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ECONOMIC IMPLICATIONS WHEN CONSIDERING AVAILABILITY IN THE OPTIMAL DESIGN AND OPERATION OF A NGCC POWER PLANT

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ABSTRACT - Traditionally, power plants are designed to fulfill a pre-specified external demand, usually by oversizing the existing equipment, which implies excessive capital costs and might even result in designs that cannot satisfy demands for certain situations. Therefore, in order to avoid large economic penalties if power demand is not satisfied, the design and operation of such systems need to consider the effect of reliability considerations and maintenance funds allocation on the system design and operative characteristics.

In the present work, a MINLP formulation is developed to address the design and operation of power plants while considering the implications of a state-space availability modeling approach and of a comprehensive maintenance funds allocation policy. Then, the decision variables are optimized simultaneously throughout several maintenance and failure situations that configure different scenarios, in order to ensure that the plant will be able to cope with them while meeting the expected requirements at minimum cost.

1. INTRODUCTION

An equations-oriented approach is here used to build a rigorous and flexible mathematical model which accounts for every functional status of the generation plant, as implications of a state-space availability modeling approach over the economic optima of a natural gas combined cycle power plant are discussed.

The probability of the system being at each functional status is evaluated through the state-space method (i.e. by means of a Markov-type approach); while the optimized probabilities are used for computing operability indices, as well as (weighted) technical and economical performance indicators.

In previous works, Aguilar et al. (2008) incorporated reliability and availability into the design and operation of flexible utility plants; and observed two different tradeoffs: capital investment versus contractual penalties for not fulfilling the power demand, and capital investment versus costs originated by different failure scenarios. Moreover, Frangopoulos and Dimopoulos (2004) introduced reliability aspects in the thermoeconomic model of a cogeneration system by means of the state-space method, so that redundancy is embedded in the optimal solution; thus obtaining more realistic values of the system profit.

Considering these findings, optimal values of the decision variables are here obtained and analyzed for every feasible funcional status, thus determining the ability of the system

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to achieve the generation goals. The rigorous availability accounting here pursued allows attaining more realistic computations of the project economic performance indicators, including (among others) the cost of electricity, total annual cost, and energy sales.

Traditional project evaluation techniques (as described for example at Biezma and Cristóbal (2006)) are usually used to obtained first-cut designs of generation systems. Nevertheless, a traditional approach does not consider neither the different scenarios that the plant will likely face across the time horizon, nor the effects of maintenance funds allocation on the generator overall economics (since maintenance cost is estimated as a fixed percentage of the capital investment). Thus, realistic designs can only be identified through subsequent refinements accomplished by benefits maximization or costs minimization.

Therefore, the state-space availability enhanced designs here optimized are compared against a natural gas combined cycle power plant obtained through a traditional approach. This discussion allows highlighting the improvements that can be attained by taking advantage of the here proposed design strategy.

2. PROCESS MODELING AND OPTIMIZATION

A natural gas combined cycle power plant is here designed and operated for fulfilling an external demand of 800 MW. This power plant consists of two gas turbines with postcombustion and regeneration, its associated three pressure level HRSGs, and a steam turbine with high, intermediate and low pressure stages (for further details, see Godoy et al. (2011; 2010)). This configuration includes innovative features which enable to obtain high efficiencies (gas to gas recuperation and postcombustion, high gas turbine inlet temperature, multiple pressure levels and parallel heat exchange sections in the HRSG). A schematic flowsheet is presented at Figure 1.

