Alessandro N. Costa
alessandronc@petrobras.com.br
Petrobras – Petróleo Brasileiro S.A.
Engenharia/IETEG/ESEB/ETER
20031-004 Rio de Janeiro, RJ, Brazil

Marcus Vinicius S. Neves
marcusv.neves@petrobras.com.br
Petrobras – Petróleo Brasileiro S.A.
E&P-ENGP/OPM/EMI
20031-170 Rio de Janeiro, RJ, Brazil

Manuel E. Cruz
manuel@mecanica.coppe.ufrj.br
UFRJ – Universidade Federal do Rio de Janeiro
Departamento de Engenharia Mecânica/COPPE
21945-970 Rio de Janeiro, RJ, Brazil

Leonardo S. Vieira
lsrv@cepel.br
CEPEL – Centro de Pesquisa de Energia Elétrica
Departamento de Tecnologias Especiais
21944-970 Rio de Janeiro, RJ, Brazil

Maximum Profit Cogeneration Plant – MPCP: System Modeling, Optimization Problem Formulation, and Solution

The well-known CGAM optimization problem was formulated to serve as a benchmark for comparison of different thermoeconomic methodologies. The CGAM cogeneration plant produced 30 MW of power and 14 kg/s of saturated vapor at 20 bar. The objective function was the total cost rate of the system, related to thermodynamic variables and installation costs. Because the CGAM problem originates from an academic viewpoint, its models do not reflect the industrial reality of energy systems, and do not conform to important operational and technological restrictions. The objective of this work is to propose an alternative cogeneration-system optimization problem, denoted the MPCP problem – Maximum Profit Cogeneration Plant, which incorporates functional economic concepts and modern technologies. The objective function is the net present value (NPV) of the monetary gain for the period of plant operation. The optimum (i.e., maximum) NPV value is obtained using two different professional optimization toolboxes appropriate for multivariable nonlinear constrained functions. The optimal operational conditions indicate that the MPCP plant reaches the allowed physical limits of the main equipment, namely, maximum efficiency of the gas turbine generator set and minimum temperature difference inside the heat recovery steam generator. Formal findings like these help to direct efforts to improve current technologies.
Keywords: *thermoeconomics, optimization, cogeneration, MPCP, NPV*

Introduction

Some fifty years ago, the field of thermoeconomics emerged from pioneering studies in analysis, optimization and design of thermal systems, as reviewed by Tsatsaronis (1993). The essence was to couple thermodynamics with economics, in order to improve efficiency and reduce environmental impacts in a cost effective way. In the past twenty to thirty years, a more systematic approach has evolved, with new definitions, methodologies and nomenclature. In this context, the well-known CGAM optimization problem (Tsatsaronis, 1994; Bejan, Tsatsaronis and Moran, 1996), named after the proponents *C*. Frangopoulos, *G*. Tsatsaronis, *A*. Valero and *M*. von Spakovsky, was formulated to serve as a benchmark for comparison of different thermoeconomic methodologies. More recently, with the aim to compare thermoeconomic diagnosis methods applicable to energy utility systems, a broader problem has been proposed by Valero et al. (2004), named the TADEUS problem.

The effort to improve efficiency and reduce environmental impacts of thermal systems firmly persists to date, promoting the continued development and improvement of methodologies, and the search for new applications. Representative examples are now briefly cited. The Specific Exergy Costing Method (SPECO) applied to the CGAM problem by Tsatsaronis (1994) has been recently updated, with cost equations derived in general matrix form (Lazzaretto and Tsatsaronis, 2006), and with consideration of specific exergy revenues instead of specific costs (Paulus and Tsatsaronis, 2006). Several different methodologies have also been put forward, e.g., MOPSA – Modified Productive Structure Analysis by Kwon, Kwak and Oh (2001), EEA – Extended Exergy Accounting by Sciubba (2001) and Milia and Sciubba (2006), EXCEM – Exergy-Cost-Energy-Mass Analysis by Rosen and Dincer (2003) and Dincer and Rosen (2007). Applications to systems other than the CGAM with existing or proposed methodologies are found, for example, in the articles by Alves and Nebra (2004), Zhang et al. (2006), Vieira, Donatelli and Cruz (2006), Koch, Cziesla and Tsatsaronis (2007), Cardona and Piacentino (2007) and Junior and Borelli (2008). A late discussion of available thermoeconomic and exergoeconomic methods and their limitations are found in the works by Valero (2006), Lazzaretto and Tsatsaronis (2006), Tsatsaronis (2007) and Dincer and Rosen (2007).

In the CGAM problem, the optimization of a hypothetic cogeneration plant with five individual components is pursued, which produces 30 MW of electrical power in a regenerative cycle and 14 kg/s of saturated vapor at 20 bar. The CGAM cogeneration system consists of an air compressor, a combustion chamber, a gas turbine, a heat recovery steam generator, which produces the saturated vapor at the required process conditions, and an air preheater, located at the compressor exit in order to recover some thermal energy of the turbine exhaust. In the problem formulation, the physical, thermodynamic and economic models are defined, as well as the objective function, the decision variables and the constraints. Several simplifications are introduced in the CGAM problem, since the main objective is to compare different thermoeconomic techniques. As a consequence, the modeling of the performance of the CGAM components is essentially theoretical, and does not correspond to the industrial reality of actual energy systems. In other words, the models do not conform to important operational and technological restrictions, so that the CGAM problem is incomplete from an engineering perspective.

The purpose of the present article is to propose and solve exactly a thermoeconomic optimization problem that is an alternative to the CGAM problem. The current proposal is entitled the MPCP problem – Maximum Profit Cogeneration Plant (Costa, 2008), which preserves the original simplicity of the CGAM, but introduces functional economic concepts and knowledge of technologies and physical limitations of modern power plants. A suitable configuration for the cogeneration plant is first established. The physical, thermodynamic and economic models are then formulated leading to the objective function that represents the net present value (*NPV*) of the monetary gain for a given period of plant operation. The optimization problem thus consists in the

Paper accepted September, 2010. Technical Editor: Amir Oliveira Junior

maximization of the net present value. Here, to obtain and validate the optimal *NPV* value for the MPCP problem, it has been decided to apply two different conventional mathematical optimization strategies. Therefore, the professional optimization toolboxes of the Mathematica® (Wolfram, 1999) and MatLab® (The MathWorks, 2005) programs are used, appropriate for multivariable nonlinear functions subject to constraints. The so validated optimal values of the objective function and decision variables serve as references for other studies, which might involve the MPCP problem. The results indicate that the MPCP plant reaches the allowed physical limits of the main equipment, namely, maximum efficiency of the gas turbine generator set and minimum temperature difference inside the heat recovery steam generator. Naturally, formal findings like these contribute to direct efforts to improve current technologies.

Two aspects of the MPCP problem represent important contributions, and make it particularly suitable to the Brazilian reality. First, as commonly observed in practice, only the production of electrical power is fixed, while the production of superheated steam is free to vary from a prescribed minimum value. The optimization algorithm must then match the electrical power demand, but will vary steam equipment and production to maximize the NPV. Second, the cost equation for the gas turbine generator set is obtained through statistical analysis, which encompasses a database of prices, converted to the national market, of a population of generators with similar capacities and constructive types commercialized by international manufacturers. Finally, it is also hoped that the MPCP problem will contribute to the practice of ecoefficiency, through an optimization paradigm which attempts to conciliate the goal of profit maximization of gas and energy enterprises with environmental impact mitigation. This important matter is routinely present in current debates by corporations and universities about the implementation of new energy projects.

