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A COMPARATIVE STUDY OF THE THERMOECONOMIC METHODOLOGIES FOR COST ALLOCATION IN A GAS TURBINE COGENERATION SYSTEM

Pedro Rosseto de Faria
Bruno Furtado de Moura
Daniel Biasutti Clemente
José Joaquim Conceição Soares Santos
Federal University of Espírito Santo – UFES/DEM/CTIII/LFTC
Av. Fernando Ferrari 514, CEP 29.075-910, Goiabeiras, Vitória-ES, Brazil
pedro_rosseto@yahoo.com.br, bfurtado.moura@gmail.com, danielbclemente@gmail.com, jjcssantos@yahoo.com.br

Abstract. *One of the thermoeconomic methodologies challenges is to define criteria that allow allocating rationally the cost of the residues to the final products. Various methodologies were proposed in the last 25 years. However, the choice of the best residue distribution criteria among possible alternatives is still an open research line. This work compares the more widespread thermoeconomic methodologies by applying them for cost allocation in a Gas Turbine Cogeneration System. The methodologies are divided into two groups according to the kind of structure used to formulate the mathematical model representing the cost formation process: (i) three of them use the physical structure; and (ii) other five ones use the productive structure of the system. The goal is to determine the exergetic and the monetary unit cost of the internal flows and final products (power and heat). The results show that the Exergetic Cost Theory as it was originally formulated overcharges the heat unit cost in detriment of the power unit cost. On the other hand, the models that use negentropy joined up with exergy overcharges the power cost in the detriment of the heat cost. The use of exergy flow (total or disaggregated into its components) obtains coherent results. However, the disaggregation of exergy into enthalpic and entropic components avoids the necessity of the use of negentropy.*

Keywords: *Thermoeconomic Modeling, Residues, Cost Allocation, Cogeneration, Cost*

1. INTRODUCTION

Thermoeconomics can be considered a new science which, by connecting Thermodynamics and Economics, provides tools to solve problems in complex energy systems that can hardly or not be solved using conventional energy analysis techniques based on First Law of Thermodynamics (mass and energy balance), as for instance a rational price assessment to the products of a plant based on physical criteria (Erlach *et al*., 1999).Various methodologies were proposed in the last 25 years and all of them have in common a cost calculated on a rational basis, which is the Second Law of Thermodynamics (Serra and Torres, 2003). However, the choice of the best residue distribution criteria among possible alternatives is still an open research line. Different thermoeconomic methodologies can provide different cost values depending on the way they define de product/fuels of each subsystem of the plant and the criteria for the residue cost allocation to the final products. Cost validation is a key issue in thermoeconomics which has not been properly solved yet. However we consider that validation of cost can be designed using the physical behavior of the plant together with thermodynamics, because irreversibility is the physical magnitude generating cost (Valero *et al.*, 2006).

In order to compare the more widespread thermoeconomic methodologies, they are applied for cost allocation in a Gas Turbine Cogeneration System, and the results are compared based on the thermoeconomics definitions and concepts. The assumptions of each methodology are presented and their implications on the results analyzed.

The methodologies are divided into two groups according to the kind of structure used to formulate the mathematical model representing the cost formation process. The Exergetic Cost Theory (ECT), the Average-Cost Exergy-Costing Approach (AVECO) and Specific Exergy Costing (SPECO) are based on physical structure and flows.

Other five methodologies are based on the productive structure and flows. They differs one from another basically due to the thermodynamic magnitude used to valorize the internal flows of the productive structure: total exergy (E Model), exergy disaggregated into its thermal and mechanical components (E^T&E^M Model), total exergy and negentropy (E&S), exergy disaggregated into thermal and mechanical component joined up with negentropy (E^T&E^M&S Model) and exergy disaggregated into enthalpic and entropic components (H&S Model).

The influence of different criteria to formulate the auxiliary equation and to allocated the residues cost to the final products are analyzed in order to determine the exergetic and monetary unit cost of the internal flows and products.

2. PHYSICAL MODEL

The physical structure of the gas turbine cogeneration system, represented in Fig. 1, is defined as having four units (subsystems): air compressor (AC), combustion chamber (CC), gas turbine (GT) and recovery boiler (RB).

