EXERGOECONOMIC ANALYSIS AND OPTIMIZATION OF A COMBINED-CYCLE COGENERATION SYSTEM

Alan Carvalho Pousa, alanpousa@terra.com.br
Elizabeth Marques D. Pereira, green@pucminas.br
Felipe R. Ponce Arrieta, felipe.ponce@ibiritermo.com.br
Pontifícia Universidade Católica de Minas Gerais, av. Dom José Gaspar, 500 Coração Eucarístico - Belo Horizonte

Abstract. *Thermoeconomics is the study of connection between the Second Law of Thermodynamic and Economy, which places theoretical fundamentation on energy's economy science and obtain in this way, models that join the restraint of having an unlimited quantity of resources and criterions, which allow the evaluating of efficiency and the cost of products on systems with intensive energy consumption. Exergoeconomics is the complementation of Thermoeconomics by using economical values in cash. Once well structured, both are used as base of system optimization in order to adequate and to operate in a great point. The present work studies four different arrangements, physical scheme and productive structure, aiming structural optimization of a combined-cycle cogeneration system (gas turbine + recovery steam generator + steam turbine) generating electric power and process steam. The results found are significant and confirm the difference between the types of chosen arrangements. To exemplify, difference of cost for the electric power of a water pump varies to more than 400% (for external electric power net supply) and 90% (for internal electric power supply). The technique of Structural Thermoeconomic Theory was used for the system optimization. This technique is easier to be worked and to be changed, hence very suitable for structural optimization. It starts from the definition of the Resources (R) and the Products (P) of each component of the system in order to make possible the assemblies such as, Productive Structure, matrix calculation to generate Thermoeconomic results for each arrangement. From the knowledge of the cost per hour of the externals resources and of each component, it is possible to migrate from Thermoeconomics to Exergoeconomics and then, generate results of monetary costs for each system's flow. With these costs, it is possible to define which is the best arrangement to be chosen in order to operate in the best cost benefit.*

Keywords*: Exergoeconomics, Thermoeconomics, Cogeneration, Optimization*

1. INTRODUCTION

Thermoeconomics is the application of exergy for the formation of exergetic cost allocation.

The first resources using this technique happened in 1950 with M. Tribus and R. B. Evans of University of California – USA, where the first mathematical formulation was constituted for Thermoeconomics.

In the decade of 80 and 90, A. Valero and M. A. Lozano, of Zaragoza University in Spain, highlighted themselves for their several contributions in the subject of Thermoeconomics.

According to Cerqueira (1999), Thermoeconomics is used in practical situations of cogeneration's systems such as refineries, sugar and alcohol mills, cellulose industries, etc. Thermoeconomics method is also used in the project phase, on-line monitoration of the operation and for maintenance.

2. OBJECTIVE

The aim of this work is to evaluate a thermal system and to propose an option for Thermoeconomic optimization, based on setup changes of the thermal system's arrangement. The system evaluated was a cogeneration plant (electricity and process steam).

The motivation for this optimization proposal was the significant sensibility experienced in the Thermoeconomics and Exergoeconomics results during light changes in the setup of the system's arrangement. Hence, these changes should be considered in order to make the best choice for the system operation.

The optimization proposed will be introduced during the development and evaluation of the cogeneration system.

3. BIBLIOGRAPHICAL REVIEW

Thermoeconomics is used to indicate the combination of exergy and economical analysis. The fundamental characteristic of this type of analysis is the allocation of the costs in function of the exergy.

In 1983, the term "Exergoeconomics" was introduced to define, in a clear way, the method that combines the exergy and economical analysis (Tsatsaronis, 1983). In other words, it is the complement and a form of cost allocation using as base the Thermoeconomic theory.

Besides, once well structured, Thermoeconomics serves as base for systems optimization in order to adapt it to operate in a great point in the optics of the Thermodynamic and of economy.