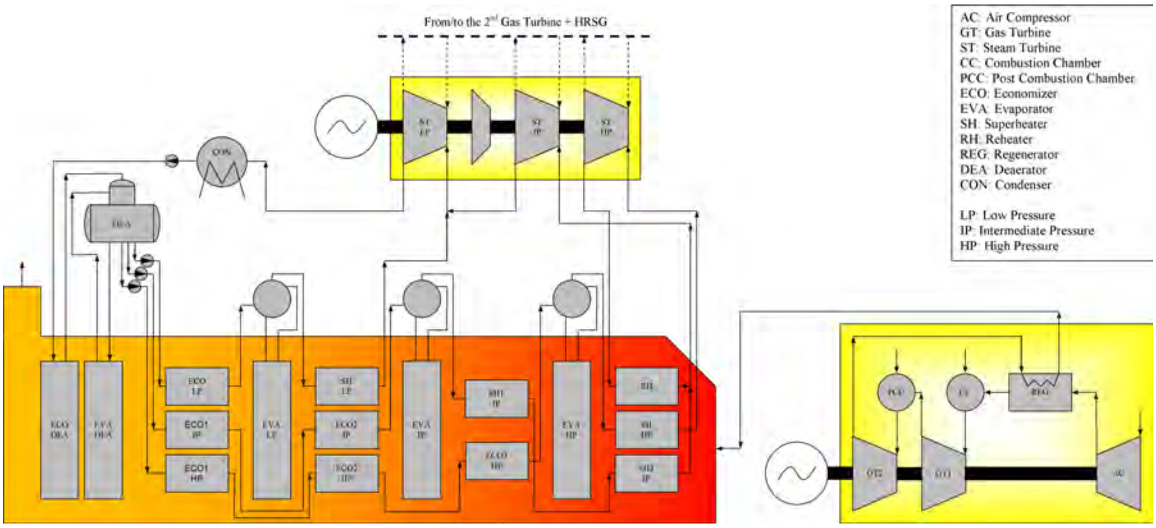

Figure 1 – NGCC Power Plant used as Case Study

The power plant model validation was previously discussed by the authors at Godoy et al. (2011; 2010), where the obtained optimal solutions were found to be in accordance with data reported at technical reports and scientific literature.

The mathematical program is implemented in the optimization software GAMS (Rosenthal, 2008) and solved by means of the reduced gradient algorithm CONOPT (Drud, 1996).

2.1. Mathematical Optimization Formulation

When taking availability into account, the mathematical statement of the economic optimization problem becomes given by Equation 1 through Equation 4.

$$\min TAC = \min\left(\frac{CAPEX}{CRF} + OPEX\right) \tag{1}$$

$$\underline{h}\left(\underline{x}, \underline{y}, A_S\right) = 0 \tag{2}$$

$$\underline{g}\left(\underline{x}, \underline{y}, A_S\right) \leq 0 \tag{3}$$

$$A_S \geq A_{S,min} \tag{4}$$

The following items are taken into account:

- The total annual cost TAC is selected as economic objective function
- The capital expenditures $CAPEX$ include acquisition cost of equipment (as a function of size and constructive characteristics), design and construction of facilities and auxiliary services, working investment, startup cost, etc. The capital recovery factor CRF is associated to the interest rate desired by the investors.
- The operative expenditures $OPEX$ include raw materials and utilities, man power, maintenance funds, taxes, operative supplies, administrative costs, etc. In order to consider the effects of availability and maintenance in the plant economics, costs are affected by the system inherent availability (as previously indicated by Goel et al. (2002)).
- The equality constraints $\underline{h}$ include standard correlations for prediction of thermodynamic properties, mass and energy balances, design equations for each piece of process equipment, and calculation of overall technical and economic performance indicators (thermal efficiency, cost of electricity, etc.). The inequality constraints $\underline{g}$ includes technical constraints in order to circumscribe a feasible operative region according to the industrial practice.
- The set $\underline{x}$ includes the operative variables (temperatures, pressures, flow rates, etc.) which are directly linked to the operative expenditures calculation; and the design variables (transfer areas, turbines sizes, etc.) that are utilized for computing the acquisition cost of process equipment.

- The set $\underline{y}$ includes the binary variables used for availability accounting. A_S stands for the overall power plant availability; while a required minimum value $A_{S,min}$ on the annualized availability level is imposed.
- Input data used in the economic model are taken from general and technical literature (for example, CAMMESA (2011) and Bernier et al. (2010)); up-to-date electricity prices and fuel costs are obtained from U.S. Department of Energy (2011); utilities costs are estimated using correlations introduced at Ulrich and Vasudevan (2006); equipment capital costs are computed considering the formulae and unitary costs reported at Kotowicz and Bartela (2010) and Bernier et al. (2010).

