplifications in KVL and n-1 security constraints

- Experiment where reality accounts for KVL and n-1 constraints
- planning stage disregards both

TABLE III
COST COMPARISON: INCONSISTENT VS PLANNING POLICIES (MMR$).

	GAP	Planning policy	Inconsistent policy	Consistent policy
95% CI upper bound	3,890.89	3,407.20	7,165.59	3,675.77
Sample average	3,686.43	3,303.18	6,989.61	3,566.79
95% CI lower bound	3,481.99	3,199.15	6,813.63	3,457.80

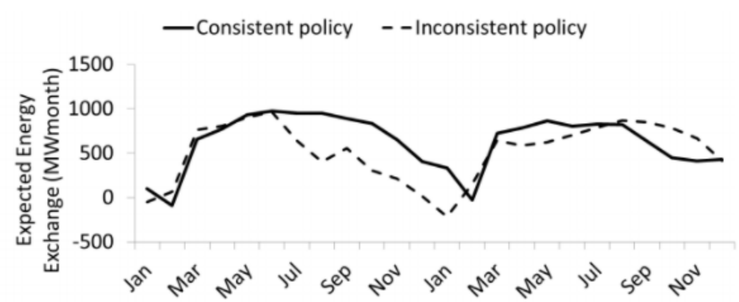
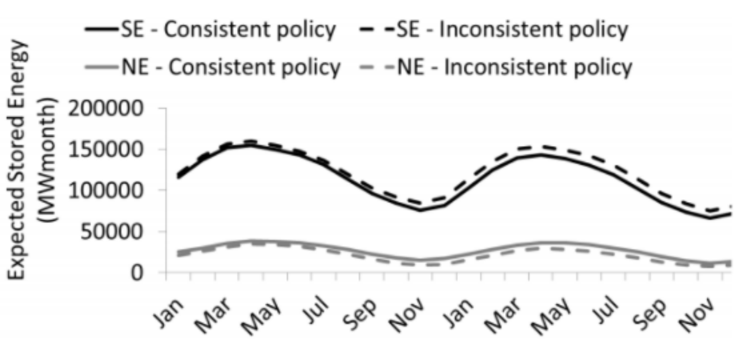


Fig. 9. Exchanged energy from the SE subsystem to the NE subsystem.



. 8. Southeastern and Northeastern stored energy.

Fig. 10. Northeastern spot prices.

Impacts in the Brazilian Power System

Simplifications in KVL and n-1 security constraints

- Experiment where reality accounts for KVL and n-1 constraints
- planning stage disregards both

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COST COMPARISON: INCONSISTENT VS PLANNING POLICIES (MMR$).

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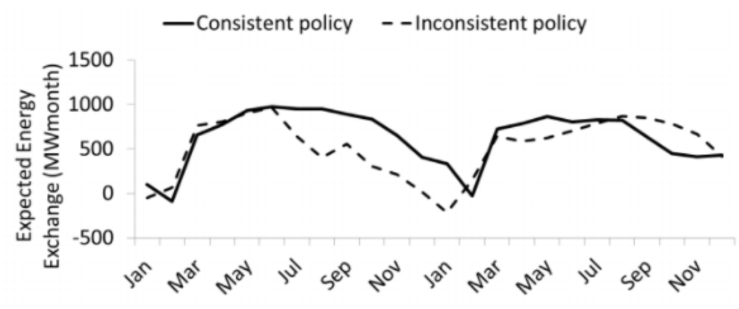

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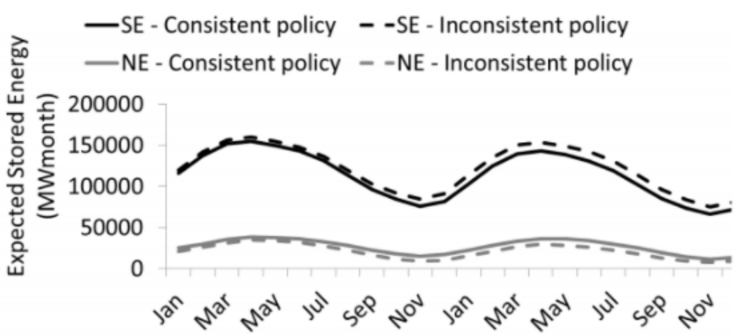

. 8. Southeastern and Northeastern stored energy.