As in this method exists the interaction of the flows of each component, in other words, the entrance flow of a component is related to the exit flow of another component and vice-versa, with the application of Thermoeconomics it is possible to optimize systems and to reach Thermoeconomic cost minimization of a flow in study.

There are many Brazilian works, for example, Modesto et al. (2003), Santana and Torres (2005), Santos et al. (2005), Higa et al. (2007) and Graciano and Matos (2007) where were discussed the Thermoeconomic optimization based on changes of the system's components or types of thermal cycles.

3.1. The Thermoeconomics Theories

In 1983, Frangopoulos developed the methodology of the Thermoeconomic Functional Analysis. In this analysis, a complex cogeneration system, for example, is composed of several interrelated units.

Each system unit, which can represent by an equipment or a component, has a product that determines the relationship with others equipments/components and with the environment. The units can also be virtual, as junctions (which receive several components products) and/or ramifications/bifurcations (which distribute a single product for several units).

Tsatsaronis and his collaborators (Tsatsaronis and Winhold, 1985; Tsatsaronis and Pisa, 1994) developed the Exergoenomic Methodology, which considers, in first analysis, the determination and identification of the energy and exergetics flows, installation and maintenance cost. With this information it is possible to generate the balance for each unit in order to obtain the exergetic costs. This methodology can be better studied in Cerqueira (1999) work.

Lozano and Valero (1993) developed the Exergetic Cost Methodology. In this methodology, the authors enumerated a group of postulates in order to generate equations to determine the exergetics costs of thermal system's flows. They also developed the graph model called "Productive Structure" based on the physical scheme of the thermal system.

The generated equations in this method are then inserted and organized into matrixes in which their solution indicates that the system and its productive structure converge. More details of this methodology can be found in Arrieta (2000) work.

A variant of the Exergetic Cost Methodology is the Structural Methodology. The proposal of this methodology is to visually facilitate the Productive Structure assembly by including ramifications and junctions (already proposed in the functional analysis) and then, it facilitates the equating method.

In spite of facilitating, this methodology, due to the fact of ramifications and junctions inclusions, turns the representation of the Productive Structure larger as well as the equations system. This is the methodology that will be used in this work.

3.2. The Structural Thermoeconomic Theory

According to 2nd Law of the Thermodynamics it is important to observe that:

$$\textit{(Entry Exergy) - (Exit Exergy) = Irreversibility} > 0 \tag{1}$$

In other words:

$$\textit{Resource (R) – Product (P) = Irreversibility (I)} > 0 \tag{2}$$

The Equations (1) and (2) are identical, but with different nomenclatures for each portion. These two equations are, in summarized terms, the 2nd Thermodynamic Law equation.

Besides that, another important relation, Eq. (3), to be presented is the exergetic efficiency (ε) for the 2nd Law of the Thermodynamics:

$$\varepsilon = \frac{\Pr oduct\,(P)}{\operatorname{Re} source\,(R)} \tag{3}$$

The reviewing of these definitions is very important for the study and understanding of this Thermoeconomic methodology.

The Resources, R, are considered as all the inputs consumed for the generation of the Product, P, for its turn, the net result generated by a system's component. Classics examples are the gas turbines where the fuel is the resource and the electric power is the product. It is important to remember that even resources and products are exergies. Hot gases exhausted to the atmosphere without any profit are considered as losses and its exergetic cost (B^*) is zero.

Like $R>P$, it can be affirmed "*the obtainment of a product always generates residues or undesirable products, because of that, it is important and necessary to pay attention and treat these losses (Irreversibility) of the process*". According to Cuandra and Valero (2000), the balance of exergy allows quantifying the losses (Irreversibility), however, the most important is not the exergy that a product or resource can contain, but its exergetic cost.

The following Eq. (4) presents the exergetic cost.

$$B^* = B + \sum_{process} I \tag{4}$$

where B^* is the exergetic cost and B is the exergy.

The Eq. (4) shows that the cost production generation is formed by the sum of the system's irreversibilities. Hence, though the exergy balance allows locating the losses, it is necessary a detailed analysis of the entire process, when it is desired to quantify and to identify the origin of the loss in the production process.