Nomenclature

$c_{f,m}$ = *cost of fuel in the first year on a mass basis, US$/kg*
$c_{O\&M}$ = *cost rate of operation and maintenance, US$/h*
$c_{p,a}$ = *air constant-pressure specific heat, kJ/kg°C*
$c_{p,g}$ = *combustion gases constant-pressure specific heat, kJ/kg°C*
e_f = *fuel specific exergy, kJ/kg*
E_f = *total expenses due to fuel consumption, US$*
$E_{O\&M}$ = *total expenses due to operation and maintenance, US$*
$\dot{E}_{Q,f}$ = *total energy rate supplied to the GTG, kW*
$\dot{E}_{Q,g}$ = *energy rate lost by the exhaust gases, kW*
h = *enthalpy, kJ/kg*
H = *hurdle rate, % annual, dimensionless*
HR = *heat rate, kJ/kWh*
$LMTD$ = *log mean temperature difference, K or °C*
$\dot{m}_a$ = *air mass flow rate, kg/s*
$\dot{m}_f$ = *fuel mass flow rate, kg/s*
$\dot{m}_{s,DA}$ = *mass flow rate of steam for deaeration, kg/s*
$\dot{m}_{s,EVAP}$ = *total steam flow rate produced in evaporator, kg/s*
$\dot{m}_{s,FT}$ = *steam flow rate got from expansion in flash tank, kg/s*
$\dot{m}_{s,PR}$ = *superheated process steam flow to be exported, kg/s*
$\dot{m}_{w,BD}$ = *blow-down water flow rate from evaporator, kg/s*
$\dot{m}_{w,EVAP}$ = *total water mass flow rate in evaporator, kg/s*
MW_a = *molecular weight of air, kg/kmol*
MW_{ng} = *molecular weight of natural gas, kg/kmol*
NPV = *net present value, R$*
P = *pressure, Pa or bar*
$R_{a/f,m}$ = *air/fuel mass ratio, dimensionless*
R_{EE} = *revenue due to electrical energy sale, US$*
$R_{s,PR}$ = *revenue due to process steam sale, US$*
t = *period of plant operation in years*
T = *temperature, K or °C*
U = *overall heat transfer coefficient, kW/m²·°C*
$\dot{W}_{AC}$ = *power consumption by the air compressor, kW*
$\dot{W}_{gr}$ = *gross power capacity, kW*
$\dot{W}_{GT}$ = *gas turbine power, kW*
$\dot{W}_L$ = *GTG power loss rate due to entropy generation, kW*
$\dot{W}_{net}$ = *net plant power exported to grid, kW*
Z = *cost, US$*

Greek Symbols

β = *dimensionless multiplier to account for various plant costs*
ΔT = *temperature difference, K or °C*
ΔT_{pp} = *ΔT at pinch point inside HRSG, K or °C*
ΔT_{appr} = *approach (ΔT between water at economizer exit and saturated vapor in evaporator), K or °C*
ε_{GTG} = *GTG exergetic efficiency*
κ = *percentage of power loss*
ζ_{IC} = *dimensionless factor for internalization cost*
Π_{EE} = *price of electrical energy in the first year, US$/MWh*
$\Pi_{s,PR}$ = *price of process steam in the first year, US$/kg*
τ = *exchange rate, R$/US$*

Subscripts

a relative to air
f relative to fuel
s relative to steam
w relative to water

Brief Summary of the CGAM Problem

The CGAM problem has been extensively documented and studied in the literature (Tsatsaronis, 1994; Bejan, Tsatsaronis and Moran, 1996; Vieira, Donatelli and Cruz, 2004; Costa, 2008), thus only a brief summary shall be included here. The formulation of the CGAM problem includes the equations that describe the cogeneration system behavior (physical model), the state equations used to calculate the thermodynamic properties of the mass streams (thermodynamic model), and the equations employed to calculate the capital, fuel and operation and maintenance costs for the system (economic model).

To simplify the physical and thermodynamic models, the following assumptions are made: (i) the air and combustion gases behave as ideal gases with constant specific heats; (ii) the fuel is considered to be pure methane, and its combustion is complete; (iii) all the components, except the combustion chamber, are adiabatic. Environmental physical references are further prescribed, so that the temperature, pressure and relative humidity of the atmospheric air are T_0 = 298.15 K (25°C), P_0 = 1.013 bar and 60%, respectively. The chemical composition of the air is specified by the following molar fractions: 0.2059 of oxygen, 0.77489 of nitrogen, 0.0003 of carbon dioxide and 0.0190 of water vapor.

The equation for the capital cost rate (in US$/s) of the system is written as a function of the purchased-equipment costs of the components (in US$), the annual capital recovery factor (%), the number of hours of plant operation per year and a dimensionless coefficient to account for the operation and maintenance costs. The economic model further establishes that the total cost rate of the CGAM system is the sum of the capital cost rate and the fuel cost rate. The latter is proportional to the mass flow rate and lower heating value of the fuel.

The CGAM optimization problem consists in the minimization of the total cost rate of the system, which is the objective function, assuming fixed production amounts of both electrical power and saturated process steam. The objective function has five degrees of freedom, represented by the selected decision variables, namely, the air compressor pressure ratio, the isentropic efficiencies of the air compressor and gas turbine, the temperature of the air at the preheater exit and the temperature of the combustion gases at the gas turbine inlet.

The MPCP Problem

In the MPCP problem, a representative cogeneration system is first conceived (Costa, 2008; Costa et al., 2008), which retains the simplicity and power range of the CGAM system; however, it reflects the actual technologies and engineering practices in modern cogeneration projects. The complete mathematical formulation of the MPCP problem is presented in the fifth and sixth parts.

