Stochastic Optimization Model of Fuel Procurement, Transportation and Storage for Coal-Fired Thermal Plants in Hydrothermal Systems

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Abstract: This work presents an optimal strategy of coal procurement for thermal plants, including transportation and storage in order to guarantee continuous supply of the fuel. The stochastic programming model developed takes into account the uncertainty associated with inflows in a hydrothermal system and other complex logistics and commercial aspects related to the international coal market. Different study cases are analysed and the results are presented through comparisons of different strategies applied to different scenarios of dispatch.

1 INTRODUCTION

Three new coal-fired thermal plants are being built in the Brazilian system: Porto do Pecém I and II (720 MW/360 MW) and Porto do Itaqui (360 MW). Projects were contracted in the energy auction of 2007/2008 "by availability", i.e. each project will receive:

(i) a fixed monthly revenue to guarantee the investment returns;
(ii) a variable payment, proportional to the energy production, to reimburse operational costs (fuel, O&M, etc.).

Because the plants were contracted by availability, an important problem is to guarantee continuous supply of coal, since severe penalties are applied if the plant is not able to meet the generation target due to fuel shortages. This problem is complex because time lengths comprising coal purchase and transportation can be up to three months, while the plant dispatch order by the operator can be placed with one day in advance. Although considering the coal storage capacity, the main challenge is forecasting the medium/long term dispatch, which is especially difficult in the case of the Brazilian system, because of its hydro characteristic (high volatility of energy spot prices).

Furthermore, in the international coal market, long-term supply contracts are usually signed with one year duration, pre-established prices and delivery deadlines. This practice is a result of unpredictability of coal prices and coal availability, leading to longer delivery deadlines and long periods of negotiation between parties.

For these reasons, coal procurement strategies must be made under uncertainty, and must be adequate to the storage capacity of thermal plants, uncertainty of dispatch, and characteristics of both coal and freight market. Uncertainties in the forecasts may lead not only to generation outages due to coal unavailability, but also to a surplus of coal, that may be stored, used for inflexible generation, or sold in the international market; situations that can result in additional costs. Figure 1 illustrates the procurement decision process for coal supply with respect to the dispatch uncertainties.

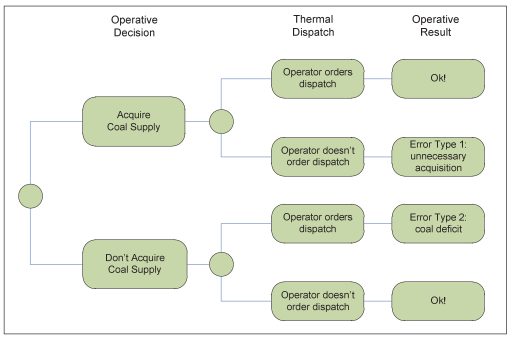

Figure 1: Coal procurement decision under uncertainty.

To summarize, the uncertainties of generation

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dispatch and/or energy spot price (SRMC) can drive decisions to two types of errors: (1) fuel is purchased but the thermal plant is not dispatched; and (2) fuel is not purchased but the thermal plant is dispatched. In this context, it is important to establish a methodology to determine a coal supply strategy for all coal-fired thermal plants. The objective is to minimize costs of procurement decisions under uncertainties, taking into account the costs caused by the corrective actions taken in case of errors (1) (2). The corrective actions to mitigate errors (1) include:

a) Fuel storage for future use – in this case, there is an opportunity cost of the coal purchased in advance;
b) Thermal plant inflexible dispatch – the energy is sold in the spot market with a loss (in this case the spot price is lower that its variable cost, unless it is dispatched by the operator); and
c) Resell the coal vessel in the international coal market.

In the case of errors (2), the possible corrective measures to avoid penalties due to fuel shortage are:

a) Buy energy from a thermal plant not dispatched in the same week, for example, from an oil-fired plant; and
b) Use "energy credits" stored in hydro reservoirs resulted from previous inflexible generation.

An overview of the optimization system for coal supply procurement is presented in the next section.

2 SYSTEM OVERVIEW

Figure 2 shows a schematic representation of the coal procurement optimization system for thermal plants operating in hydro-dominated systems, composed by two blocks:

a) The first block (blue area) illustrates the module responsible for the hydrothermal simulation. The objective is to estimate scenarios of generation dispatch and SRMC. Generation scenarios of coal-fired thermal plants are converted into coal consumption scenarios, which are used by the procurement optimization module.
b) The second block (grey area) illustrates the coal procurement optimization model (MOCCA), which is responsible for evaluating an optimal strategy for supply procurement and coal delivery schedule for thermal plants.