Maintenance funds C_{Mant} are computed as function of the capital investment IFC, and are here allocated as necessary according to Equation 5; while minimum and maximum bounds ($F_{Mant,Min}$ and $F_{Mant,Max}$, respectively) on the allocated funds are set according to the available resources, as stated at Equation 6.

$$C_{Mant} = F_{Mant}\ IFC \tag{5}$$

$$F_{Mant,Min} \leq F_{Mant} \leq F_{Mant,Max} \tag{6}$$

Haghifam and Manbachi (2011) concluded that improving repair rates have a direct relation with the annual budget assigned to maintenance. Erguina (2004) considered that allocation of funds for preventive maintenance actions has an asymptotic effect on the system reliability, as beyond a given point, no significant performance improvement will be achieved even though additional resources are assigned to such effort.

Following these guidelines, it is here assumed that an exponential relationship exists between the overall availability and the assigned maintenance funds, as presented at Equation 7.

$$A_S = 8760\ \gamma_1\ \left(1 - e^{\gamma_2\ C_{Mant}}\right) \tag{7}$$

Parameters γ_1 and γ_2 to be used at Equation 7 can be computed from industry historic data on assigned maintenance funds versus achieved annualized operative times (or annual availability values).

2.2. Availability Model

A reliability block diagram for the power plant is presented in Figure 2. The logically arranged subsystems ASS, also referred as components, that form the system are listed at Equation 8. The total number of components N_{ASS} reaches 7.

$$ASS = \{AuxGT, GT1, GT2, AuxST, ST, HRSG1, HRSG2\} \tag{8}$$

The probability of incidence of functional modes FM^f with 2 or more simultaneous and independent non-operative components is very low or negligible, and can therefore be discarded while still obtaining a good inference on a practical solution. Then, the

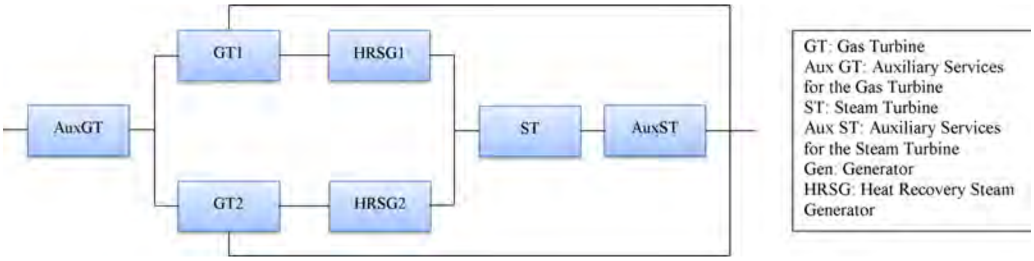

Figure 2 – Reliability Block Diagram for the Case Study

number of functional modes N_{FM^f} becomes given by Equation 9 (when the number of simultaneously and independently failed components N_{SIFC} is set at 1).

$$N_{FM^f} = 2^{N_{ASS}} - \sum_{k=0}^{(N_{ASS}-N_{SIFC})} \frac{N_{ASS}!}{k!\,(N_{ASS}-k)!} = 8 \tag{9}$$

A full inventory of functional modes is listed in Table 1, along with the value of the binary variable associated to each component y_{ASS,FM^f} which describes its status at each functional mode, as given by Equation 10.

$$y_{ASS,FM^f} = \begin{cases} 0 & failed \\ 1 & operative \end{cases} \tag{10}$$

Table 1 – Inventory of Functional Modes

Functional Mode	Binary Variable Associated to Each Component							Power Plant Functional Status
	AuxGT	GT1	GT2	AuxST	ST	HRSG1	HRSG2	
FM1	1	1	1	1	1	1	1	FS1
FM2	1	1	1	1	1	1	0	FS2
FM3	1	1	1	1	1	0	1	FS2
FM4	1	1	1	1	0	1	1	FS3
FM5	1	1	1	0	1	1	1	FS3
FM6	1	1	0	1	1	1	1	FS4
FM7	1	0	1	1	1	1	1	FS4
FM8	0	1	1	1	1	1	1	FS5

In conjunction, operative/ failed status of components at a given functional mode ultimately determine the functional status of the power plant as a whole, which are identified in the last column of Table 1 and described at Table 2.