After a detailed analysis of the characteristics and drawbacks of the CGAM system, Costa (2008) and Costa et al. (2008) propose the MPCP cogeneration system with the following distinguishing attributes: (i) the air compressor (AC), combustion chamber (CC) and gas turbine (GT) are integrated in one single equipment, the gas turbine generator set (GTG), whose cost is obtained through an statistical analysis (sixth part); (ii) as in real GTGs, there is no air preheater; (iii) the inequality constraint $\Delta T_{pp} \geq 10$°C is imposed for the temperature difference at the pinch point inside the heat recovery steam generator (HRSG); (iv) natural gas, rather than methane, is the fuel to be burned in the new system; the adopted composition of the natural gas is shown in Table 1; (v) 100ºC is the minimum permissible value for the stack gas temperature; (vi) the method employed to compute the properties of the streams across the gas turbine generator set (fifth part) leads to realistic values for the pressure ratio in the compressor; (vii) also, practical values for the energy losses and temperature of the exhaust gases of the gas turbine generator set are obtained through statistical correlations of simulated data for a population of GTGs with similar characteristics; (viii) only the exergetic efficiency of the gas turbine generator set and the mass flow rate of process steam exported by the HRSG are selected as decision variables; (ix) optimization is effected for the profit of the cogeneration plant, keeping the electrical power demand fixed at 30 MW, while letting the steam production free to vary from a minimum value of 12 kg/s; (x) instead of using the capital recovery method (as in the CGAM problem) or the cost of energy method, the commonly used economic indicator *NPV* – net present value (Blank and Tarquin, 2005) is adopted as the objective function in the MPCP problem, discounting future cashflows at the capital cost of today; (xi) equipment costs are obtained through statistical regressions of real cost and performance data (sixth part); (xii) the rate of energy consumption by the auxiliary equipment (BOP – Balance of Plant) is considered to amount to 2.5% of the power produced by the plant, and the capital cost of the auxiliary equipment is taken into account in the economic model; the pumping power demand for the feedwater is calculated separately, since it depends on the process steam mass flow rate; (xiii) there is a deaerator in the MPCP system; (xiv) a specification commonly used in refineries is prescribed for the process steam, namely, 14 bar and 285ºC; therefore, because the steam is superheated, the HRSG is split into four different sections, water preheater (WPH), economizer (ECO), evaporator (EVAP) and superheater (SH); (xv) the approach, i.e., the temperature difference between the water at the exit of the economizer and the saturated vapor in the evaporator is ΔT_{appr} = 5ºC; (xvi) the blow-down of the evaporator amounts to 1% of the total feedwater mass flow rate entering the HRSG; in addition, the blow-down water is expanded in a flash tank, to generate part of the steam for the deaerating process; and (xvii) the water-side pressure drops inside the HRSG are accounted for, as percentages of the inlet pressure in each HRSG section.

Table 1. Chemical composition of the plant fuel – natural gas.

Chemical component	Volume fraction
Methane	87.63%
Ethane	6.45%
Propane	2.97%
I-Butane	0.45%
N-Butane	0.23%
I-Pentane	0.17%
N-Pentane	0.14%
Hexane	0.08%
Nitrogen	1.63%
Carbon dioxide	0.25%
Hydrogen	0
Hydrogen sulfide	0
Total	100%
Constant-pressure specific heat at 30°C	2.00 kJ/kg·°C
Mean molecular weight	18.75
Lower heating value (*LHV*)	45595.53 kJ/kg
Upper heating value (*UHV*)	50627.77 kJ/kg

Thermodynamic and Physical Models

The configuration of the cogeneration plant for the MPCP problem consists of the following main components, according to the propositions stated in the fourth part: a gas turbine generator set (GTG), a heat recovery steam generator (HRSG) with four sections (WPH, ECO, EVAP, SH), a deaerator vessel (DA), a flash tank for fluid expansion (FT) and a feedwater pump (FWP). A schematic flow diagram for the MPCP system is shown in Fig. 1, with the indication of the principal equipment and the relevant stream numerals for the mass and energy balances.

The parameters and constraints adopted in the MPCP problem are shown in Table 2 (Costa, 2008; Costa et al., 2008). The environmental references are the same as those of the CGAM (third part). It is also assumed in the MPCP problem, that the air and the combustion gases behave as ideal gases with constant specific heats, denoted respectively by $c_{p,a}$ and $c_{p,g}$. While this assumption could have been avoided, it not only simplifies the problem formulation, but it also does not affect the trends found in the problem solution (seventh part).

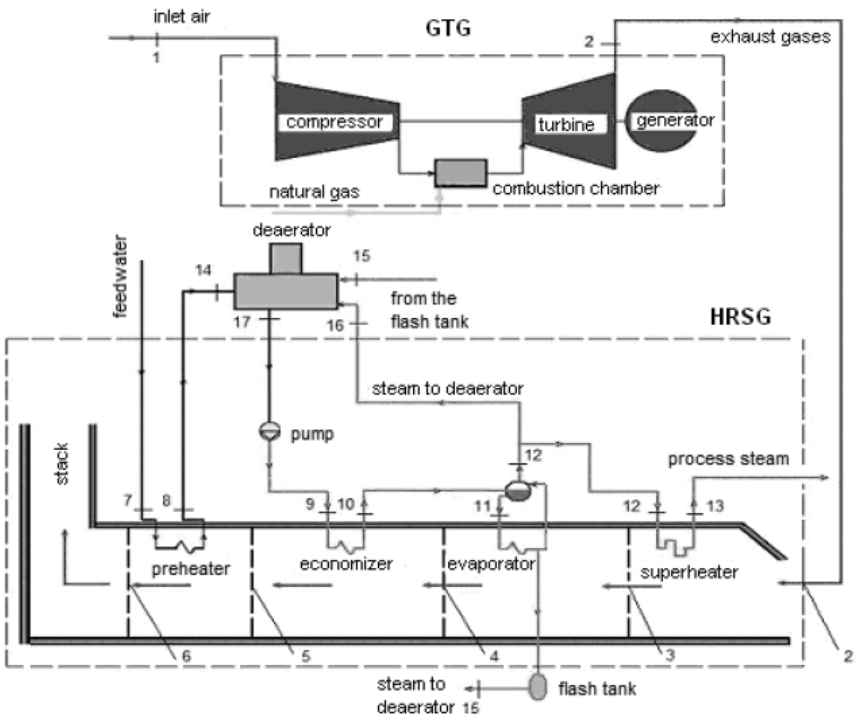

Figure 1. Conceived configuration for the cogeneration system of the MPCP problem.

Table 2. Parameters and constraints of the MPCP problem.

Description	Value/Range
molecular weight of the air	$MW_a = 28.648$ kg/kmol
molecular weight of the natural gas	$MW_{ng} = 18.75$ kg/kmol
temperature difference at the pinch point inside the HRSG	$\Delta T_{pp} \geq 10^oC$
approach (temperature difference between water at economizer exit and saturated vapor in evaporator)	$\Delta T_{appr} = 5^oC$
temperature of stream 4	$T_4 = T_{11} + \Delta T_{pp}$
temperature of stream 6	$T_6 \geq 100^oC$
pressure of stream 7	$P_7 = 1.213$ bar
temperature of stream 7 (ambient temperature plus 1°C due to pumping)	$T_7 = T_0 + 1$
pressure of stream 8	$P_8 = P_{DA} = 1.113$ bar
temperature of stream 9 (saturation temperature of steam in deaerator plus 1°C due to pumping)	$T_9 = T_{sat,DA} + 1$
temperature of stream 10	$T_{10} = T_{11} - \Delta T_{appr}$
temperature of streams 11 and 12	$T_{11} = T_{12} = T_{sat,EVAP}$, $T_{sat,EVAP} = 196.7^oC$
pressure of streams 11 and 12	$P_{11} = P_{12} = 14.5$ bar
temperature of stream 13 (process steam)	$T_{13} = 285^oC$
pressure of stream 13 (process steam)	$P_{13} = 14$ bar
mixture quality in the flash tank	0.18

Equations for the Gas Turbine Generator Set

In Costa (2008) and Costa et al. (2008) a method to calculate the exhaust gas temperature, T_2 (Fig. 1), at the exit of the GTG component is developed. The basis of the method is a thermodynamic formulation, which makes use of a database obtained from manufacturers of gas turbines. Two GTG quantities are considered given, the gross power capacity, $\dot{W}_{gr}$ (kW), and the heat rate, HR, related to the total energy rate supplied to the GTG, $\dot{E}_{Q,f}$ (kW), by

$$\dot{E}_{Q,f} = \dot{m}_f \, LHV = \dot{W}_{gr} \, HR \tag{1}$$

where $\dot{m}_{\rm f}$ is the mass flow rate of fuel (kg/s). It is remarked that $\dot{W}_{\rm gr}$ is not equal to the net power exported by the plant to the grid, $\dot{W}_{\rm net}$, because of the power consumption by the auxiliary equipment.