Fig. 10. Northeastern spot prices.

Some final remarks for practical applications

- Claim: In real life, we can try to manage or control time inconsistency, but we cannot avoid it completely

- Real-life decision processes are generally time inconsistent
- The fact that models generally produce time inconsistent policies is not an excuse to do not measure and try control it
  - Because small one-step ahead errors might produce huge cumulative deviations
- The time inconsistency GAP can be a monitoring measure
  - To rank simplifications
  - And to support the decision of enhancing the model

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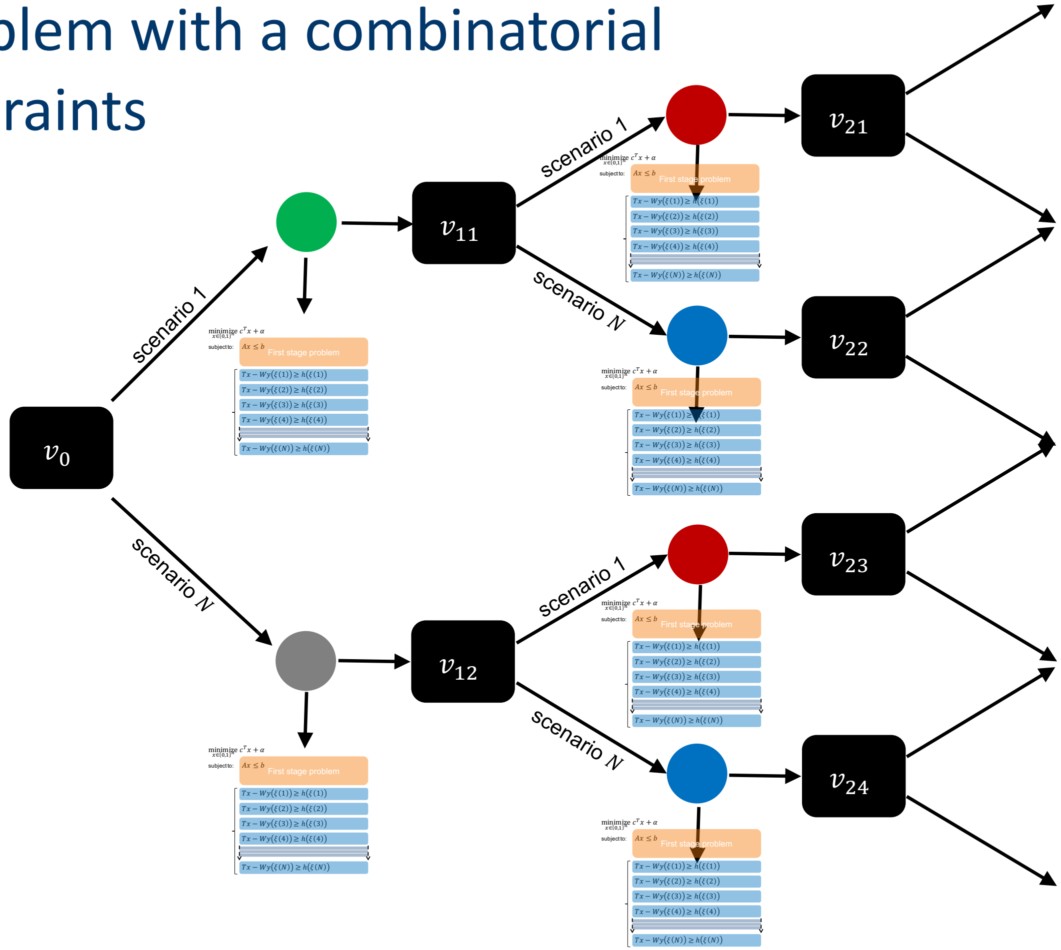
n-K security criterion in SDDP