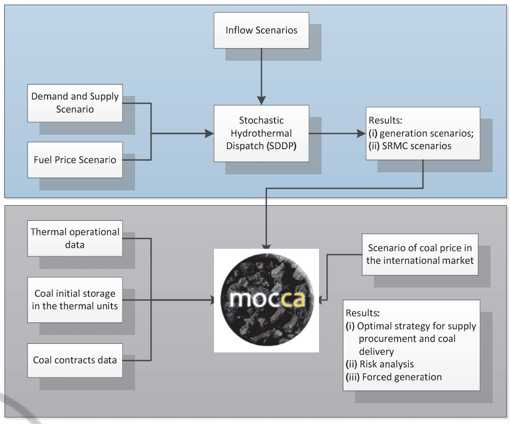

Figure 2: Coal procurement optimization system.

As illustrated, besides thermal plants data (such as heat rate, installed capacity, O&M costs), MOCCA needs information about coal initial storage, cargoes in transit, coal availability (prices, quantities, and delivery conditions), coal price projections (international market), coal consumption scenarios and energy spot prices scenarios.

3 PROBLEM FORMULATION

In this section, the mathematical formulation of the coal procurement optimization model is discussed. The objective function of the model is given by the sum of four shares:

$$Min \frac{1}{|S|} \sum_{t \in T} A + B - C - D \tag{1}$$

Where $|S|$ represents the size of the set S, that represents the set of all hydrothermal dispatch scenarios. T is the number of stages (months or weeks) of the study horizon. The first share $1/|S| \cdot A$ represents the expected payments of coal supply procurement that will be shipped to the thermal plant

$$A = \sum_{k \in K_{t-\Delta}} N_{t-\Delta,k} \cdot \delta_{t-\Delta} \cdot \sum\nolimits_{b \epsilon \mathcal{B}} \sigma_{t-\Delta,k,b} \tag{2}$$

Where $K_{t-\Delta}$ represents the set of dispatch scenarios in stage $t-\Delta$ that share the same procurement decision (procurement cluster), Δ is the required antecedence (in stages) for the supply procurement; $N_{t-\Delta,k}$ represents the number of dispatch scenarios in the procurement cluster k; $\delta_{t-\Delta}$ is the coal supply procurement unitary cost (including transportation cost) and $\sigma_{t-\Delta,k,b}$

represents the amount of the coal procured in stage $t-\Delta$, cluster k, that will be shipped to the thermal plant using the cargo type b.

The second share $1/|S| \cdot B$ represents the expected fines which are imposed on the thermal plant for not meeting the generation target determined by the system operator:

$$B = \sum_{s \in S} \mu \cdot \tilde{r}_{t,s} \quad (3)$$

Where μ is the penalty value and $\tilde{r}_{t,s}$ is the deficit related to the target in stage t and scenario s.

The third share $1/|S| \cdot C$ represents the expected revenue due to the thermal production for meeting the generation target, forced generation and energy exportation:

$$C = \sum_{s \in S} \gamma_t \cdot u_{t,s} + \pi_{t,s} \cdot e_{t,s} + \psi_t \cdot p_{t,s} \quad (4)$$

Where γ_t is the unitary reimbursement of the thermal plant for meeting the generation target $u_{t,s}$ in stage t and scenario s; $\pi_{t,s}$ and $e_{t,s}$ are respectively the energy spot price forecast and the inflexible generation in stage t and scenario s and; ψ_t and $p_{t,s}$ represent, respectively, the energy exportation price and the energy exported amount.

The last share $1/|S| \cdot D$ represents the expected revenues from the procured loading resale which is redirected to the international market:

$$D = \sum_{k \in K_{t-\Delta}} N_{t-\Delta,k} \cdot (\lambda_{t-\Delta} - \delta_{t-\Delta}) \cdot \phi_{t-\Delta} \quad (5)$$

Where λ_t is the forecasted coal resale price in the international market and $\phi_{t-\Delta}$ is the redirected coal amount.

The coal supply procurement optimization process is subjected to a set of physical or logical constraints which are briefly and discussed next.

The first constraint represents the energy supply target set by the system operator, formulated as:

$$u_{t,s} + \tilde{r}_{t,s} = d_{t,s}, \forall t = 1, \dots, T, s = 1, \dots, S \quad (6)$$

It means that the generation target $d_{t,s}$ in stage t and scenario s, is met by the sum of thermal generation $u_{t,s}$ and energy deficit $\tilde{r}_{t,s}$, penalized in the objective function.