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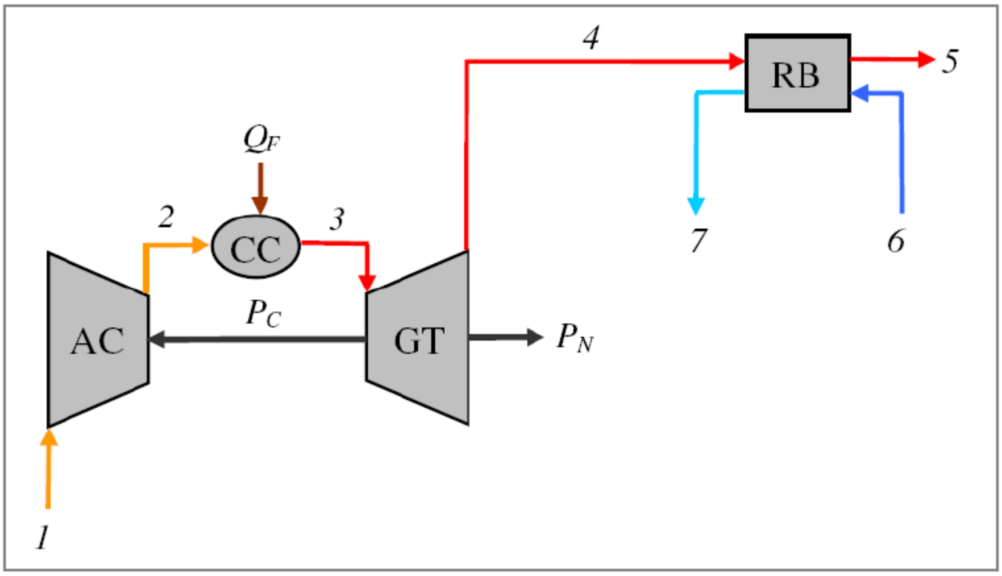

Figure 1. Physical Structure of the Gas Turbine Cogeneration System (Santos *et al*., 2010)

The thermodynamic model considers Cold Air-Standard Analysis assuming the specific heat (c_P) as constant and equal 1 KJ/Kg.K. The parameters of the main streams of the physical structure of the cogeneration system are in Tab. 1.

Table 1 - Main Parameters of the Main Physical Flows of the Gas Turbine Cogeneration System (Santos, 2009)

Physical Flows (*i*)	m [Kg/s]	p [KPa]	T [°C]
1	15.00	101.320	25.00
2	15.00	510.400	230.20
3	15.00	484.800	850.00
4	15.00	102.070	537.30
5	15.00	101.320	151.10

The gas turbine produces 4,690.50 KW of mechanical power (P_M) and the air compressor consumes 3,078.00 KW (P_C), consequently the mechanical net power (P_N) is 1,612.50 KW. The fuel consumption (Q_F), in exergetic basis, is 9,761.85 KW. The recovery boiler produces 2,233.59 kW of heat exergy (Q_U). In order to calculate the exergy of the physical flows, the reference temperature and pressure is fixed at 25 °C and 101.320 KPa, respectively.

The external monetary flows due to the equipment of the cycle are shown in Tab. 2.

Table 2 – Equipment external monetary cost (Santos, 2009)

Equipment		Z [$/h]
Description	Abbreviation	
Combustion Chamber	CC	5.72
Gas Turbine	GT	21.75
Air Compressor	AC	16.03
Recovery Boiler	RB	13.74

The monetary unit cost of the external fuel (Q_F) is 6.91 $/MWh.

3. THERMOECONOMIC MODELING

The thermoeconomic model is a set of equations which describes the cost formation process of the system. To carry out a thermoeconomic analysis, it is convenient to make up a thermoeconomic model, which define the productive propose of the subsystems (products and fuels), as well as the distribution of the external resources and internal product throughout the system. It could be represented by means of the productive diagram. The only limitation with must be imposed it that it should be possible to evaluate all the flows of the productive structure in relation to the state of the

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plant as defined by the physical structure (Lozano and Valero, 1993). The way in which we define the productive structure is a key point in thermoeconomic analysis. In other words, the deeper the conceptual disaggregation of the system in components and flows, the better the results (Lozano and Valero, 1993). As mentioned above, in this paper the methodologies are divided into two groups according to the kind of structure used to represent the cost formation process: (i) three of them use physical structure; and (ii) other five define the productive structure of the system.