At each stage in the SDDP we need to solve a problem with a combinatorial set of constraints



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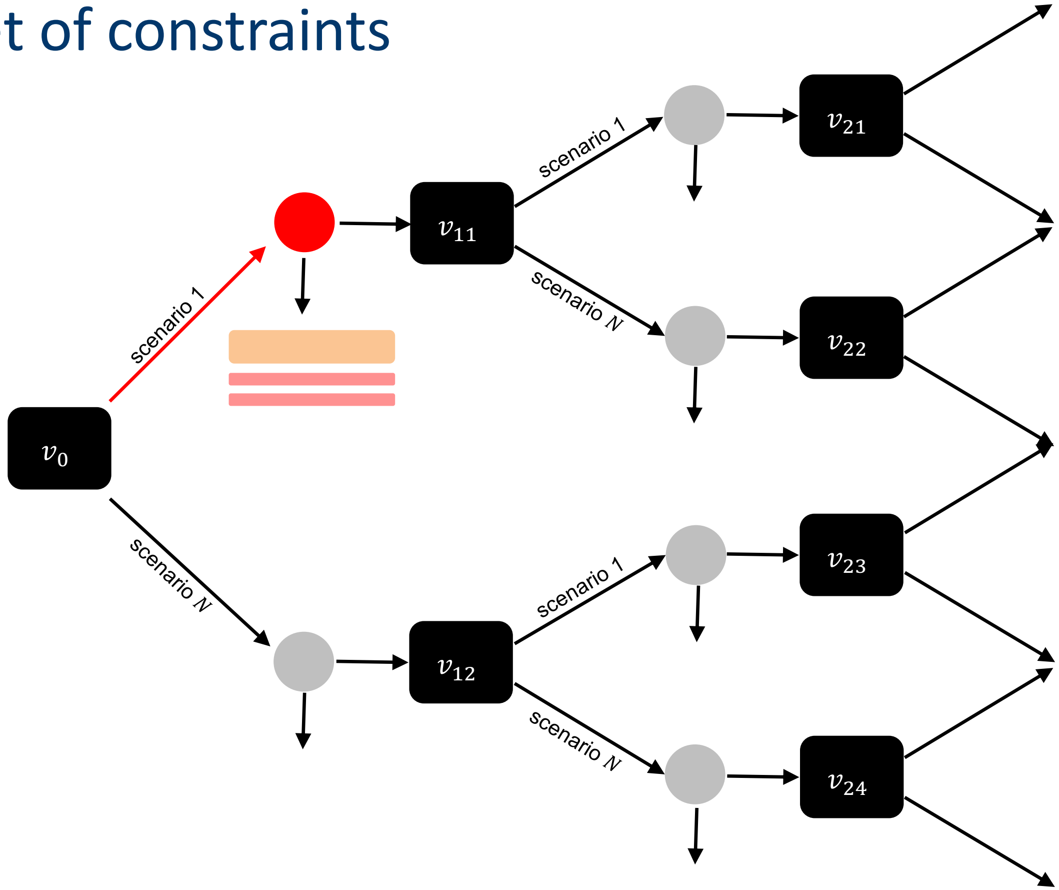
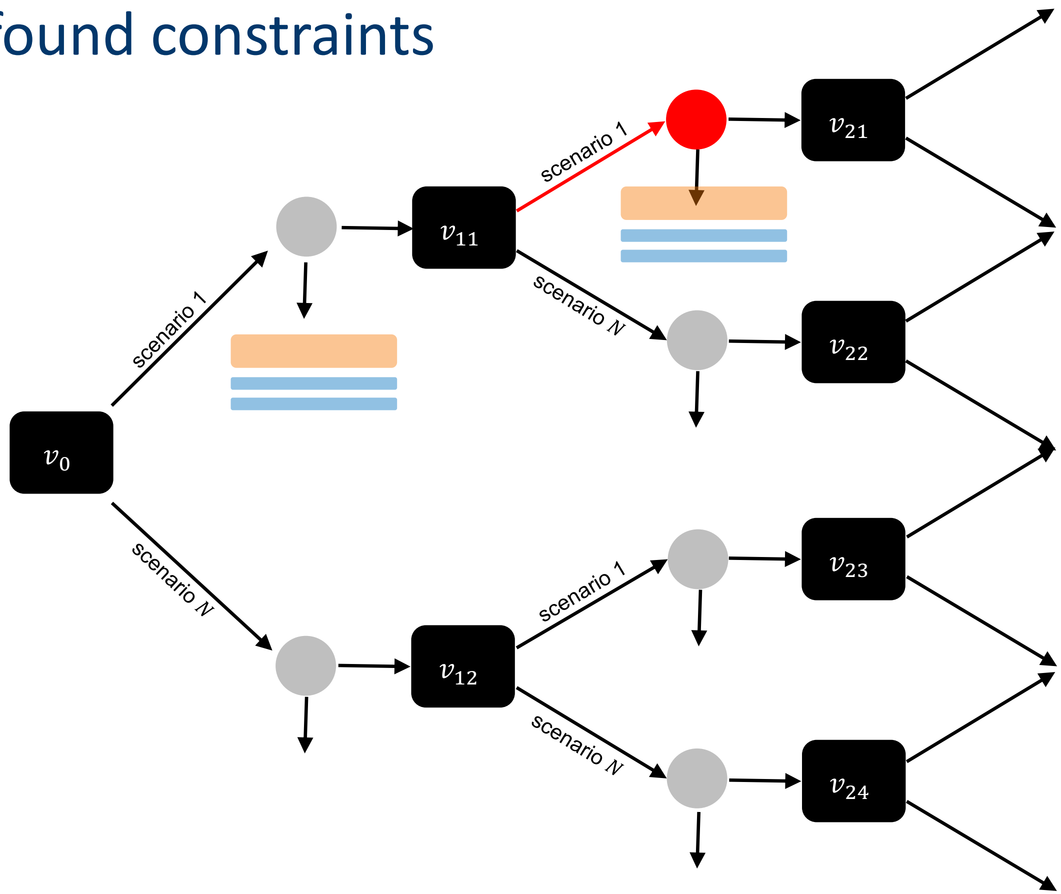
n-K security criterion in SDDP