The energy production in the thermal plant is limited by its installed capacity, that is:

$$u_{t,s} + e_{t,s} + p_{t,s} \leq \bar{g}, \forall t = 1, \dots, T, s = 1, \dots, S \quad (7)$$

The coal storage of the thermal plant is basically modeled by two constraints:

- Coal storage balance:

$$v_{t+1,s} = v_{t,s} - w_{t,s} + a_{t,s}, \quad \forall t = 1, \dots, T, s = 1, \dots, S \quad (8)$$

- Coal storage capacity

$$v_{t+1,s} \leq \bar{v}, \forall t = 1, \dots, T \quad (9)$$

Where $v_{t,s}$ represents the stored coal in the thermal plant; $w_{t,s}$ is the coal amount used for energy production and $a_{t,s}$ is the coal amount delivered in the storage, all values in stage t and scenario s.

The first of the two storage constraints is the coal balance in each stage, which means, the stored coal at the end of the stage is a function of the stored coal at the beginning of the stage and the net difference between the amount of coal used (to produce energy) and the amount of coal unloaded in the thermal plant during this stage. The second constraint represents the coal storage physical limit in the thermal plant yard.

The next constraint establishes the connection between the amount of coal delivered $a_{t,s}$ in the plant at stage t and scenario s, with the amount of procured coal $\sigma_{t-\Delta}$, with Δ being the required antecedence to request the coal amount.

$$a_{t,s} = \sum_{b \epsilon \mathcal{B}} \sigma_{t-\Delta,k(t-\Delta,s),b}, \quad \forall t = 1, \dots, T, s = 1, \dots, S \quad (10)$$

And the last set of constraints represents the allocation of the procured coal to the ships:

$$\sigma_{t-\Delta,k(t-\Delta,s),b} \leq \mathrm{K}_b \cdot x_{t-\Delta,k(t-\Delta,s),b}, \quad (11)$$

Where K_b is the capacity of cargo type b, and $x_{t-\Delta,k(t-\Delta,s),b}$ is a binary variable that represents that the cargo b is being used to transport the amount of the coal $\sigma_{t-\Delta,k(t-\Delta,s),b}$ in stage $t-\Delta$.

4 TEST CASES

The results of the optimization model for coal supply procurement are illustrated by the following test cases:

a) Case 1: Stochastic case considering 20 scenarios of generation dispatch and spot price, obtained from the studies with the hydrothermal Brazilian system (considering the horizon from May 2011 to Dec 2015). The coal procurement decisions for this case study was represented in a deterministic way, i.e. supply decisions are the same for all 20 scenarios;
b) Case 2: Case 1, but using a decision tree (instead of a deterministic decision) to represent supply procurement decisions.
c) Case 3: Case 2, but considering 200 scenarios (instead of 20 scenarios) of generation dispatch and spot price.

The main objective of the proposed studies is to determine the coal amount to be procured in the long term by the thermal plant. As mentioned before, the long-term contracts have greater execution deadlines (typically one year), but are associated to more attractive prices than the short-term contracts. It should be emphasized that the data used in the test cases of this particular work, associated to thermal plants, coal supply contracts, and others, have been created in order to illustrate the optimization model behavior and may be different from a real case data.

Thermal Plant Data

The model was applied in the procurement strategy optimization of the Porto do Itaqui thermal plant, located in the Northern region of the Brazilian system, assuming the following basic data:

- Installed capacity: 360 MW;
- Efficiency (coal consumption): 4.84×10^{-7} MWh/kcal (or 2 066 kcal/kWh);
- Coal storage capacity: 210 000 tons (equivalent to approximately 70 days of the thermal plant nominal power operation);
- O&M cost: 7.5 US$/MWh;
- Losses and self-consumption are neglected;
- Operational cost: 61.2 US$/MWh.

Scenarios

For the coal resale price scenario, a constant value of 105 US$/ton (FOB-Colombia, i.e. no shipping cost is considered for the buying market) was adopted.

In order to represent thermal dispatch and spot price scenarios, the results obtained from the studies with the hydrothermal Brazilian system (May 2011) using the SDDP dispatch model (PSR, 2011a, PSR, 2011b) were used.

Candidate Contracts Data

In each one of the test cases, 30 candidate contracts were considered, where 8 of them are long-term contracts and the rest are short-term contracts.

Parameters associated to the long-term contracts:

- Availability: 500 000 tons;
- Procurement cost (FOB): 110 US$/ton;
- Shipping cost: 20 US$/ton (Handymax ships);
- Antecedence in procurement decision: up to 1 year;
- Time interval for boarding the procured amount: 3 months (travel time of 1 month).