In order to calculate the monetary unit cost, the mathematical model for cost allocation is obtained by formulating cost equation balance in each subsystem (using physical or productive structure), as shown in Eq. (1).

$$\Sigma(c.Y) = Z \tag{1}$$

Where c is the monetary unit cost of the internal flows and finals products (unknown variable); Y represents the generic flow, which can be mechanical power, useful heat exergy, exergy, negentropy, and enthalpy, etc.; and Z represents the external financial flow due to investment, operation and maintenance of the equipment or subsystem.

In order calculate the exergetic unit cost, Z value is considered zero for all subsystems and the fuel exergetic unit cost is equal one. In order to formulate the cost equation balance in each productive unit or subsystem, the inlet flows assume negative value and the outlet flows assume positive value.

Since the number of flows is always greater than the number of productive units, it's necessary some auxiliary equations that will be mentioned in each model.

3.1 Using Physical Structure

The first three thermoeconomic methodologies that use the physical structure to formulate the mathematical model describing the cost formation process are presented below. The internal flows are determined as the exergy in each point (state i) of the physical flows, according to Eq. (2)

$$E_i = m\{c_p(T_i - T_0) - T_0\left[c_p\, ln\left(\frac{T_i}{T_0}\right) - Rln\left(\frac{P_i}{P_0}\right)\right]\} \tag{2}$$

Where T_0 and P_0 are reference temperature and pressure, m the mass flow, c_p the air specific heat and R the universal gas constant.

3.1.1 Exergetic Cost Theory (ECT)

Figure 2 represents the physical structure of the Gas Turbine Cogeneration System showing how the Exergetic Cost Theory, as it was originally formulated, allocate the residue cost, i. e., to the recovery boiler only (Valero *et al*., 1994).

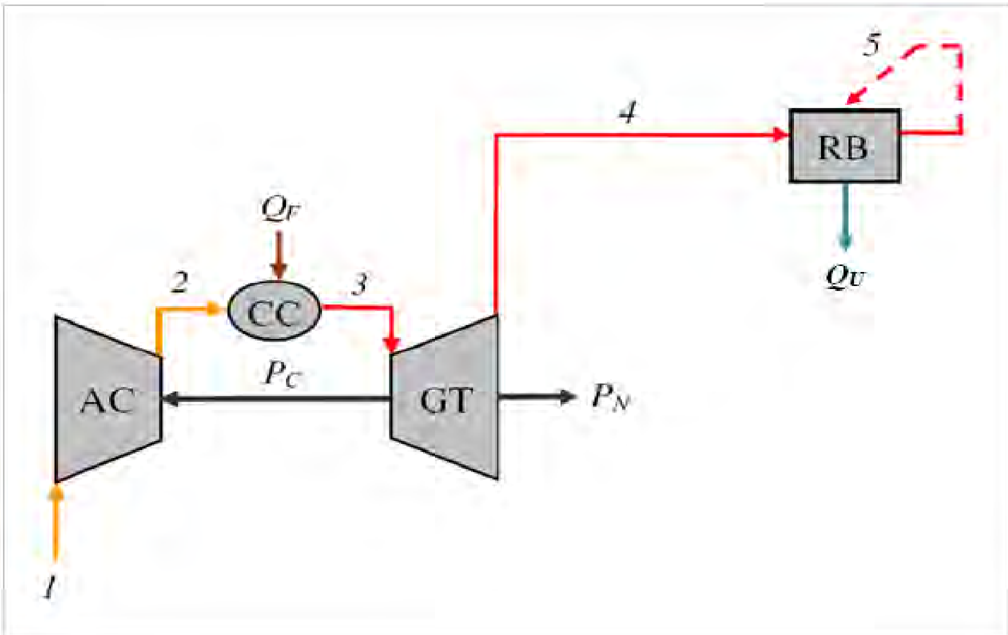

Figure 2. Physical Structure of the System according to the Original Exergetic Cost Theory

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As shown in the Fig. 2, in this Theory the residues are allocated to the heat only thought the recovery boiler. The air entering in the air compressor (point 1) has zero exergy and comes freely from the environment.