Solve the first problem and find the umbrella set of constraints



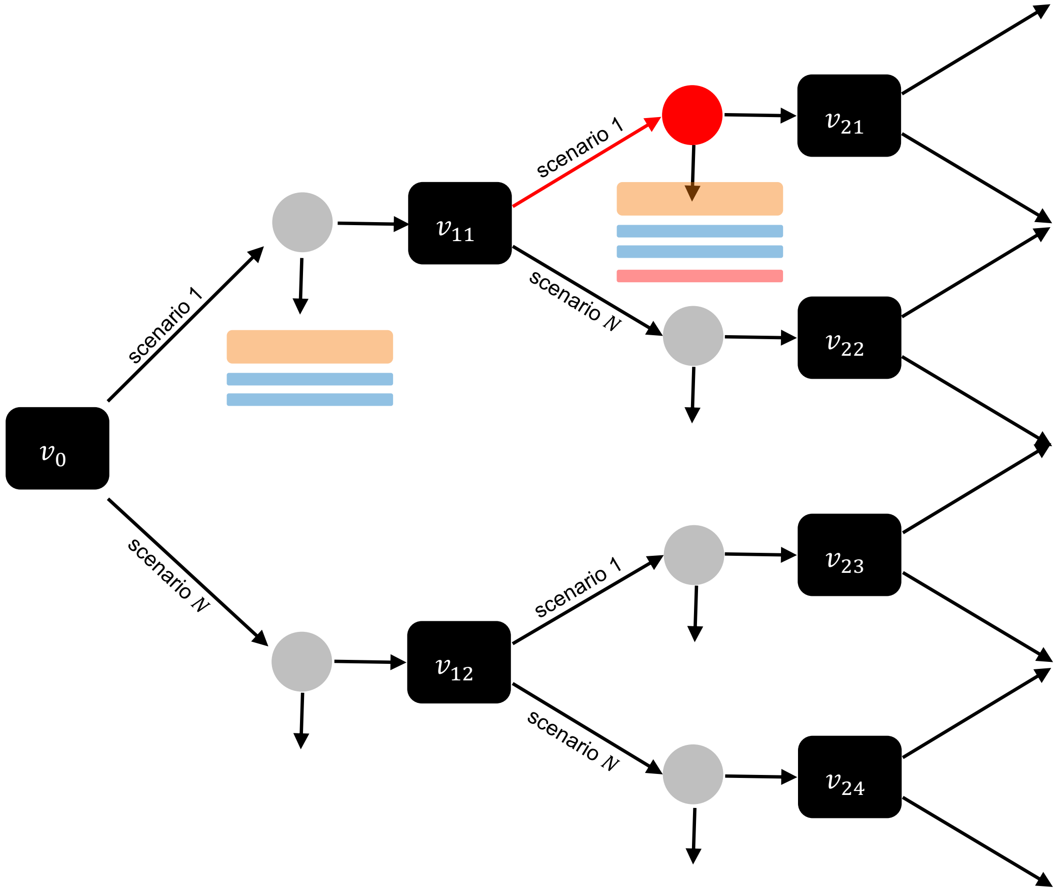
n-K security criterion in SDDP

Second problem is initialized with previously found constraints



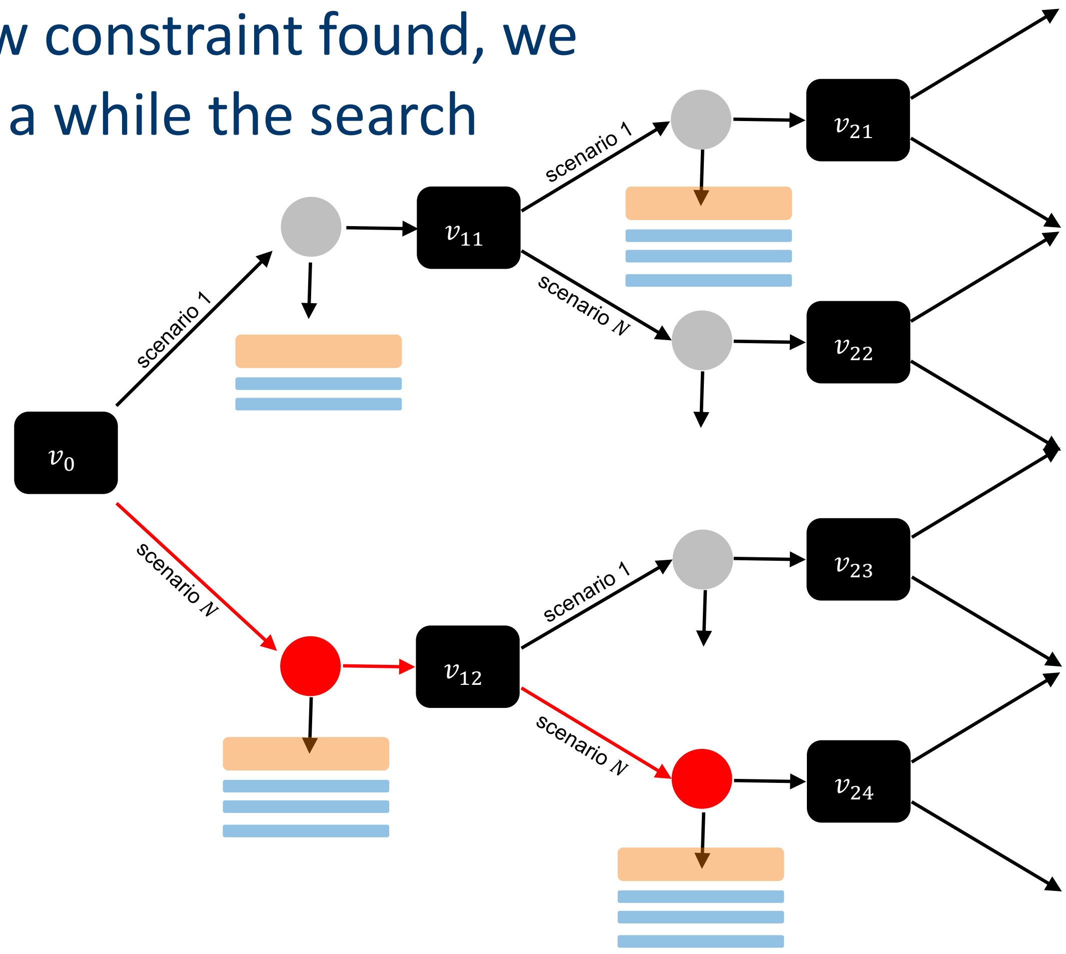
n-K security criterion in SDDP

New violated constraints are added if any



n-K security criterion in SDDP

If a complete forward step finishes with no new constraint found, we turn off for a while the search