The following figure illustrates the eight long-term contracts, emphasizing the intervals that define their procurement decision and shipping:

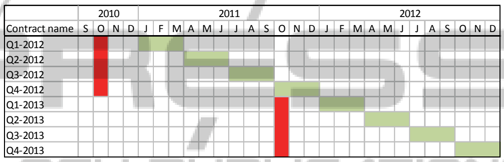

Figure 3: Long-term contract data.

The green blocks illustrate, for each candidate contract, the period in which the procured coal can be shipped from the origin port (in Colombia), being the loading available for the thermal plants one month after boarding (expedition time).

The red blocks illustrate the procurement decision date of each contract. Note that all long-term contracts for a specific year should be decided up to October of the previous year.

Parameters associated to the short-term contracts:

- Availability: 500 000 tons;
- Procurement cost (FOB): 115 US$/ton;
- Shipping cost: 20 US$/ton (Handymax ships);
- Antecedence in procurement decision: 3 months:
- Time interval for boarding the procured amount: 4 months (travel time of 1 month).

In the same way as the long-term contracts, Figure 4 illustrates the required antecedence for a short-term contract. Note that, in this case, the antecedence is of four months, because loading acceptance must be informed one month in advance regarding long-term contracts (due to an additional period of negotiation).

Also, short-term contracts don't require the procurement decision to be taken too long in advance (October of the previous year), which makes them more attractive from the point of view of the uncertainties of generation dispatch and spot prices. However, the coal supply procurement cost is around 5% greater than the long-term contracts.

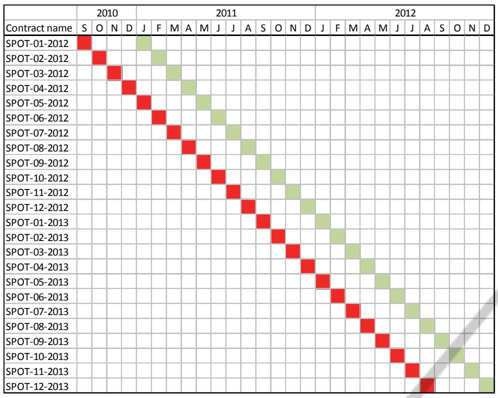

Figure 4: Short-term contract data.

General Data
The following execution options were considered:

- Stage type: monthly
- Horizon: 09/2011 – 12/2012 (+ 1 Year)
- Annual discount factor: 12 %
- Maximum number of ships unloading coal by stage (one month): 3 ships
- Penalty for not meeting generation target: 382 US$/MWh.

4.1 Case 1: Deterministic Decision

In this case, there has been used a subset of 20 dispatch and spot price scenarios extracted from the original dispatch case (PMO from May 2011). The next figure illustrates the variability of generation dispatch of the thermal plant Porto do Itaqui.

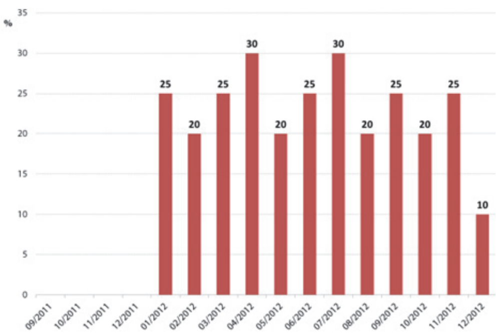

Figure 5: Probability of dispatch of Porto to Itaqui.

From the figure above, one can see that the average dispatch probability for the first year for the thermal plant is around 20%. However, it is interesting to see that in the operating month, (Jan-2012 – 25% probability) the dispatch scenarios labeled 2-10-14-16-20 (from the sample of 20 scenarios) are the ones with non-null generation; and in Jun-2012 the scenarios are 7-12-13-16-19; that means, although there is a reasonable probability that the thermal plant will be used in any month of 2012, the probability of continual generation for several months is much lower. This level of uncertainty in the dispatch scenarios is typical in the Brazilian system, because the high dependence of reservoir inflow conditions.

In order to represent the variability of the SRMC of the Brazilian system, the next figure shows the range for the SRMC of the same sample of 20 scenarios used for generation dispatch.