According to Valero *et al.*(1994), two auxiliary equations are necessary. They consider that: (i) the power consumed in the air compressor (P_C) have the same unit costs as the net power (P_N) and the streams 3 and 4 have the same unit cost.

3.1.2 Average-Cost Exergy-Costing Approach (AVECO)

The physical structure of the Gas Turbine Cogeneration System using the Average-Cost Exergy-Costing Approach (AVECO) (Tsatsaronis and Pisa, 1994) can be demonstrated as show in Fig. 1. The residue cost is calculated as a final product and it is posteriori allocated to the final product (heat and power) proportionally to their exergy (respectively). Related to the auxiliary equation, it assumes the same considerations as the previous model, and additionally it considers that the streams 4 and 5 have the same unit cost (Tsatsaronis and Pisa, 1994).

3.1.3 Specific Exergy Costing (SPECO)

Thermoeconomic modeling based on physical structure and flows is also a characteristic of the Exergoeconomics methodologies (AVECO and LIFO) by Tsatsaronis and Pisa (1994) unified recently by SPECO (Lazzaretto and Tsatsaronis, 2006). Figure 3 represents the physical structure of the Gas Turbine Cogeneration System using the Specific Exergy Costing (SPECO). The exhaust gases are allocated in the combustion chamber.

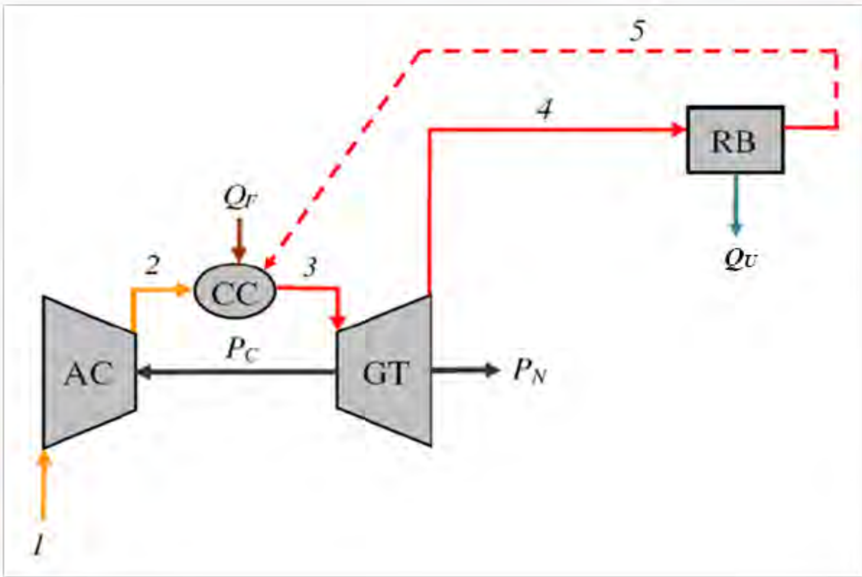

Figure 3. Physical Structure of the Cogeneration System according to SPECO

Related to the auxiliary equation, SPECO assumes the same considerations as AVECO. The cost allocation of exhaust gases in the combustion chamber is also a recently solution adopted from Exergetic Cost Theory (Torres and Valero, 2000), because they agree that the residues should be allocated to equipment in which it was originated. Today, related to a Gas Turbine Cogeneration Plant, we can say that SPECO and ECT are unified.

3.2 Productive structure

Describe the process of cost formation in thermal systems based on productive flows is originally a characteristic of Functional Methodologies: Thermoeconomic Functional Approach - TFA (Frangopoulos, 1994) and Engineering Functional Analysis – EFA (von Spakovsky, 1994).

The productive structure offers the advantage to show clearly and graphically how the product of a given subsystem is distributed to be used as input to another subsystem or as a final product of the plant.

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3.2.1 E Model

Figure 4 shows the productive structure of the Gas Turbine Cogeneration System according to the E Model. The rectangles are the real components (or subsystem). The rhombuses and circles are fictitious unit called junction and bifurcation, respectively. Each subsystem has inlet arrows (fuels) and outlet arrows (products).

The productive diagram of Fig. 4 uses only total exergy to define the fuels and the product of the subsystems (E Model). The productive flows are defined as function of the physical flows.