Having established a population sample of fourteen aeroderivative GTG models from international suppliers, all with ISO-conditions capacities similar to the one used in this work (30 MW ± 6 MW), simulations have then been conducted using the GT PRO® software (Thermoflow, 2004), to obtain average values for the following quantities: the loss rate, $\dot{W}_{\rm L}$, defined as the fraction of the total energy rate supplied to the GTG that is not converted to power due to entropy generation inside the GTG; the power consumption by the air compressor, $\dot{W}_{\rm AC}$; and the air/fuel mass ratio, $R_{\rm a/f,m}$. The results can be expressed mathematically in the following form:

$$\dot{W}_{\rm L,n} = \kappa_{\rm n}\ \dot{E}_{\rm Q,f} \quad (2)$$

$$\dot{W}_{\rm AC} = \dot{m}_{\rm a} c_{\rm p,a} (T_{\rm AC,e} - T_{\rm AC,i}) = 36.41\%\ \dot{E}_{\rm Q,f} \quad (3)$$

$$R_{\rm a/f,m} = \frac{\dot{m}_{\rm a}}{\dot{m}_{\rm f}} = 55.49 \quad (4)$$

In Eq. (2), the subscript n identifies the type of turbine generator loss. Specifically, the appropriate percentages are given by Costa (2008): $\kappa_{\rm AC}$ = 5.12%, $\kappa_{\rm GT}$ = 8.38%, $\kappa_{\rm mec}$ = 0.92% and $\kappa_{\rm el}$ = 0.74% for the air compression, gas expansion, mechanical and electrical losses, respectively. In Eq. (3), $\dot{m}_{\rm a}$ is the air mass flow rate, and the subscripts i and e denote inlet and exit, respectively. It is important to note that the GTG works with very high excess of air for combustion, since the air flow also works to cool the equipment. Therefore, there is no risk of obtaining extremely high temperature values in the model, relative to those truly reached in GTGs of the main manufacturers.

Denoting by $\dot{E}_{\rm Q,g}$, the energy rate carried away by the exhaust gases, and $\dot{W}_{\rm GT}$, the gas turbine power, the energy balance equations for the gas turbine generator set are:

$$\dot{W}_{\rm gr} = \dot{E}_{\rm Q,f} - (\dot{W}_{\rm AC} + \dot{W}_{\rm L,GT} + \dot{W}_{\rm L,mec} + \dot{W}_{\rm L,el} + \dot{E}_{\rm Q,g}) \quad (5)$$

$$\dot{W}_{\rm GT} = \dot{W}_{\rm gr} + \dot{W}_{\rm AC} + \dot{W}_{\rm L,el} + \dot{W}_{\rm L,mec} = \dot{m}_{\rm g}\ c_{\rm p,g} \left(T_{\rm CC,e} - T_2\right) \quad (6)$$

where $T_{\rm CC,e}$ is the combustion chamber exit temperature, and the mass flow rate of gases is $\dot{m}_{\rm g} = \dot{m}_{\rm a} + \dot{m}_{\rm f}$. It is important to note that $\dot{W}_{\rm AC}$ and $\dot{W}_{\rm GT}$ already include the losses $\dot{W}_{\rm L,AC}$ and $\dot{W}_{\rm L,GT}$, respectively.

Now, in terms of the combustion chamber inlet and exit temperatures, the total energy rate supplied to the GTG may also be expressed as

$$\dot{E}_{\rm Q,f} = \dot{m}_{\rm g} c_{\rm p,g} \left(T_{\rm CC,e} - T_{\rm CC,i}\right) = \dot{m}_{\rm g} c_{\rm p,g} \left(T_{\rm CC,e} - T_{\rm AC,e}\right) \quad (7)$$

where, clearly, $T_{\rm AC,e} = T_{\rm CC,i}$. The desired GTG exhaust temperature T_2 results from the combination of Eqs. (6) and (7), so that

$$T_2 = T_{\rm CC,e} - \frac{\dot{W}_{\rm GT}}{\dot{m}_{\rm g}\ c_{\rm p,g}} = T_{\rm AC,e} + \frac{\dot{E}_{\rm Q,f} - \dot{W}_{\rm GT}}{\dot{m}_{\rm g}\ c_{\rm p,g}} \quad (8)$$

The GTG exergetic efficiency, $\varepsilon_{\rm GTG}$, is given by (Costa, 2008; Costa et al., 2008)

$$\varepsilon_{\rm GTG} = \frac{\dot{W}_{\rm gr}}{\dot{m}_{\rm f}\ e_{\rm f}} \quad (9)$$

where $e_{\rm f}$ = 49552.61 kJ/kg is the specific exergy of the fuel, encompassing the physical and chemical components. The relationship between the exergetic efficiency and the heat rate is

$$HR = \frac{LHV}{\varepsilon_{\rm GTG}\ e_{\rm f}} \quad (10)$$

Equations for the HRSG and Other Vessels

The equations that represent the mass and energy balances for the HRSG, deaerator and flash vessels of the MPCP system are given in this part, after Costa (2008) and Costa et al. (2008). To produce superheated steam, the HRSG must have four sections: the feedwater preheater (WPH), the economizer (ECO), the evaporator (EVAP) and the superheater (SH). The water-side pressure drops inside the HRSG are given as percentage values of the inlet pressure in each section: 8.24% for the WPH (0.1 bar), 3.33% for the ECO (0.5 bar) and 3.45% for the SH (0.5 bar). The gas-side pressure drops inside the HRSG are given as 0.48% for each section (0.05 bar), relative to the pressure at the entrance to the HRSG; relative to this same pressure, the drop in the stack is 0.67% (0.007 bar). A schematic plot of temperature, T, versus heat exchange surface area, A, is shown in Fig. 2, with the indication of each HRSG section and relevant temperatures.

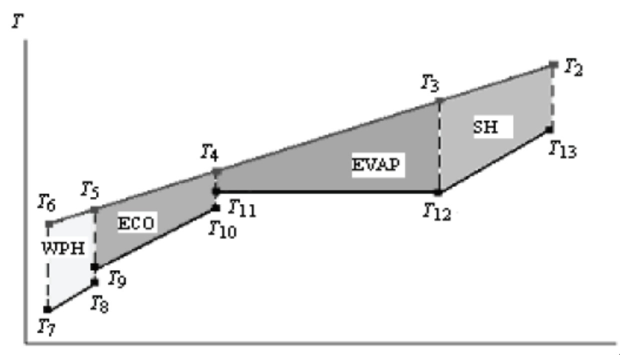

Figure 2. Temperatures of both streams, gas (high) and water (low), across the HRSG.