In general, the cost of a product is the amount of resources for its obtaining.

The exergetic cost for a simple process (k), presented in the Eq. (5) below, is the ratio of exergetic consumption or resource (R) by the product (P), in other words, the inverse of exergetic efficiency (ε).

$$k = \frac{F}{P} = k^* \tag{5}$$

where k^* is the unitary exergetic cost.

As already explained, all of the processes are chained, in other words, the input of a process is product of another, which for its time consumes inputs that are products of other previous processes.

In this way, the exergetic cost of a product is the exergy plus the sum of the accumulated irreversibilities along the process.

According to Arrieta (2008), it is possible to define the exergetic cost from:

- The limits of a process and its components;
- The function of the components that defines its production objective;
- The employed inputs in the process and its components;
- The efficiency of the process and its components.

In complex energy processes, the system's productive structure has a predominant role for studying its efficiency and costs.

The Thermoeconomic Structural theory is a methodology that formulates a procedure of costs allocation, based on echoing the resources costs of each equipment in an exclusive way to their useful products and proportional to their exergies. It is essentially a numeric technique that allows quantifying the costs, starting from the exergies values of the flows.

The first step to identify the process of cost formation is to create a table identifying the Resources (R) and Products (P) from the physical scheme of the thermal system.

After defined the table of Resources and Products, it is elaborated the productive scheme, in other words, the Productive Structure, which indicates where the product of each component is used, which part is used as resource in other component and which part turns the system's net product. It also reveals which are the origins of the resources of each component.

To elaborate a productive structure using the Structural Thermoeconomic theory it is necessary to proceed with the following rules:

A – The physical components of the system are drawn in rectangle form and they only have one entry and one exit and follow the Eq. (6) form:

$$k^*_{P,j} = k^*_{R,i} \cdot k_{ij} \tag{6}$$

where k_{ij} is the reason between resource and product of each component, $k^*_{P,j}$ is the unitary exergy cost of exit (product), $k^*_{R,i}$ is the unitary exergy cost of entry (resource). For each component there is only one equation.

B – The junctions, represented by the lozenges, are used to connect common points of component's products or external resources that will be only one resource for other component, or that together (in this case products) will be the useful produced product. The junctions receive many entries but have only one exit. Each junction is an equation like the Eq. (7) below:

$$k^*_{P,j} = \sum_i r_{ij} \cdot k^*_{R,i} \tag{7}$$

where r_{ij} is the reason between the exit exergy for each admission exergy.

C – The bifurcations, represented by the circumferences, are used to distribute a resource or product flow to others components, to be in part, resources of others components and in other part a useful product of a plant. They have one entry and many exits. Each exit of the bifurcation has an equation like the following Eq. (8):

$$k^*_{P,j} = k^*_{R,j} \tag{8}$$

D – External resources, for the Thermoeconomics, have the unitary exergetic cost (k*) equal to one, yet for the Exergoeconomics, this value is the acquisition cost of this resource multiplied by the inverse of its own exergy value.

E – The numbering of the mounted Productive Structure is ruled in the following manner:

E.1 – First, it is numbered with Romans algorisms all external resources and then, the components (identified as rectangles). Then it is numbered the junctions and at last, the bifurcations (one number for each exit).

E.2 – Once finished the Romans algorisms numbering, it is started the numbering of the flows lines, with Arabics algorisms. It is suggested that it initiates from the external resources. The quantity of Arabics algorisms numbers must be the same of Romans algorisms.

F – Finally, all flow lines are identified with their respective entrances and exits exergies for the components, bifurcation and junctions.

The understanding and application of these rules must be followed in order to generate accurate Thermoeconomic results.