Each component has a transition rate z_{ASS,FM_i^f,FM_j^f} between its two statuses, as given by its failure and repair rates (λ_{ASS} and μ_{ASS}, respectively), according to Equation 11.

Table 2 – Description of Functional Statuses

Power Plant Functional Status	Description
FS1	Power Plant Operates at Full Capacity
FS2	Both Gas Turbines Operate at Full Capacity, Steam Turbine Operates at Half Capacity
FS3	Both Gas Turbines Operate at Open Loop
FS4	Only One Gas Turbine Operates at Full Capacity, the Other Gas Turbine is Down, Steam Turbine Operates at Half Capacity
FS5	Power Plant is Down

$$z_{ASS,FM_i^f,FM_j^f} = \begin{cases} \mu_{ASS} & if \quad y_{ASS,FM_i^f} = 0 \quad and \quad y_{ASS,FM_j^f} = 1 \\ \lambda_{ASS} & if \quad y_{ASS,FM_i^f} = 1 \quad and \quad y_{ASS,FM_j^f} = 0 \\ 0 & if \quad y_{ASS,FM_i^f} = 0 \quad and \quad y_{ASS,FM_j^f} = 0 \\ 0 & if \quad y_{ASS,FM_i^f} = 1 \quad and \quad y_{ASS,FM_j^f} = 1 \end{cases} \tag{11}$$

Failure and repair rates to be used at Equation 11 are those associated to components defined at Equation 8. Note that the logical arrangement (series, parallel, redundancies) of the pieces of process equipment that constitute a given component should be used to compute its overall failure and repair rates.

The overall transition rate from state FM_i^f to state FM_j^f is given by the transition rate matrix $TRM_{FM_i^f,FM_j^f}$ as described in Equation 12, aided by the auxiliary parameter $TRMsum_{FM_i^f}$ as defined at Equation 13, while condition introduced at Equation 14 is observed (where the number of simultaneous events N_{SE} is assumed as 1).

$$TRM_{FM_i^f,FM_j^f} = \begin{cases} \sum\limits_{ASS} z_{ASS,FM_i^f,FM_j^f} & \forall\ i \neq j \\ -TRMsum_{FM_i^f} & \forall\ i = j \end{cases} \tag{12}$$

$$TRMsum_{FM_i^f} = \sum_{FM_j^f, i \neq j} TRM_{FM_i^f,FM_j^f} \tag{13}$$

$$0 < \sum_{ASS} \left| y_{ASS,FM_i^f} - y_{ASS,FM_j^f} \right| \leq N_{SE} \tag{14}$$

The probability of the system being at every functional mode $Pr_{FM_i^f}$ is obtained by solving the homogenous linear system of equations given by Equation 15, while observing the additional constraint introduced at Equation 16.

$$\sum_{FM_i^f} Pr_{FM_i^f}\ TRM_{FM_i^f,FM_j^f} = 0 \quad \forall\ j \tag{15}$$

$$\sum_{FM_i^f} Pr_{FM_i^f} = 1 \tag{16}$$

The operative time associated to each functional mode is computed according to Equation 17 as the length of a whole year affected by the probability of occurrence of such functional mode.

$$POT_{FM_i^f} = 8760\ Pr_{FM_i^f} \tag{17}$$

The power plant availability gets computed as the summation of the probabilities associated to those statuses where the process is able to fulfill the expected demand, as given by Equation 18.

$$A_S = \sum_{FM_i^a} Pr_{FM_i^f} \quad , \quad FM_i^a \subseteq FM_i^f \tag{18}$$

3. OPTIMAL DESIGNS

In order to optimize the design and operative characteristics of the power plant, the mathematical problem defined by Equation 1 through Equation 4 is solved. System availability (defined at Equation 18) is jointly optimized, as the mathematical formulation also finds the optimal values of the probabilities associated to each functional status by means of Equation 11 through Equation 16.