Denoting by $\dot{m}_{\rm s,EVAP}$, $\dot{m}_{\rm s,PR}$, $\dot{m}_{\rm s,DA}$, $\dot{m}_{\rm w,BD}$, $\dot{m}_{\rm s,FT}$ and $\dot{m}_{\rm w,EVAP}$, the mass flow rates of, respectively, steam produced in the evaporator (total), superheated process steam to be exported, steam for deaeration, blow-down water from the evaporator, steam obtained from the expansion in the flash tank and water in the evaporator (total), the following mass relations apply in the MPCP problem:

$$\dot{m}_{\mathrm{s,EVAP}} = \dot{m}_{\mathrm{s,PR}} + \dot{m}_{\mathrm{s,DA}} = 0.99\,\dot{m}_{\mathrm{w,EVAP}} \tag{11}$$

$$\dot{m}_{\mathrm{w,BD}} = 0.01\,\dot{m}_{\mathrm{w,EVAP}} \tag{12}$$

$$\dot{m}_{\mathrm{s,FT}} = 0.1811\cdot(0.01\,\dot{m}_{\mathrm{w,EVAP}}) = 0.001811\,\dot{m}_{\mathrm{w,EVAP}} \tag{13}$$

In each section j (j = WPH, ECO, SH) and for each non-saturated fluid l (gas, water) in the HRSG, the relation

$$Q_j = UA_j\,LMTD_j = \dot{m}_l c_{p,l}(T_{\mathrm{H},l} - T_{\mathrm{L},l}) \tag{14}$$

applies, where U is the global heat transfer coefficient (in kW/m$^2\cdot$°C) for the section considered, A is the heat transfer area (in m^2), T_{H} and T_{L} are, respectively, the high and low temperatures of the fluid l, and $LMTD$ is the log mean temperature difference:

$$LMTD = \frac{\Delta T_{\max} - \Delta T_{\min}}{\ln\left(\dfrac{\Delta T_{\max}}{\Delta T_{\min}}\right)} \tag{15}$$

Finally, the energy balances for the evaporator and deaerator are given, respectively, by

$$\dot{Q}_{\mathrm{EVAP}} = UA_{\mathrm{EVAP}}\,LMTD_{\mathrm{EVAP}} = \dot{m}_{\mathrm{w,EVAP}}\cdot\left[(h_{11}-h_{10}) + 0.99\,(h_{12}-h_{11})\right] \tag{16}$$

$$\dot{Q}_{\mathrm{DA}} = \dot{m}_{\mathrm{s,FT}}\cdot(h_{g,\mathrm{DA}} - h_{f,\mathrm{DA}}) + \dot{m}_{\mathrm{s,DA}}\cdot(h_{\mathrm{DA}} - h_{f,\mathrm{DA}}) \tag{17}$$

where h_f and h_g are the enthalpies of saturated water in the liquid and vapor phases, respectively, and h_{DA} is the enthalpy of the steam for deaeration after expansion at the deaerator entrance.

Economic Model and Objective Function

In the proposed problem, the goal is to optimize (in fact, maximize) the profit of the plant as a whole, by varying the GTG specification and the production of process steam. Thus, instead of using the capital recovery method in order to minimize the total system cost, herein the objective function is identified with the financial index *NPV*, the net present value for the plant investment, using discounted financial flows (Blank and Tarquin, 2005). The decision variables selected in the MPCP problem are only two: the GTG exergetic efficiency, $\varepsilon_{\mathrm{GTG}}$ (related to *HR* thru Eq. (10)), and the process steam mass flow rate, $\dot{m}_{\mathrm{s,PR}}$.

The purchased-equipment costs are obtained from statistical analyses (Costa, 2008). In the case of the gas turbine generators, in particular, their costs are related to the power capacities and efficiencies. From a set of points generated with the individual data (cost, power, heat rate) for each GTG in the selected sample, the behavior of the cost Z_{GTG} (in 10^3 US$) as a function of power, $\dot{W}_{\mathrm{gr}}$ (in kW), and heat rate, *HR*, is obtained through a nonlinear regression, such that

$$Z_{\mathrm{GTG}}\left(\dot{W}_{\mathrm{gr}},\,HR\right) = \frac{9181.9\,\dot{W}_{\mathrm{gr}}}{1 + 0.5589\,\dot{W}_{\mathrm{gr}} + 0.7208\,HR} \tag{18}$$

By inserting the desired power, 30000 kW, in Eq. (17), the GTG cost as a function of *HR* only is obtained:

$$Z_{\mathrm{GTG}}\left(30000\ \mathrm{kW},\,HR\right) = \frac{2.75457\cdot10^8}{16768 + 0.7208\,HR} \tag{19}$$

The cost of the HRSG (in US$) is equal to the sum of the costs of its individual sections, i.e.,

$$Z_{\mathrm{HRSG}} = Z_{\mathrm{WPH}} + Z_{\mathrm{ECO}} + Z_{\mathrm{EVAP}} + Z_{\mathrm{SH}} \tag{20}$$

Costa (2008) develops the following relations for the costs of the HRSG sections:

$$Z_{\mathrm{WPH}} = 2080.7\cdot UA_{\mathrm{WPH}} - 64128 \tag{21}$$

$$Z_{\mathrm{ECO}} = 2080.7\cdot UA_{\mathrm{ECO}} - 64128 \tag{22}$$

$$Z_{\mathrm{EVAP}} = 1301.5\cdot UA_{\mathrm{EVAP}} + 230759 \tag{23}$$

$$Z_{\mathrm{SH}} = 2173\cdot UA_{\mathrm{SH}} - 1468.3 \tag{24}$$

The plots displaying the costs of the HRSG sections as functions of *UA* are shown in Fig. 3.

To complete the economic formulation, the costs due to taxes and other expenses related to importation of equipment must also be considered. These costs are classified as internalization costs, and, for one given component, they are taken into account through a dimensionless factor, ζ_{IC}, which multiplies the purchased-equipment cost, Z, of the component. For the gas turbine generator set and heat recovery steam generator, Costa (2008) calculates the internalization cost factors as $\zeta_{\mathrm{IC,GTG}}$ = 1.661 and $\zeta_{\mathrm{IC,HRSG}}$ = 1.803, respectively. The total investment cost for the MPCP problem is finally written as

$$Z_{\mathrm{MPCP}} = \beta\left(\varsigma_{\mathrm{IC,GTG}} Z_{\mathrm{GTG}} + \varsigma_{\mathrm{IC,HRSG}} Z_{\mathrm{HRSG}}\right) \tag{25}$$

where the dimensionless multiplier β is applied to account for the other costs of the plant, namely, the deaerator, flash tank, pump, other accessories and engineering costs. In practice, the value of β is 2.5 on average (Costa, 2008).