The exergy variation ($E_{i:j}$) between two physical flows (i and j), is shown in Eq. (3).

$$E_{i:j} = E_i - E_j = m\{c_p(T_i - T_j) - T_0\left[c_p \ln\left(\frac{T_i}{T_j}\right) - R\ln\left(\frac{P_i}{P_j}\right)\right]\} \tag{3}$$

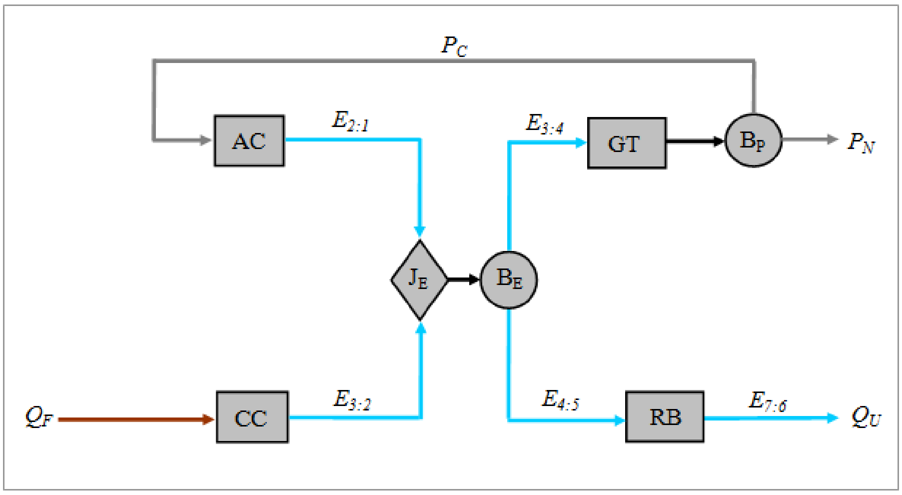

Figure 4. Productive Diagram of the System according to the E Model (Santos *et al*., 2010)

The fuel and the product of a subsystem based on the exergy flows of the working fluid are defined by taking into account this magnitude removed and added from and to this subsystem, respectively.

3.2.2 E^T&E^M Model

This model, represented in Fig. 5, consist in the disaggregation of physical exergy flows into their thermal ($E^T_{i:j}$) and mechanical ($E^M_{i:j}$) components. This productive structure is equivalent to that of the CGAM plant introduced by Frangopoulos (1994) and used by Torres *et al*. (1996). Therefore, the fuel and the product of the subsystems are power (P_C and P_N), external fuel heat exergy (Q_F) the useful heat exergy (Q_U).

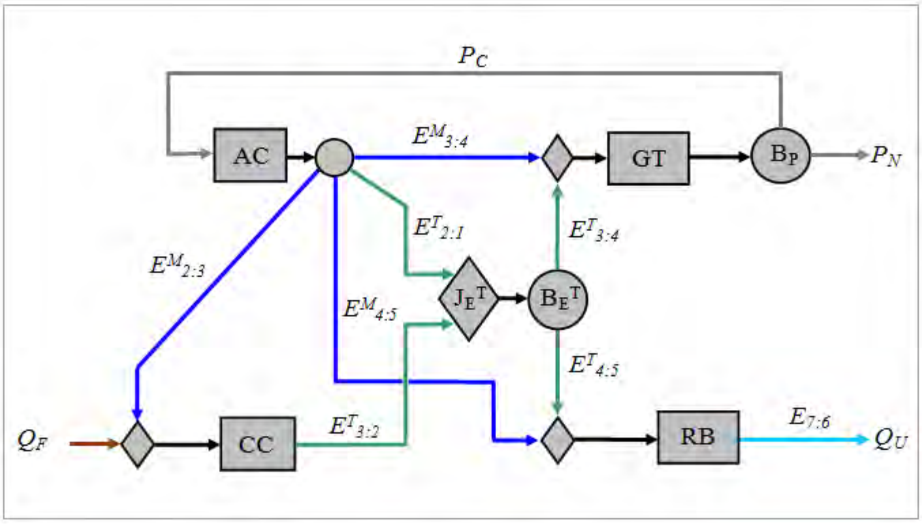

Figure 5. Productive Diagram of the System according to the E^T&E^M Model (Santos *et al.,* 2010)