Resultant functional statuses probabilities are reported at Table 3, as well as the associated operative times.

Table 3 – Probabilities and Operative Times for Every Functional Status

Power Plant Functional Status	Probability (%)	Operative Time (hs)
FS1	93.17	8162
FS2	1.90	167
FS3	2.58	226
FS4	1.60	140
FS5	0.74	65

Figure 3 presents the generation capacity of the power plant at each functional status, which is related to the feasibility of fulfilling the external demand, as follows:

- The power plant operates at full capacity at state $FS1$, delivering 800 MW during an average annual time span of 8162 hours (as introduced at Table 3).
- Statuses $FS2$, $FS3$ and $FS4$ represent operation at derated conditions, where one gas turbine and/or the steam turbine are down. The remaining generation capacity is then destined to partially satisfying the external demand. It is noted that economic penalties could be applied by regulatory entities for not delivering the required power/energy.
- The whole power plant is off-line at status $FS5$, so no power gets delivered. As a key task, the designer always tries to minimize the time that the system spends at this status, thus also minimizing the associated economic losses.

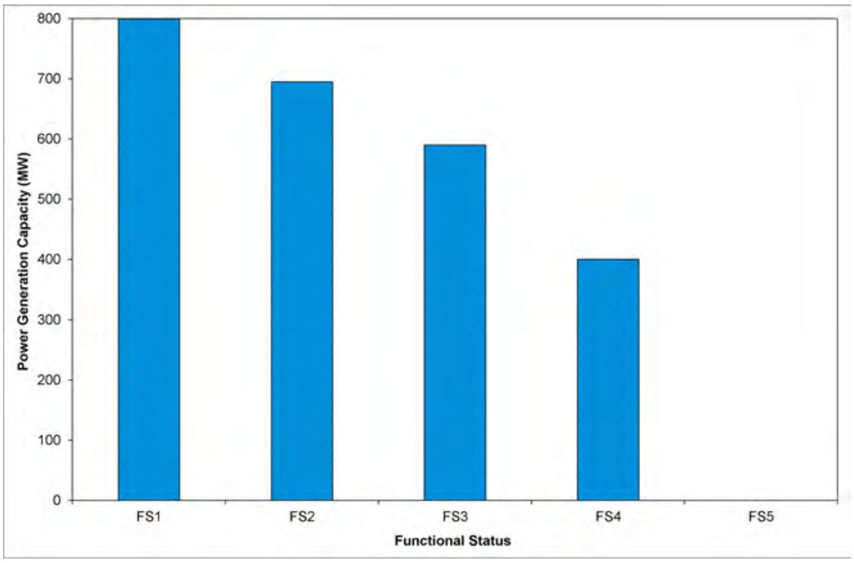

Figure 3 – Generation Capacity for Every Functional Status

Table 4 and Table 5 detail the cost components computed when estimating the capital and operative expenditures of the project, respectively. Note that the values reported for each operative cost component have been weighted by the probabilities associated to each functional status. The following observations are drawn:

Table 4 – Capital Expenditures (millions us$)

		Traditional Approach	Economic Optimization with State-space Availability Model
Gas turbine (2)	C_{GT}	152.40	152.40
HRSG (2)	C_{HRSG}	26.20	26.20
Steam turbine (1)	C_{ST}	54.24	54.24
Total equipment acquisition cost	$C_{Inv} = \sum C_{GT} + C_{HRSG} + C_{ST}$	232.84	232.84
CAPEX	$= 5 \, . C_{Inv}$	1164.19	1164.19

- As the power plant is designed for fulfilling an external demand of 800 MW, the necessary capital expenditures do not change in spite of considering an availability-enhanced optimization approach. The annualized capital investment represents only about 30% of the total annual cost.
- The total operative expenditures are larger (+4%) at the state-space enabled economic optimization approach here utilized (compared to a traditional one), due to the more detailed evaluation of each cost component across every functional status of the power plant. Even though, while achieving higher values of the system availability (as it will be shown further ahead), maintenance funds result smaller.