An economic analysis can then be performed, to determine the *NPV* (in R$) of the cogeneration plant project, discounting the monetary gain of the several cash flows with a prescribed hurdle rate. The hurdle rate (Park, 2010) is the minimum acceptable rate of return or minimum attractive rate of return of an investment, and it represents the minimum expectation of gain of an investor before starting a new project. It is the appropriate rate of return to be used in a project analysis through the *NPV* indicator. The plant revenues are obtained by selling electrical power and process steam. The expenses arise from the purchased-equipment costs, engineering (construction and assembly), fuel consumption and operation and maintenance. The plant is considered to operate during 26 years. The general equation expressing the *NPV* function is

$$NPV = \tau\left[R_{\mathrm{EE}} + R_{\mathrm{s,PR}} - \left(Z_{\mathrm{MPCP}} + E_{\mathrm{f}} + E_{\mathrm{O\&M}}\right)\right] \tag{26}$$

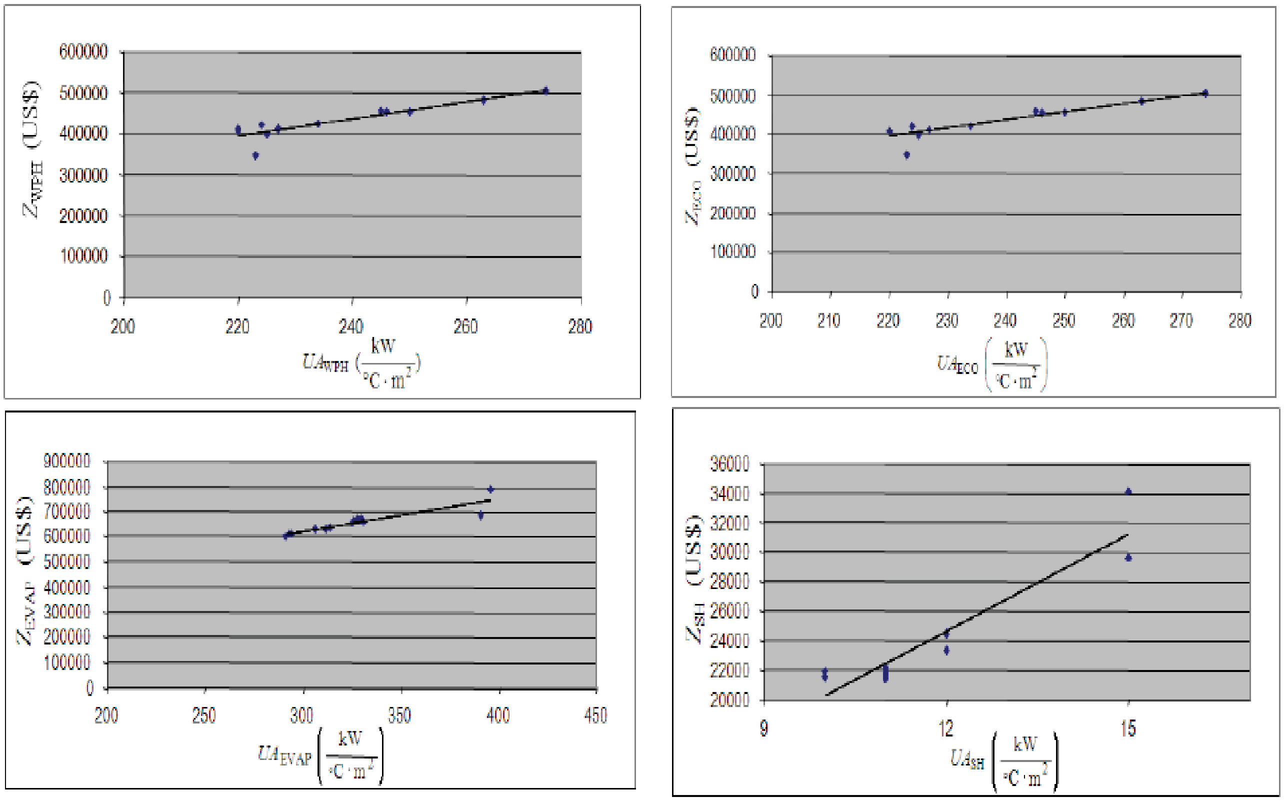

Figure 3. Costs of the individual HRSG heat-transfer sections.

where the coefficient τ is the exchange rate (τ = 2.50 R$/US$). In Eq. (26), R_{EE} (in US$) is the revenue obtained by selling electrical energy, given by

$$R_{\mathrm{EE}} = \sum_{t=0}^{25} \frac{24 \cdot 365 \cdot \Pi_{\mathrm{EE}} \cdot 1.062^t \cdot \dot{W}_{\mathrm{net}}}{(1+H)^t} \tag{27}$$

where t is the period of operation in years (t = 26), Π_{EE} is the price of electrical energy in the first year (Π_{EE} = 89.95 US$/MWh), the factor 1.062 projects a rate of energy price increase of 6.2% per year due to natural gas usage and H is the hurdle rate (H = 12% per year). The revenue obtained by selling process steam, $R_{\mathrm{s,PR}}$ (in US$), may be written as

$$R_{\mathrm{s,PR}} = \sum_{t=0}^{25} \frac{3600 \cdot 24 \cdot 365 \cdot \Pi_{\mathrm{s,PR}} \cdot 1.062^t\, \dot{m}_{\mathrm{s,PR}}}{(1+H)^t} \tag{28}$$

$\Pi_{\mathrm{s,PR}}$ being the price of process steam in the first year ($\Pi_{\mathrm{s,PR}}$ = 0.012 US$/kg). The total expenses due to fuel consumption, E_{f}, and operation and maintenance, $E_{\mathrm{O\&M}}$, are given by

$$E_{\mathrm{f}} = \sum_{t=0}^{25} \frac{3600 \cdot 24 \cdot 365 \cdot c_{\mathrm{f,m}} \cdot 1.062^t\, \dot{m}_{\mathrm{f}}}{(1+H)^t} \tag{29}$$

$$E_{\mathrm{O\&M}} = \sum_{t=0}^{25} \frac{24 \cdot 365 \cdot c_{\mathrm{O\&M}}}{(1+H)^t} \tag{30}$$

where $c_{\mathrm{f,m}}$ is the cost of fuel in the first year on a mass basis ($c_{\mathrm{f,m}}$ = 0.334 US$/kg) and $c_{\mathrm{O\&M}}$ is the cost rate of operation and maintenance ($c_{\mathrm{O\&M}}$ = 100 US$/h). It must be remarked that the exchange rate, electrical energy and process steam prices, and fuel and O&M costs are input economic parameters dictated by the market, and may consequently vary in time. Therefore, the values adopted for these parameters in the present work must be viewed as reference values for the MPCP problem with the correct orders of magnitude, but they are not necessarily representative of the market reality in a given period of time.