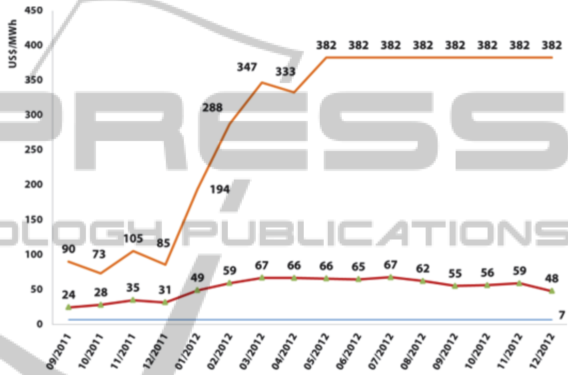

Figure 6: Variability of SRMC.

As one can see, average values for SRMC (illustrated in red) are closer to the minimum values (in blue) than to maximum values (in orange), indicating that the number of low-SRMC scenarios is greater than the number of high-spot price scenarios. This high volatility of SRMC is also a characteristic of the Brazilian system.

The purpose of this first test case is to determine a coal supply procurement decision which is valid for all 20 dispatch and spot price scenarios, in other words, to seek for a single procurement sequence that optimizes the coal trade results for the thermal plant. Just for complementary information, the optimization model for this problem contains 138 600 constraints and 24 065 decision variables, where 4 400 of them are binary variables.

The results in terms of the delivery schedule in the thermal plant and the contracts acceptance are illustrated in the following figures:

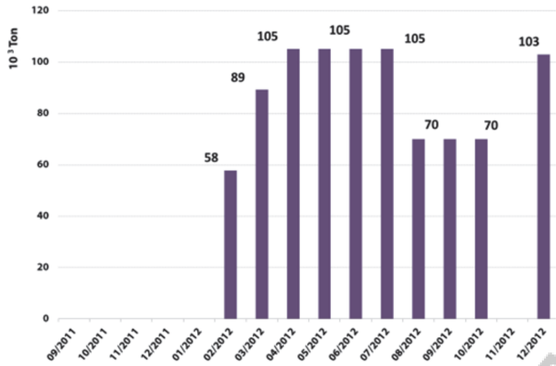

Figure 7: Deliveries in Porto do Itaqui (case 1).

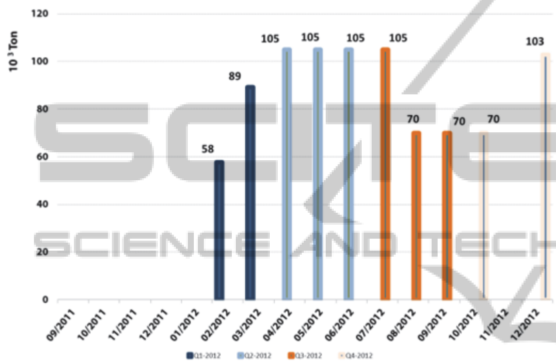

Figure 8: Acceptances of candidate contracts (case 1).

The figures above show that the optimal solution indicates the coal procurement through long-term contracts only (more economic). The solution is coherent to the fact that it is not possible to adjust the procurement decision according to the dispatch and spot price uncertainties.

The first loading acceptance, approximately 60 thousand tons (Q1-2012), occurs on Feb-2012, and the associated coal amount is available to be used by the thermal plant on Mar-2012 (expedition time). In summary, the result of the supply procurement optimization model indicates the procurement of approximately 900 thousand tons in long-term contracts over a price of almost 100 million dollars. It is important to emphasize that this procurement policy is based on negotiating all coal amount at the beginning of the study horizon – because long-term contracts must be decided up to October of the previous year of the delivery date.

As a result of this procurement policy, the coal average stored volume is shown in red in the following figure containing the stored coal for all 20 scenarios considered.

It is important to highlight that average volume illustrated above is not an indication of the optimal coal storage level of the thermal plant.

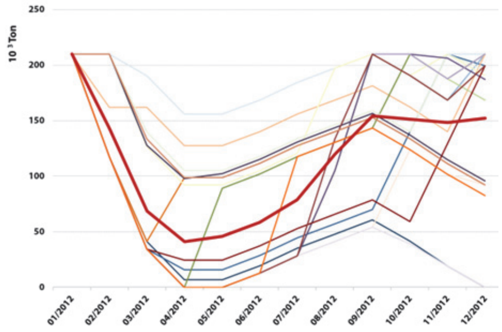

Figure 9: Scenarios of storage in Porto do Itaqui (case 1).

The financial result for the coal trade is illustrated in the following table:

Table 1: Financial result for the coal trade (case 1).