- The raw materials and utilities cost rises to 2/3 of the total operative expenditures, while the fuel expenses comprise about 50% by themselves.

Table 5 – Operative Expenditures (millions us$, annual basis, weighted values)

		Traditional Approach	Economic Optimization with State-space Availability Model
Cooling water	C_{CW}	23.66	24.59
Fuel	C_F	118.29	127.53
Water make up	C_{WMU}	15.57	16.19
Total raw materials and utilities cost	$C_{RM} = \sum C_{CW} + C_F + C_{WMU}$	157.52	168.31
Total operative man power cost	C_{MP}	1.26	1.26
Total maintenance cost	C_{Mant}	2.33	1.16
OPEX	$= C_{RM} + 2.2\ C_{MP} + C_{Mant} + 0.35\ IFC$	244.11	253.74

For actual market conditions, the operative costs dominate the plant economics, mainly driven by high fuel costs. Costs structure here found is similar to values previously reported in the literature (see Kuprianov et al. (2008), Bernier et al. (2012)), although not directly comparable due to the characteristic differences of the studied systems and the up-to-date economic parameters here used for the calculation of the total annual cost.

Figure 4 presents a comparison of relative weights between the economic performance indicators of the power plant design obtained through the state-space enhanced optimization approach versus a traditionally designed one.

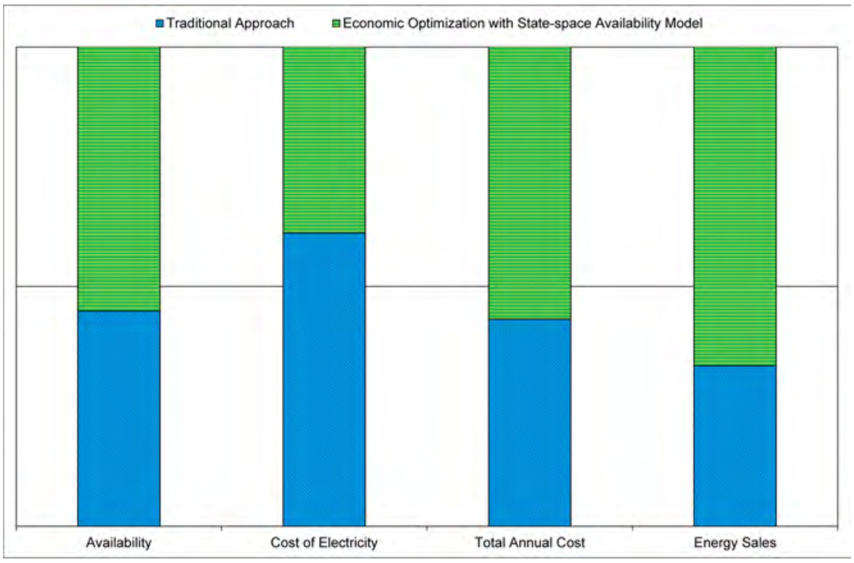

Figure 4 – Performance Indicators Comparison

Note that a traditional approach for the design of power plant implies the resolution of an economic optimization formulation where fixed values are assumed for the annual operative span (usually 8000 hours) and for the assigned maintenance funds (usually about 5% of the capital investment). Therefore, a traditional approach does not consider neither different operative scenarios within the time horizon nor the effects of maintenance funds allocation on the system availability.

It is observed that a higher availability value is achieved when state-space availability modeling is considered, which also implies attaining larger energy sales by about 6.8%.