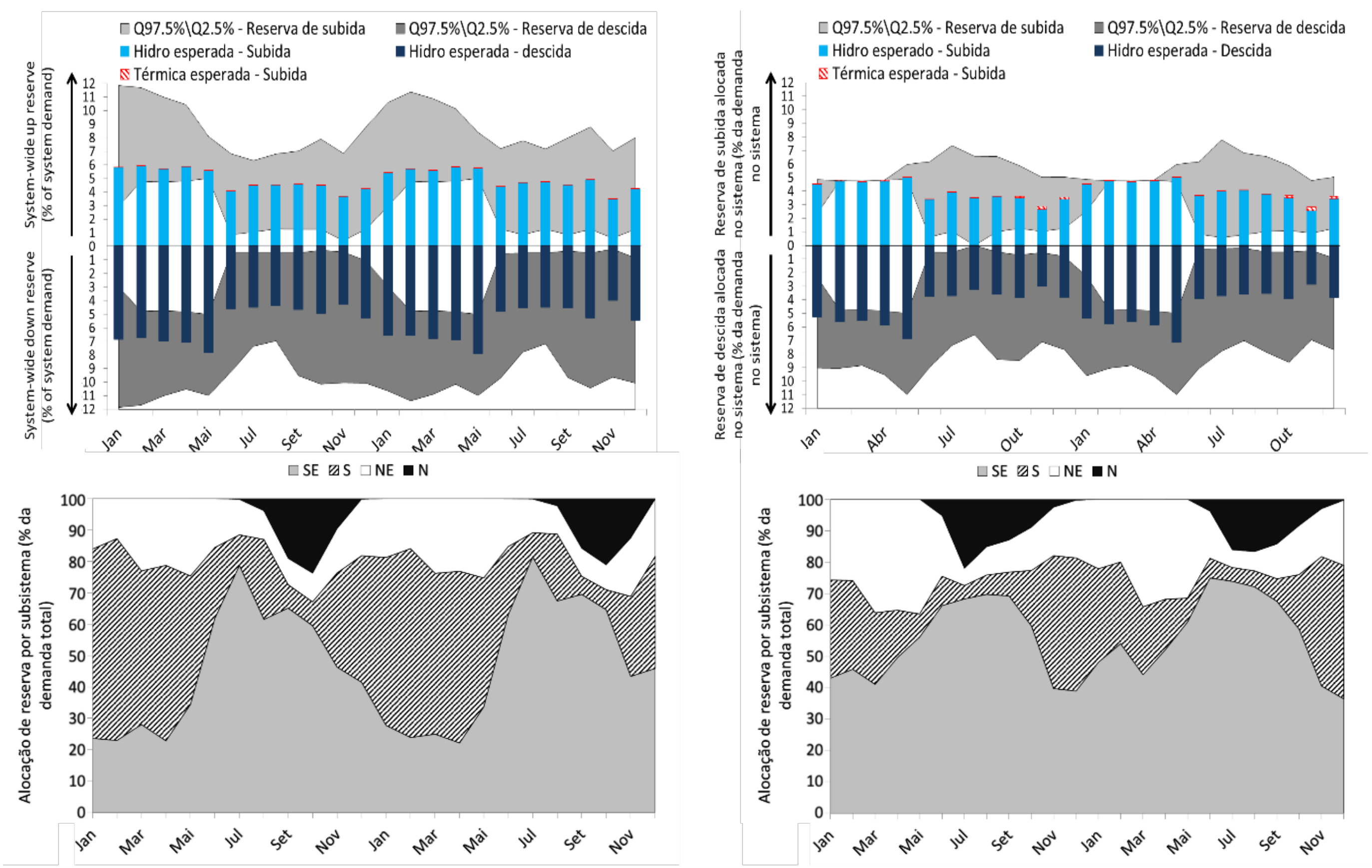
Results for the Brazilian System

Case	Running time (hours) FCD			$\lvert\mathcal{C}^*\rvert$	$\frac{\lvert\mathcal{C}^*\rvert}{\lvert\mathcal{C}\rvert}$
	FCD	CCG_{MILP}	CCG_{INSP}		
$n-0$	6.7	-	-	-	-
n_T-1	22.9	13.8	12.5	3	30.0%
$n_{GT}-1$	#	19.8	19.8	7	6.67%
$n_{GT}-2$	#	27.0	53.6	12	0.22%

Case	Lower bound ($\underline{z}$) (10^6R$)	Operational cost ($\overline{z}$) (10^6R$)			System-wide Up-reserves (% of total demand)			System-wide Down-reserves (% of total demand)		
		CI(95%) LB	Sample average	CI(95%) UB	$Q_{2.5\%}$	Sample average	$Q_{97.5\%}$	$Q_{2.5\%}$	Sample average	$Q_{2.5\%}$
$n-0$	13,483.17	14,889.61	15,165.83	15,442.07	-	-	-	-	-	-
n_T-1	13,729.48	15,570.95	15,850.17	16,129.40	0.82	0.95	1.06	0.82	0.96	1.07
$n_{GT}-1$	13,868.83	15,707.45	15,988.48	16,269.51	0.91	1.18	1.51	0.83	0.97	1.11
$n_{GT}-2$	18,463.96	21,600.69	21,924.60	22,248.52	3.51	4.00	4.44	3.78	4.45	5.17

Results for the Brazilian System

- A new n-K secure hydrothermal policy devised based on the GAP information
  - The reserves level are are now part of the optimal policy



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Laboratory for research and development on mathematical programming (optimization) and statistics to resolve relevant issues for industry and society, in particular for energy and financial sectors. LAMPS comprises professors, researchers and students associated with the Electrical and Industrial Engineering Departments of Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil.

Papers

- STREET, A.; BRIGATTO, A. C. ; VALLADAO, D. ; "Co-optimization of Energy and Ancillary Services for Hydrothermal Operation Planning Under a General Security Criterion." IEEE Transactions on Power Systems, 2017
- BRIGATTO, A. C. ; STREET, A. ; VALLADAO, D. ; "Assessing the Cost of Time-Inconsistent Operation Policies in Hydrothermal Power Systems." IEEE Transactions on Power Systems, 2017
- RUDLOFF, B. ; STREET, A. ; VALLADÃO, D. ; "Time consistency and risk averse dynamic decision models: Definition, interpretation and practical consequences." European Journal of Operational Research (EJOR), 2014.