Stage	Cargos acceptance	Freight	O&M costs	Penalty	Energy reemb.	Coal resell	Total	Net value
01/2012	0	0	-2	0	9	0	7	6.5
02/2012	-6	-1	-2	0	8	0	-2	-1.6
03/2012	-10	-2	-2	0	11	0	-3	-3.1
04/2012	-12	-2	-2	0	10	0	-6	-5.3
05/2012	-12	-2	-2	0	11	0	-5	-4.3
06/2012	-12	-2	-2	0	9	0	-6	-5.4
07/2012	-12	-2	-2	0	10	0	-5	-4.6
08/2012	-8	-1	-2	0	9	0	-1	-1.3
09/2012	-8	-1	-2	0	9	0	-2	-2.0
10/2012	-8	-1	-2	0	8	0	-2	-2.0
11/2012	0	0	-2	0	9	0	6	5.3
12/2012	-11	-2	-1	0	6	0	-7	-6.4

As one can see in the previous table (column "Penalty"), no fuel shortages were estimated for meeting the generation target dispatch scenarios, as a result of the procurement model. Another observation can be made about the coal resale on the international market, which hasn't been economically attractive (column "Resale" of the table). A low resale level against a high forced generation level is explained by the difference between the resale price and the forced generation refund value given by the spot prices.

The result of the coal trading operations, as can be seen, is negative in US$ 24 million dollars, which was already expected since the single procurement for all generation and spot price scenarios implies in significant losses due to the coal acquisition needed for scenarios with thermal generation and also due to the coal inefficient usage in forced generation for scenarios without thermal generation, which may be required because of storage limitations.

4.2 Case 2: Decision Tree for Coal Supply Procurement

The objective of this case is to determine a procurement policy (not deterministic), which means that the procurement decisions can be adjusted according to the dispatch and spot prices scenario uncertainties. In order to accomplish that, the procurement policy has been modeled by a binary decision tree, with openings in stages 2 (Oct-2010) and 8 (Apr-2012), as illustrated in the next figure:

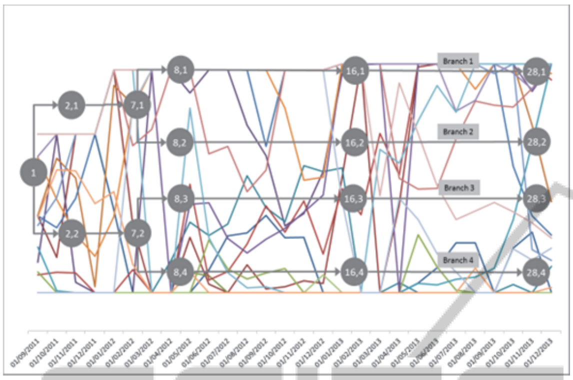

Figure 10: Decision tree – coal procurement policy.

To determine the dispatch/spot price scenarios allocation in coal procurement decision clusters a standard k-means clustering algorithm was used (Hartigan and Wong, 1979), where the clusterization criteria used to determine which generation dispatch/spot price scenarios share the same procurement decision, was the minimum value between the spot prices, which varies by scenario, and the thermal unitary cost.

One of the consequences of representing the supply procurement by a decision tree is that the optimization model dimensionality grows with respect to the problem variables. In this case, the optimization model has 142 800 constraints and 54 100 variables, where 5 640 of them are binary.

The results in terms of the average procured amount are illustrated in the next figure:

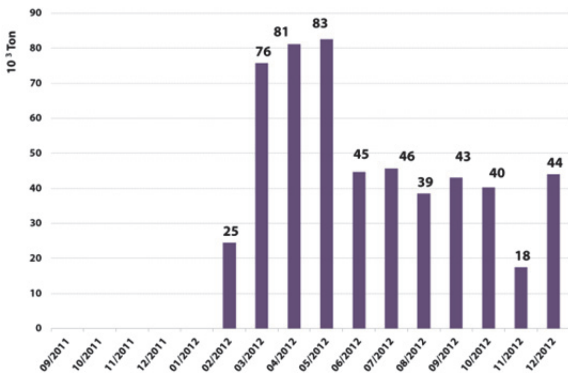

Figure 11: Deliveries in Porto do Itaqui (case 2).

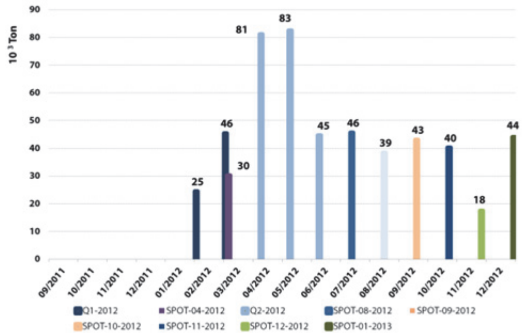

Figure 12: Acceptances of candidate contracts (case 2).