Developing Eq. (26) for the objective function in the Mathematica® program (Wolfram, 1999), NPV can finally be expressed as a function of the two selected decision variables for the MPCP problem (Costa, 2008; Costa et al., 2008); the appropriate general equation with the problem parameters is

$$NPV\left(\varepsilon_{GTG},\, \dot{m}_{s,PR}\right) = \tau\Big[3.8013\cdot10^{6}\Pi_{EE} - 77465.9\cdot c_{O\&M} + 4.56156\cdot10^{8}\cdot\dot{m}_{s,PR}\cdot\Pi_{s,PR}\cdot\frac{c_{f,m}\cdot\left(-2.83071\cdot10^{8} - 15914.9\cdot\dot{m}_{s,PR}\right)}{\varepsilon_{GTG}} -$$

$$\beta\cdot\Bigg[\frac{2.75457\cdot10^{11}\cdot\varsigma_{IC,GTG}\cdot\varepsilon_{GTG}}{0.663245+16768\cdot\varepsilon_{GTG}} + 1.33333\cdot\varsigma_{IC,HRSG}\cdot\Big[101035 +$$

$$\frac{1.7968\cdot\left(30750+1.72883\cdot\dot{m}_{s,PR}\right)\cdot\ln\left[\dfrac{2.71523\cdot10^{6}+152.656\dot{m}_{s,PR}}{1.62601\cdot10^{7}+914.179\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-1.75986\cdot10^{6}\dot{m}_{s,PR})\varepsilon_{GTG}}\right]}{\varepsilon_{GTG}} +$$

$$\frac{847236\dot{m}_{s,PR}\cdot\left(30750+1.72883\dot{m}_{s,PR}\right)\cdot\ln\left[\dfrac{2.15092\cdot10^{7}+1209.29\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-2.33587\cdot10^{6}\dot{m}_{s,PR})\varepsilon_{GTG}}{1.85449\cdot10^{7}+1042.63\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-2.04093\cdot10^{6}\dot{m}_{s,PR})\varepsilon_{GTG}}\right]}{2.9643\cdot10^{6}+166.659\cdot\dot{m}_{s,PR}-294943\dot{m}_{s,PR}\cdot\varepsilon_{GTG}} -$$

$$\frac{807375\dot{m}_{s,PR}\cdot\left(30750+1.72883\dot{m}_{s,PR}\right)\cdot\ln\left[\dfrac{1.9123\cdot10^{7}+1075.13\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-2.04093\cdot10^{6}\dot{m}_{s,PR})\varepsilon_{GTG}}{1.64139\cdot10^{7}+922.823\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-1.75986\cdot10^{6}\dot{m}_{s,PR})\varepsilon_{GTG}}\right]}{2.70908\cdot10^{6}+152.31\cdot\dot{m}_{s,PR}-281067\dot{m}_{s,PR}\cdot\varepsilon_{GTG}} -$$

$$\frac{803193\dot{m}_{s,PR}\cdot\left(30750+1.72883\dot{m}_{s,PR}\right)\cdot\ln\left[\dfrac{1.62601\cdot10^{7}+914.179\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-268987\dot{m}_{s,PR})\varepsilon_{GTG}}{1.35449\cdot10^{7}+761.523\dot{m}_{s,PR}+(-2.22735\cdot10^{7}-1252.27\dot{m}_{s,PR})\varepsilon_{GTG}}\right]}{2.71522\cdot10^{6}+152.656\dot{m}_{s,PR}-267734\dot{m}_{s,PR}\cdot\varepsilon_{GTG}}\Big]\Bigg]\Big]. \quad (31)$$

Optimization Processes and Results

On substituting the prescribed values for τ, β, $\zeta_{IC,GTG}$, $\zeta_{IC,HRSG}$, Π_{EE}, $c_{O\&M}$, $\Pi_{s,PR}$ and $c_{f,m}$ in Eq. (31), the objective function *NPV* may thus be expressed (and stored) solely in terms of ε_{GTG} and $\dot{m}_{s,PR}$. The MPCP problem can then be solved, i.e., the optimal values ε^*_{GTG} and $\dot{m}^*_{s,PR}$ as well as the global maximum value NPV^* of the objective function can be pursued through an optimization process. Here, first, the *NMaximize* tool of the Mathematica® optimization toolbox is used – as in Costa and Cruz (2008), which selects automatically the Nelder&Mead Simplex optimization algorithm (Wolfram, 1999).

The allowable interval of variation for the exergetic efficiency is 29% ≤ ε_{GTG} ≤ 35% to guarantee realistic values for the efficiency, compatible with those of manufacturers of gas turbine generators. Furthermore, the allowable interval of variation for the mass flow rate of process steam is 12 kg/s ≤ $\dot{m}_{s,PR}$ ≤ 20 kg/s, to be consistent with the interval for ε_{GTG} and with the constraints $\Delta T_{pp} \geq 10$ °C and $T_6 \geq$ 100°C. Two initial points are used to start the optimization process, respectively corresponding to the following values of the decision variables: $\dot{m}_{s,PR}$ = 14 kg/s, ε_{GTG} = 30% and $\dot{m}_{s,PR}$ = 13 kg/s, ε_{GTG} = 32%. On executing the *NMaximize* tool starting from either initial point, it returns the following optimal values: NPV^* = R$ 177,770,000.00, ε^*_{GTG} = 35% and $\dot{m}^*_{s,PR}$ = 13.579 kg/s. The final values of the constrained variables are ΔT_{pp} = 10°C and T_6 = 114.6°C.

To further certify the results obtained through the *NMaximize* optimization tool, the same objective function and constraints are submitted to a second optimization process, using the optimization tool *fmincon* of the MatLab® program (The MathWorks, 2005). This tool uses an integrated combination of the SQP – Sequential Quadratic Programming, Quasi-Newton and Linear Search methods. On executing the *fmincon* tool, starting from either initial point, it returns to the following optimal values: NPV^* = R$ 177,770,000.00, ε^*_{GTG} = 35% and $\dot{m}^*_{s,PR}$ = 13.579 kg/s, which exactly match the results obtained through the Mathematica® program. It is then confirmed that the optimization processes are robust, and that the results are correct and validated for reference.

To close this part, a brief sensitivity analysis is performed to investigate the behavior of the objective function and decision variables as some changes are effected in the prices of electrical energy and process steam. Specifically, when the price of electrical energy in the first year is reduced to Π_{EE} = 71.25 US$/MWh, while all other values are maintained, the new results are: NPV^* = R$ 170.19 (close to zero), ε^*_{GTG} = 35% and $\dot{m}^*_{s,PR}$ = 13.58 kg/s. The corresponding values of the constrained variables are ΔT_{pp} = 10°C and T_6 = 114.6°C. On the other hand, when the price of process steam in the first year is reduced to $\Pi_{s,PR}$ = 0.005 US$/kg, while all other values are maintained, the new results are: NPV^* = R$ 30,901,160.00, ε^*_{GTG} = 35% and $\dot{m}^*_{s,PR}$ = 13.20 kg/s. The corresponding values of the constrained variables are ΔT_{pp} = 17.75°C and T_6 = 124.9°C. The sensitivity analysis indicates that the optimization process really advances towards the maximum allowable ε_{GTG}. When the steam price is reduced, some reduction in steam production is verified, with consequent reduction in the HRSG cost. Overall, it can be observed that there is a strong tendency to obtain high global efficiency in order to maximize the *NPV*. A thorough sensitivity analysis, while useful, is beyond the scope of the present study, and is left as a suggestion for future work.

Conclusions

The proposal, modeling and solution of the MPCP thermoeconomic optimization problem exposed in this paper successfully lead to a relatively simple objective function formulation and a profit-optimal cogeneration system, which is compatible with the Brazilian industrial reality. It is hoped that the thermodynamic and economic modeling will be useful to designers of real cogeneration systems of similar sizes. Also, the problem formulation is simple enough to serve as an application for different types of thermoeconomic optimization techniques. Two aspects of the MPCP problem represent important contributions, and should be remarked. First, as commonly observed in practice, the products of the plant (electricity and process steam) are not both fixed. Thus, the optimum search process must match the electrical power demand, but may vary steam equipment and production to maximize the NPV. Second, statistical analyses have been carried out, to obtain the main equipment costs practiced in the national market. Such costs are not easily available in the literature.