The Structural Thermoeconomic theory comes to results of Thermoeconomic and Exergoenconomic costs through the matrix equation represented by Eq. (9) below:

$$[A]x[D]=[Ce] \tag{9}$$

where *[A]* is the square matrix containing the k values of each component, *[D]* is the column vector containing k* (this is the vector to be calculated) and *[Ce]* is the column vector with external valorization. All the values contained are non-dimensional, for the Exergoeconomic cost evaluation, the column vector *[Ce]* has data with dimensional values, for example, $/MWh.

4. CASE EVALUATED

The system studied in this work was a combined-cycle cogeneration plant composed of a 41.42 MWe gas turbine associated to a heat recovery steam generation (HRSG) coupled to a 8.60 MWe steam turbine. The 250.00 kPa steam process is extracted from the steam turbine at 15.00kg/s.

The Figure 1 below presents the physical scheme of the cogeneration plant studied.

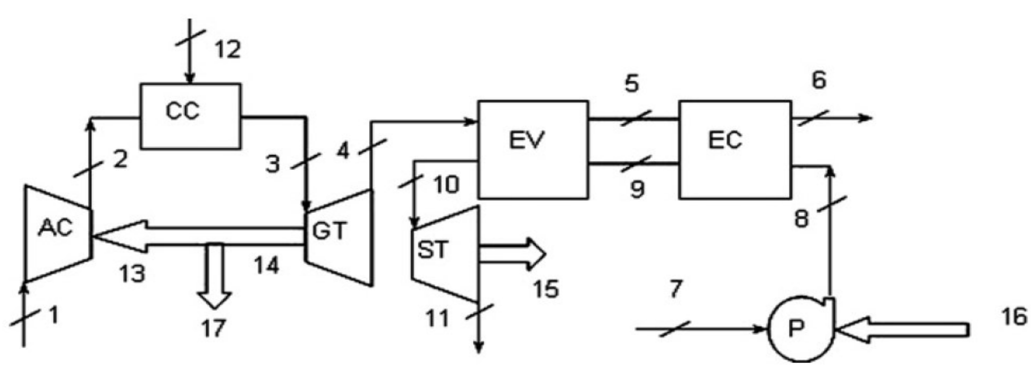

Figure 1. Cogeneration system studied

The following Table 1 shows the main Thermodynamic proprieties of the cogeneration plant above presented in order to calculate the Thermoeconomic and Exergoeconomic values.

Table 1. Thermodynamic proprieties.

Point	$\dot{m}$	**T**	**p**	**h**	**s**	**B**
	(kg/s)	(K)	(kPa)	(kJ/kg)	(kJ/kgK)	(MW)
1	96.31	298.10	101,00	-164.50	67844.00	0.00
2	96.31	515.80	101,30	60.50	68520.00	19.70
3	98.79	1500.00	962,00	-83.30	83686.00	108.40
4	98.79	1002.50	113,00	-721.90	84865.00	41.90
5	98.79	726.80	107,00	-1054.60	81141.00	20.00
6	98.79	598.00	102,00	-1203.80	79034.00	11.40
7	15.00	298.10	101,00	104.90	0.37	0.00
8	15.00	299.60	5000,00	115.60	0.39	0.10
9	15.00	525.80	4900,00	1098.20	28151.00	4.00
10	15.00	710.30	4802,00	3289.40	67999.00	19.00
11	15.00	400.60	250,00	2716.50	70525.00	9.30
12	2.48	298.10	1013,00	-4672.80	21875.00	127.50

Where for each point: $\dot{m}$ is the mass flow, T is the temperature, p is the pressure, h and s are, respectively, the enthalpy and entropy per unit of mass.

Economic parameters for the cost of the plant components are shown in the Tab. 2 below. These data, presented in USD Dollar per hour, are a miscellany of many costs related for each component, for example, initial investment cost, installation, maintenance and operation.

Table 2. Component cost for the cogeneration system studied.

Plant Component	$/h
Fuel (F)	5743.68
Combustion Chamber (CC)	11.78
Air Compressor (AC)	133.44
Gas Turbine (GT)	102.41
Economizer (EC)	96.27
HRSG Evaporator (EV)	26.46
Pump (P)	0.9
Steam Turbine (ST)	10.28

The information about the Resources (R) and Products (P) for the plant presented can be seen in the Tab. 3 below.