The first important result to be highlighted is that the procurement representation by a decision tree encourages the short-term procurement. As it can be seen in the figure, the coal supply procurement solution is a combination of both long- and short-term contracts. Moreover, the total acquisition (calculated by the average of the branches of the procurement decision tree) is approximately half of the amount indicated in the previous case, that is, 537 thousand tons. However, it should be clear that this value is the average of the 4 branches of the tree, which means that for clusters associated to the series with high generation level, the procurement is greater and, otherwise, it should be lower. The total procurement for each branch of the decision tree is shown in the following table:

Table 2: Total procurement coal for each branch.

Branch	Tons
1	229 256
2	868 926
3	328 513
4	897 975

It is also observed that approximately half of the average amount of procured coal (278 thousand tons) is associated to long-term contracts, which must be negotiated one year in advance. Therefore, the total amount that should be immobilized in long-term contracts is around 32 million dollars (almost 70% less than the amount estimated in the previous case). The additional amount of coal supply is associated to the short-term contracts, which are only negotiated in the future, when there is more information about the thermal dispatch conditions.

The implementation of the supply procurement policy leads to a distribution of the stored coal variable illustrated in the next figure:

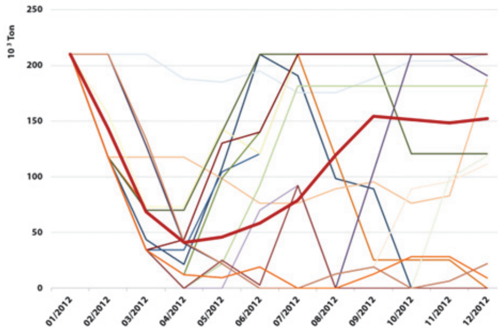

Figure 13: Scenarios of storage in Porto do Itaqui.

The financial result for the coal trading operations is illustrated in the following table:

Table 3: Financial result for the coal trade (case 2).

Stage	Cargos acceptance	Freight	O&M costs	Penalty	Energy reemb.	Coal resell	Total	Net value
01/2012	0	0	-2	0	8	0	6	6.1
02/2012	-3	0	-2	0	8	0	3	2.6
03/2012	-8	-2	-1	0	9	0	-2	-1.9
04/2012	-9	-2	-1	0	9	0	-3	-2.4
05/2012	-9	-2	-2	0	10	0	-2	-2.0
06/2012	-11	-1	-1	0	9	6	1	1.2
07/2012	-5	-1	-2	0	10	0	2	1.7
08/2012	-4	-1	-1	0	8	0	2	1.7
09/2012	-5	-1	-1	0	7	0	0	0.3
10/2012	-5	-1	-1	0	7	0	1	0.8
11/2012	-2	0	-1	0	7	0	4	3.1
12/2012	-5	-1	-1	0	5	0	-1	-1.0

From this table, it is interesting to highlight that no outages in the generation target due to fuel shortages were reported – according to column "Penalty" of the table. Another interesting result that can be seen in the column "Coal resell", is that coal was redirected for resale in the international market in June 2012, while no resale was observed in the previous case. This behavior is also explained by the procurement strategy formulated as a decision tree, since the resale price was more attractive than forced generation refunding for the scenarios that share the cluster where resale occurred.

Finally, the financial result of the trading operations, when using a procurement strategy represented by a decision tree, is positive in almost 10 million dollars.

4.3 Case 3: Stochastic Case Considering All 200 Dispatch/SRMC Scenarios

The purpose of this test case is to show the results of the supply procurement model considering the complete set of generation dispatch and spot price scenarios, obtained from the simulations of the operation scheduling case study.

A straightforward consequence of increasing the number of scenarios is the dimension growth of the procurement optimization model which happens to be formulated by a programming problem of 1.4 million constraints and 260 thousand variables, where 45 thousand of them are binary. This increase in the number of variables and constraints are also the result of the binary decision tree adopted for this problem, which has more openings (branches) compared to those used in the previous case – the new decision tree is composed by 16 branches with openings in stages 2 (Oct-2011), 5 (Jan-2012), 8 (Apr-2012) and 11 (Jul-2012). For the series allocation in the decision clusters, the same k-means clustering algorithm of the previous case has been used.