The more detailed evaluation of each cost component throughout every operative scenario implies an increase of 2.7% in the total annual cost. Even though, as the amount of generated energy also increases, the cost of the electricity (measured as the total expenditures per unit of produced energy) is 4.4% smaller.

4. CONCLUSIONS

It is here shown that a state-space enhanced economic optimization approach delivers a more accurate assessment of the generators' economics, when compared with the estimation of the performance indicators associated with a traditional evaluation scheme.

In addition, considering the full span of operative scenarios that the system will face across the whole time horizon allows a deeper insight on its technical and economic performance, and point towards new optimization opportunities.

The proposed formulation is robust enough to tackle problems of the size and complexity commonly found in industry and has the potential of yielding significant economic savings, as shown throughout the presented case study.

Further exploration may be pursued by considering other failure modes and different types of maintenance actions, in order to broaden in the analysis those scenarios here left aside.

5. REFERENCES

Aguilar, O.; Kim, J.; Perry, S.; Smith, R. Availability and reliability considerations in the design and optimisation of flexible utility systems. *Chem. Eng. Sci.*, 63(14), 3569–3584, 2008.

Bernier, E.; Maréchal, F.; Samson, R. Multi-objective design optimization of a natural gas-combined cycle with carbon dioxide capture in a life cycle perspective. *Energy*, 35(2), 1121–1128, 2010.

Bernier, E.; Maréchal, F.; Samson, R. Optimal greenhouse gas emissions in NGCC plants integrating life cycle assessment. *Energy*, 37(1), 639–648, 2012.

Biezma, M.; Cristóbal, J. Investment criteria for the selection of cogeneration plants– a state of the art review. *Appl. Therm. Eng.*, 26(5-6), 583–588, 2006.

CAMMESA. Portal web cammesa. http://www.cammesa.com.ar, 2011.

Drud, A. *CONOPT: A system for large scale nonlinear optimization.* ARKI Consulting and Development A/S, Bagsvaerd, Denmark, 1996.

ERGUINA, V. *Safety assured financial evaluation of maintenance.* Tese de Doutorado, Texas A&M University, 2004.

FRANGOPOULOS, C.; DIMOPOULOS, G. Effect of reliability considerations on the optimal synthesis, design and operation of a cogeneration system. *Energy*, 29(3), 309–329, 2004.

GODOY, E.; BENZ, S.; SCENNA, N. A strategy for the economic optimization of combined cycle gas turbine power plants by taking advantage of useful thermodynamic relationships. *Appl. Therm. Eng.*, 31, 852–871, 2011.

GODOY, E.; SCENNA, N.; BENZ, S. Families of optimal thermodynamic solutions for combined cycle gas turbine (CCGT) power plants. *Appl. Therm. Eng.*, 30(6-7), 569–576, 2010.

GOEL, H.; GRIEVINK, J.; HERDER, P.; WEIJNEN, M. Integrating reliability optimization into chemical process synthesis. *Reliab. Eng. Syst. Safe.*, 78(3), 247–258, 2002.

HAGHIFAM, M.; MANBACHI, M. Reliability and availability modelling of combined heat and power (CHP) systems. *Int. J. Elec. Power*, 33(3), 385–393, 2011.

KOTOWICZ, J.; BARTELA, L. The influence of economic parameters on the optimal values of the design variables of a combined cycle plant. *Energy*, 35(2), 911–919, 2010.

KUPRIANOV, V.; KAEWBOONSONG, W.; DOUGLAS, P. Minimizing fuel and environmental costs for a variable-load power plant (co-) firing fuel oil and natural gas - part 2. optimization of load dispatch. *Fuel Process. Technol.*, 89(1), 55–61, 2008.

ROSENTHAL, R. *GAMS: A User's Guide.* GAMS Development Corp., Washington DC, USA, 2008.

ULRICH, G.; VASUDEVAN, P. How to estimate utility costs. *Chem. Eng.*, 113(4), 66–69, 2006.

U.S. DEPARTMENT OF ENERGY. U.S. Energy Information Administration. http://www.eia.gov, 2011.