Table 3. Resources and Products identification.

Component	Resource (MW)	Product (MW)
Combustion Chamber	B12+B2	B3
Air Compressor	B13	B2
Gas Turbine	B3-B4	B14
HRSG Evaporator	B4-B5	B10-B9
Economizer	B5-B6	B9-B8
Pump	B16	B8
Steam Turbine	B10-B11	B15
Plant	B12	B17+B15+B11

As explained, the Structural Thermoeconomic theory technique, in order to organize and represent the Resources and Products, needs the representation of the Productive Structure (PS) based on the physical scheme. With the information provided above, it is possible to assembly the PS of the cogeneration plant studied. The following Fig. 2 represents the PS for the case studied.

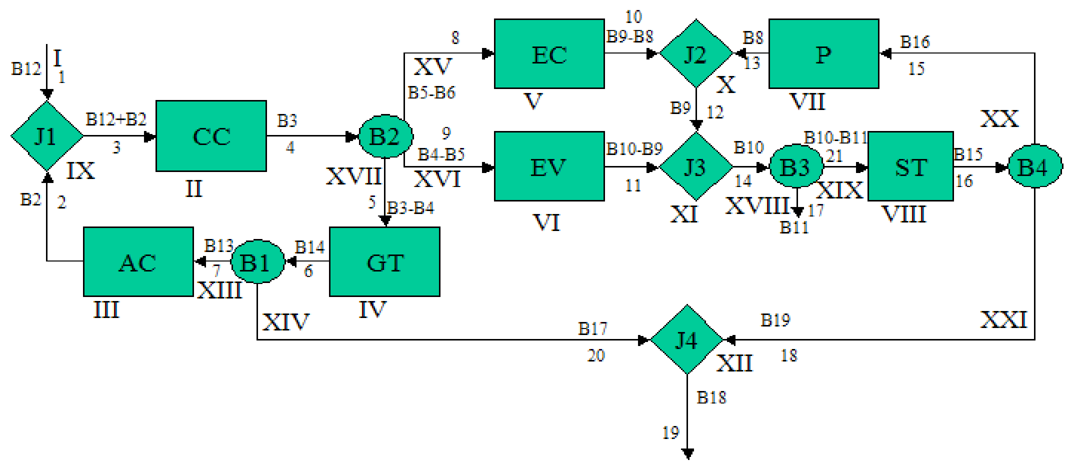

Figure 2. Productive Structure for the system analyzed

Where the letter B, into the circles, are the bifurcations and letter J, into the lozenges, are the junctions.

With all these information gathered, it was possible to mount the Thermoeconomic equations, assembly them into the matrix and generate the Thermoeconomic and Exergoeconomic results.

The following table, Tab. 4, shows the equations developed for the PS setup presented in Fig. 2.

Table 4. Thermoeconomic developed Equations.

Eq. Number	Equation	Eq. Number	Equation
I	$k^*_1=1$	XII	$k^*_{19}=r_{18\text{-}19} \cdot k^*_{18} + r_{20\text{-}19} \cdot k^*_{20}$
II	$k^*_4=k_{cc} \cdot k^*_3$	XIII	$k^*_7=k^*_6$
III	$k^*_2=k_{ac} \cdot k^*_7$	XIV	$k^*_{20}=k^*_6$
IV	$k^*_6=k_{gt} \cdot k^*_5$	XV	$k^*_8=k^*_4$
V	$k^*_{10}=k_{ec} \cdot k^*_8$	XVI	$k^*_9=k^*_4$
VI	$k^*_{11}=k_{ev} \cdot k^*_9$	XVII	$k^*_5=k^*_4$
VII	$k^*_{13}=k_p \cdot k^*_{15}$	XVIII	$k^*_{17}=k^*_{14}$
VIII	$k^*_{16}=k_{st} \cdot k^*_{21}$	XIX	$k^*_{21}=k^*_{14}$
IX	$k^*_3=r_{1\text{-}3} \cdot k^*_1 + r_{2\text{-}3} \cdot k^*_2$	XX	$k^*_{15}=k^*_{16}$
X	$k^*_{12}=r_{10\text{-}12} \cdot k^*_{10} + r_{13\text{-}12} \cdot k^*_{13}$	XXI	$k^*_{18}=k^*_{16}$
XI	$k^*_{14}=r_{12\text{-}14} \cdot k^*_{12} + r_{11\text{-}14} \cdot k^*_{11}$		