The results for the coal deliveries (average values) are illustrated in the following figures:

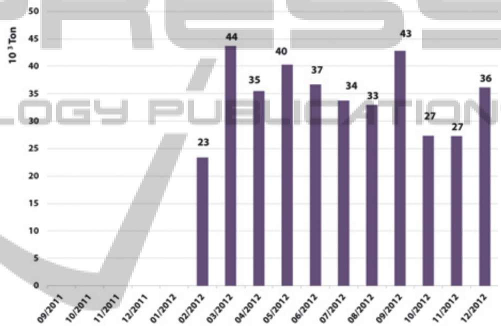

Figure 14: Delivers in Porto do Itaqui (case 3).

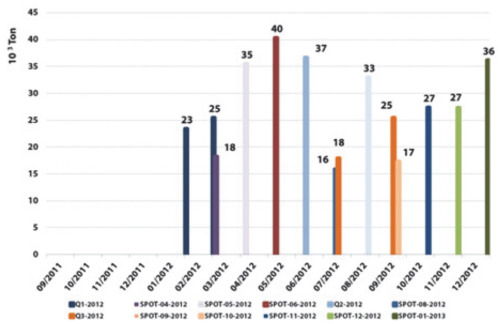

Figure 15: Acceptances of candidate contracts (case 3).

From the above figures, it can be seen that the average level of coal supply procurement is lower (379 thousand tons) than in the case 2, where a subset of 20 generation dispatch/spot price scenarios were used. But, as in the case of 20 scenarios, there is an encouragement for short-term acquisitions (66% of the total procured amount, that means, 250 thousand tons come from this type of contract), since this type of contract allows greater flexibility and, consequently, fits better the uncertainties of thermal plant dispatch. Regarding long-term contracts, in the first year there was a procured amount of 129 thousand tons (33% of the total amount), which requires an investment of approximately 14 million dollars.

The next figure illustrates the result of the procurement model for the variable “stored coal in the thermal plant” (red curve shows the average value for the 200 scenarios).

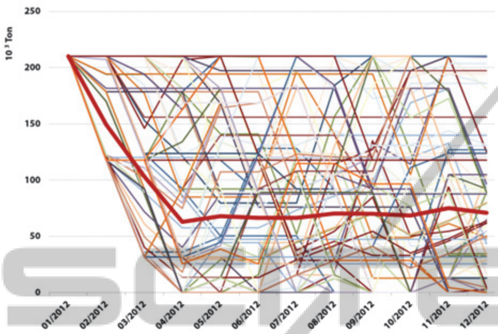

Figure 16: Scenarios of storage in Porto do Itaqui.

Once again a low average level is observed for the coal stored amount, nevertheless, the average level is not an indication for the optimal level since it varies accordingly to each one of the generation dispatch/spot price scenarios associated to coal supply procurement decision tree of the thermal plant.

The financial result for the coal trading operation is illustrated in the following table:

Table 4: Financial result for the coal trade (case 3).

Stage	Cargos acceptance	Freight	O&M costs	Penalty	Energy reemb.	Coal resell	Total	Net value
01/2012	0	0	-2	-1	8	0	6	5.8
02/2012	-3	-1	-1	0	7	0	2	2.1
03/2012	-11	-2	-2	0	7	6	-2	-1.7
04/2012	-4	-1	-1	0	7	0	1	0.5
05/2012	-5	-1	-1	0	8	0	1	0.8
06/2012	-12	-1	-1	0	8	7	1	1.1
07/2012	-4	-1	-1	0	7	0	1	0.9
08/2012	-5	-1	-1	0	7	2	1	1.2
09/2012	-10	-1	-1	0	7	5	0	-0.3
10/2012	-3	-1	-1	0	7	0	2	2.2
11/2012	-3	-1	-1	0	7	0	2	1.6
12/2012	-4	-1	-1	0	5	0	-1	-0.6

Regarding the table results, the case with 200 dispatch scenarios presents some supply outages on the generation target (column “Penalty”). It is also noted a higher level of coal resale on the international market, this behavior was already expected in both because of the increase in the number of dispatch scenarios as well as because of the number of branches in the decision tree, which leads to a greater number of clusters in which the forced generation refund at energy spot price is less than coal redirection price to the international market. As for the final result, a positive value of almost 14 million dollars is observed for the coal trading operation.

5 CONCLUSIONS

This paper presents an optimization model for coal supply procurement strategy of coal-fired thermal plants operating in the Brazilian system, which is hydro dominated and characterized to have a high volatility of its energy spot prices.

The results of three test cases for the coal procurement model were presented and discussed. These results showed the efficiency of the model, especially when coal procurement strategy is represented by a decision tree, which allows a better adjustment of the coal procurement decisions to the uncertainties of generation dispatch and energy spot prices (variables that present a high volatility in the Brazilian system because of its hydro dominancy).

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