The resulting optimal values show that, for the established sale prices of electrical energy and process steam, the maximum *NPV* corresponds to the maximum allowable value for the GTG exergetic efficiency and to a process steam flow rate which leads to the minimum value of ΔT_{pp} in the HRSG. Even when the prices of electrical energy and process steam are reduced individually, the optimization process reaches the maximum allowable GTG exergetic efficiency. It can thus be ascertained that it pays to design cogeneration systems of the size considered here with high global efficiency. This conclusion makes one realize that it appears possible to conciliate the goal of maximum economic gain with the reduction of greenhouse gases emissions and conservation of natural resources.

Acknowledgements

M. E. Cruz gratefully acknowledges support from CNPq (Grants PQ-302725/2009-1 and 470306/2010-6).

References

Alves, L.G. and Nebra, S.A., 2004, “Basic Chemically Recuperated Gas Turbines-Power Plant Optimization and Thermodynamics Second Law Analysis”, Energy, Vol. 29, No. 12-15, pp. 2385-2395.

Bejan, A., Tsatsaronis, G. and Moran, M., 1996, “Thermal Design and Optimization”, John Wiley & Sons, New York, NY, 542 p.

Blank, L. and Tarquin, A., 2005, “Engineering Economy”, 6th ed., McGraw-Hill Series in Industrial Engineering and Management, New York, NY, 770 p.

Cardona, E. and Piacentino, A., 2007, “Optimal Design of CHCP Plants in the Civil Sector by Thermodynamics”, Applied Energy, Vol. 84, No. 7-8, pp. 729-748.

Costa, A.N., 2008, “Profit Optimization of Cogeneration Plants: MPCP Problem Modeling”, M.Sc. Dissertation (in Portuguese), PEM/COPPE/UFRJ, Rio de Janeiro, RJ, Brazil.

Costa, A.N. and Cruz, M.E.C., 2008, “Solution of the MPCP Optimization Problem Using the Mathematica Program”, Proceedings of the 12th Brazilian Congress of Thermal Engineering and Sciences (ENCIT), Paper 4-5475, ABCM, Rio de Janeiro, RJ, Brazil.

Costa, A.N., Neves, M.V.S., Cruz, M.E.C. and Vieira, L.S.R., 2008, “Modeling of the MPCP Problem: An Alternative to the CGAM Problem” (in Portuguese), Anais do V Congresso Nacional de Engenharia Mecânica (CONEM), Paper CON08-0881, ABCM, Rio de Janeiro, RJ, Brazil.

Dincer, I. and Rosen, M.A., 2007, “Exergy, Energy, Environment and Sustainable Development”, Elsevier Ltd., Oxford, UK, 454 p.

Junior, S.O. and Borelli, S.J.S., 2008, “Exergy-Based Method for Analyzing the Composition of the Electricity Cost Generated in Gas-Fired Combined Cycle Plants”, *Energy*, Vol. 33, No. 2, pp. 153-162.

Koch, C., Cziesla, F. and Tsatsaronis G., 2007, “Optimization of Combined Cycle Power Plants Using Evolutionary Algorithms”, Chemical Engineering and Processing: Process Intensification, Vol. 46, No. 11, pp. 1151-1159.

Kwon, Y.-H., Kwak, H.-Y. and Oh S.-D., 2001, “Exergoeconomic Analysis of Gas Turbine Cogeneration Systems”, *Exergy, Int. J.*, Vol. 1, No. 1, pp. 31-40.

Lazzaretto, A. and Tsatsaronis, G., 2006, “SPECO: A Systematic and General Methodology for Calculating Efficiencies and Costs in Thermal Systems”, *Energy*, Vol. 31, No. 8-9, pp. 1257-1289.

Milia, D. and Sciubba, E., 2006, “Exergy-Based Lumped Simulation of Complex Systems: An Interactive Analysis Tool”, *Energy*, Vol. 31, No. 1, pp. 100-111.

Park, C.S., 2010, “Contemporary Engineering Economics”, 5th ed., Prentice Hall, Inc., Upper Saddle River, NJ, 960 p.

Paulus, D.M. and Tsatsaronis, G., 2006, “Auxiliary Equations for the Determination of Specific Exergy Revenues”, *Energy*, Vol. 31, No. 15, pp. 3235-3247.

Rosen, M.A. and Dincer, I., 2003, “Exergy-Cost-Energy-Mass Analysis of Thermal Systems and Processes”, *Energy Conversion and Management*, Vol. 44, No. 10, pp. 1633-1651.

Sciubba, E., 2001, “Beyond Thermoeconomics? The Concept of Extended Exergy Accounting and Its Application to the Analysis and Design of Thermal Systems”, *Exergy, Int. J.*, Vol. 1, No. 2, pp. 68-84.

The Mathworks, Inc., 2005, “Learning MatLab 7 – MathLab & Simulink, Student Version”, Natick, MA (http://www.mathworks.com).

Thermoflow, Inc., 2004, “GT PRO Manual”, Sudbury, MA (http://www.thermoflow.com).

Tsatsaronis, G., 1993, “Thermoeconomic Analysis and Optimization of Energy Systems”, *Progress in Energy and Combustion Science*, Vol. 19, No. 3, pp. 227-257.

Tsatsaronis, G. (guest editor), 1994, “Special Issue, Invited Papers on Exergoeconomics”, Energy, Int. J., Vol. 19, No. 3, pp. 279-381.

Tsatsaronis, G., 2007, “Definitions and Nomenclature in Exergy Analysis and Exergoeconomics”, *Energy*, Vol. 32, No. 4, pp. 249-253.

Valero, A., 2006, “Exergy Accounting: Capabilities and Drawbacks”, *Energy*, Vol. 31, No. 1, pp. 164-180.

Valero, A., Correas, L., Zaleta, A., Lazzaretto, A., Verda, V., Reini, M. and Rangel, V., 2004, “On the Thermoeconomic Approach to the Diagnosis of Energy System Malfunctions Part 1: the TADEUS Problem”, *Energy*, Vol. 29, No. 12-15, pp. 1875-1887.

Vieira, L.S., Donatelli, J.L. and Cruz, M.E., 2004, “Integration of an Iterative Methodology for Exergoeconomic Improvement of Thermal Systems With a Process Simulator”, *Energy Conversion and Management*, Vol. 45, No. 15-16, pp. 2495-2523.

Vieira, L.S., Donatelli, J.L. and Cruz, M.E., 2006, “Mathematical Exergoeconomic Optimization of a Complex Cogeneration Plant Aided by a Professional Process Simulator”, *Applied Thermal Engineering*, Vol. 26, No. 5-6, pp. 654-662.

Wolfram, S., 1999, “The Mathematica Book”, 4th ed., Cambridge University Press, Cambridge, UK, 1464 p.

Zhang, C., Wang, Y., Zheng, C. and Lou, X., 2006, “Exergy Cost Analysis of a Coal Fired Power Plant Based on Structural Theory of Thermoeconomics”, *Energy Conversion and Management*, Vol. 47, No. 7-8, pp. 817-843.