The matrix equation obtained by these equations is shown in the following adaptable table, Tab. 5.

Table 5. Thermoeconomic/Exergoeconomic matrix calculus for the system.

PS flow	1	2	3	4	5	6	7	8	9	10	11	12	13	...	21					
Eq.								[A]									[D]		[Ce]	[Ce] ($/MWh)
1	1																k^*_1		1	45.05
2			k_{cc}	-1													k^*_2		0	-0.11
3		-1					k_{ac}										k^*_3		0	-6.77
4					k_{gt}	-1											k^*_4		0	-1.62
5								k_{ec}		-1							k^*_5		0	-24.68
6									k_{ev}		-1					x	k^*_6	=	0	-1.76
7													-1	...			k^*_7		0	-9.00
8															k_{st}		k^*_8		0	-1.20
9	$r_{1\text{-}3}$	$r_{2\text{-}3}$	-1														k^*_9		0	0.00
10										$r_{10\text{-}12}$		-1					k^*_{10}		0	0,00
11											$r_{11\text{-}14}$		$r_{12\text{-}14}$				k^*_{11}		0	0,00
12																	k^*_{12}		0	0,00
13						1	-1										k^*_{13}		0	0.00
⋮								⋮									⋮		⋮	⋮
21																	k^*_{21}		0	0.00

The last right column in this table shows the option for Exergoeconomics calculation.

The optimization proposed in this work, in order to obtain the correct and the best results, must pass through all these Thermoeconomic theory. One of the optimization types was the previously presented in the Fig. 2, in this case, this setup represents the type n^o 4 of the four options of arrangement optimization studied.

Although it generates the same energetic and exergetic values, each arrangement studied has its own optimization propose in which generates different Thermoeconomic and Exergoeconomic values. In order to create different arrangements, few modifications in the equations and in the PS must be done.

The arrangements were created following the above setup criteria:

- Type 1 → Pump's electric power consumed by the external Electric power net;
- Type 2 → Pump's electric power consumed by the total Electric power generated by the GT and ST;
- Type 3 → Pump's electric power consumed by the Electric power generated by the GT;
- Type 4 → Pump's electric power consumed by the Electric power generated by the ST.

5. RESULTS AND DISCUSSION

The following table, Tab. 6, shows the exergetic efficiency (ε) for the four types of arrangements of the cogeneration plant.

Table 6. Exergetic efficiency for the different arrangements.

Type	1	2	3	4
ε (%)	46.52%	46.39%	46.39%	46.39%

As it can be seen, there were no significant changes in their exergetic efficiency.

The following figure, Fig. 3, shows the four types of arrangements optimization studied and their effects in the Thermoeconomic results, represented by B^*, and in the Exergoeconomic results, represented by C, for the pump, gas turbine, fuel, process steam and steam turbine.

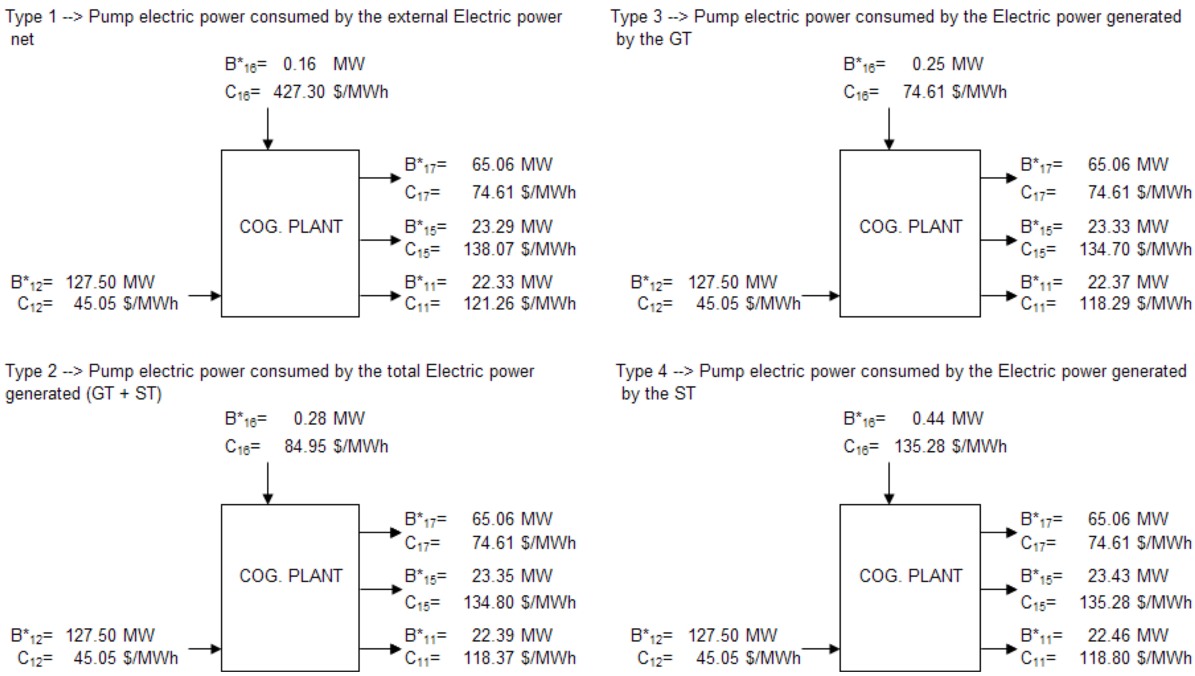

Figure 3. Arrangement optimization scheme

As it can be seen, the four types of arrangement optimization didn't have any influence in the Thermoeconomic and Exergoeconomic values for the external fuel (B^*_{12} and C_{12}) and for the gas turbine product (B^*_{17} and C_{17}). Also, no significant influence occurred in the Thermoeconomics for the process steam (B^*_{11}) and steam turbine electric power (B^*_{15}).

The differences in values were experienced in:

A – Thermoeconomic values of the pump resource (B^*_{16}):

- → For the type 1, the value 0.16 MW was due the consideration of using the value of exergy of the external resources of the plant, in this case electric power. The biggest value occurred in the type 4, because it uses the electric power produced by the steam turbine in which has the water steam as its resource.

B – Exergoeconomic values of the pump resource (C_{16}), steam turbine product (C_{15}) and process steam (C_{11}):

- → Type 1 had the biggest value for the pump resource, C_{16} = 427.30 $/MWh. This can be explained due the fact of using external electric power net supply to the pump. In terms of percentage, it is 472.75% bigger than type 3. The second biggest value was the type 4, because the steam turbine has the water steam as its resource.
- → Yet for type 1, the steam turbine product, C_{15} = 138.07 $/MWh, was the biggest value among the others types of arrangement. The reason is due the high cost of the pump resource in this arrangement type that affects the final cost of the steam turbine electricity. The second biggest value occurred in the type 4, also because of the high cost of pump resource.
- → Similarly, again for the type 1, the process steam, C_{11} = 121.26 $/MWh, and its value for the type 4, 118.80 $/MWh, was respectively, the first and second highest values in the optimization study.

The optimization arrangement type 3 is the most economical, because it presented the lowest Exergoeconomics values for resources and products.

It can be seen that a simple change in the system setup, for example, different methods for the pump's resource, made very significant changes in values of cost using the Thermoeconomic theory of cost allocation.

For each arrangement proposed, the Thermoeconomic theory considers the setup features in order to calculate the correct cost of each flow.

The electric power costs calculated can be also used in order to indicate the sale prices of this energy to external users.

Hence it is important to know the products costs of the steam turbine and gas turbine separated in order to decide the correct prices for each electric power generator. Moreover, for operation and maintenance, for example, it is also very important this knowledge in order to decide where to focus more, having as reference the Thermoeconomic and Exergoeconomic values.

6. CONCLUSIONS

The arrangement optimization proposed in this work was able to generate the best economical option for different system setup and showed that Thermoeconomic optimization also depends on the setup chosen (destination of electric power flow, for example), suggesting that the system's setup should be considered in all optimization process, mainly when the system has one type of energy, like electric power, generated from two different components.

All the arrangements proposed in this work have its own proposal, in others words, the choice of one or the commutation from one to another must be analyzed very carefully through the Thermoeconomic and Exergoeconomic values and business goals.

7. REFERENCES

Arrieta, F.P., 2000, "Utilização do Gás Natural como Combustível Complementar em Sistemas BIG para a Cogeração no setor Sucro-Alcooleiro", Mh.D. Dissertação, Instituto de Engenharia Mecânica da Escola Federal de Engenharia de Itajubá, MG.

Cerqueira, S.A., 1999, "Metodologias de Análise Termoeconômica de Sistemas", Ph.D. Thesis, Faculdade de Engenharia Mecânica da Unicamp, Campinas, SP.

Cuandra, C.T. and Valero, A., 2000, "Curso de Doctorado Termoeconomía", Departamento de Ingenieria Mecánica de la Universidad de Zaragoza, España.

Frangopoulos, C.A., 1983, "Thermoeconomic functional analysis: A method for optimize design or optimization of complex thermal systems", Ph.D. Thesis, Georgia Institute of Technology, Atlanta, USA.

Graciano, V. and Matos, R., 2007, "Thermoeconomic Analysis and Optimization of a Thermal Power Plant: Case Study- Figueira Power Plant", Proceedings of the 19th Brazilian Congress of Mechanical Engineering, Vol.1, Brasília, Brazil.

Higa, M., Gonçalvez T. and Titerickz T., 2007, "Thermal Analysis of Steam Generator System", Proceedings of the 19th Brazilian Congress of Mechanical Engineering, Vol.1, Brasília, Brazil.

Lozano, M.A. and Valero, A., 1993, "Theory of the exergetic cost; Energy", Vol. 18, No. 9, pp. 939-960.

Modesto, M., Nebra, S. and Morimoto, T., 2003. "Analysis of a Steel Mill Power System using Exergoeconomic factors", Proceedings of the 17th Brazilian Congress of Mechanical Engineering, Vol.1, São Paulo, Brazil.

Santana, G. and Torres, E., 2005, "Exeregoconomic Analysis in Two Cogenerations Plants for a Shopping Center in Salvador", Proceedings of the 18th Brazilian Congress of Mechanical Engineering, Vol.1, Ouro Preto, Brazil.

Santos, J., Schneider, P. and Vielmo, H., 2005, "Exergoeconomic Analisys and Evaluation of Diferent Cogeneration Systems", Proceedings of the 18th Brazilian Congress of Mechanical Engineering, Vol.1, Ouro Preto, Brazil.

Tsatsaronis, G. and Winhold, M., 1985, "Exergoeconomic analysis and evaluation of energy conversion plants – 1: A new general methodology", Energy, Vol. 10, No. 1, pp. 69-80, 1985.

Tsatsaronis, G. and Pisa, J, 1994, "Exergoeconomic evaluation and optimization of energy systems – Application to the CGAM problem", Energy, Vol. 19, pp. 287-321.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.