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The meaning of the internal flows representing the thermal and mechanical components of exergy is explained in Eq. (4) and Eq. (5).

$$E_{i:j}^{T} = E_i^T - E_j^T = mc_p[T_i - T_j + T_0 ln(\frac{T_j}{T_i})] \quad (4)$$

$$E_{i:j}^{M} = E_i^M - E_j^M = mRT_0 ln(\frac{P_i}{P_j}) \quad (5)$$

According to Thermoeconomic Functional Approach - TFA (Frangopoulos, 1994), the air compressor produces all mechanical exergy used by the others equipment in the system. The air compressor also produces thermal exergy, which justify the existence of the small circle indicating that its product has multiple output streams. The main consideration in TFA is that all products of a given productive unit have the same unit cost.

Disaggregation of exergy in their thermal and mechanical components is also used by the structural version of the Exergetic Cost Theory (Lozano *et al.,* 1993). This Theory, the Structural Analysis Approach (SAA), introduced the concept of byproduct. The exergy thermal component produced by the air compressor is a byproduct, because the air compressor function is to produce mechanical exergy. The temperature increase (thermal exergy) is a consequence.

To differentiate the product and byproduct cost, the SAA proposes a new rule for the auxiliary equations: the byproduct (thermal exergy) should have the same unit cost as the thermal exergy produced by the combustion chamber, which is the only equipment whose function is to produce thermal exergy only.

3.2.3 E&S Model

The negentropy flow has been used together with the exergy flow as a fictitious flow (E&S Model) by three known thermoeconomic methodologies: Thermoeconomic Functional Analysis (Frangopoulos, 1987), Structural Theory of Thermoeconomics (Lozano *et al.*, 1993) and Engineering Functional Analysis (von Spakovsky, 1994). Figure 6 shows the productive diagram of the Gas Turbine Cogeneration System according to the E&S Model.

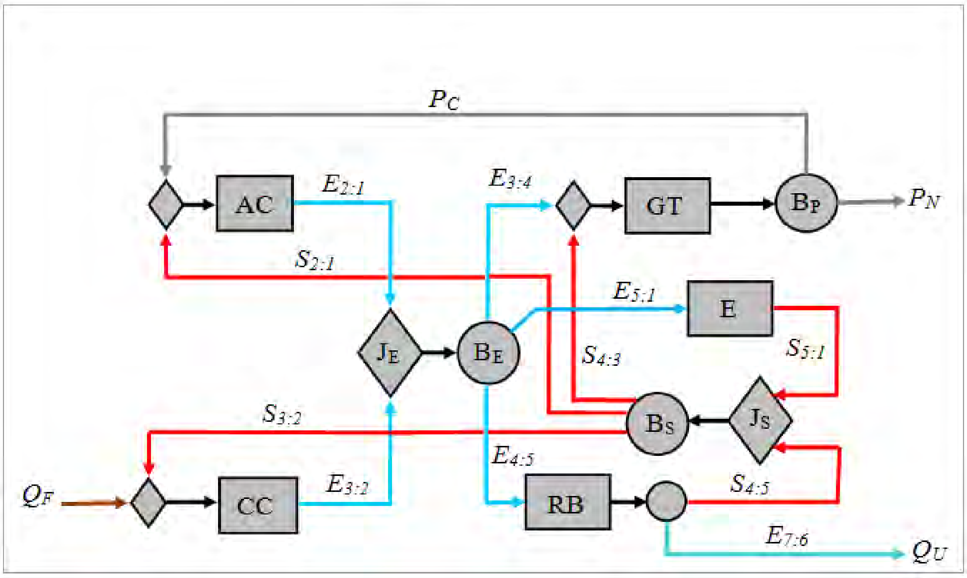

Figure 6. Productive Diagram of the Cogeneration System according to the E&S Model

The rectangle (E) is an imaginary unit that represents the environment. It receives the residues exergy flow ($E_{5:1}$) and cools down this working fluid to the atmospheric conditions, i.e., its function is to reduce the entropy of the working fluid. By definition, reduce the entropy of the work fluid means produce negentropy (Frangopoulos, 1987). On the other hand, the negentropy is considered as a fuel of the components that increase the working fluid entropy.

Using the E&S Model, the Structural Theory uses the concept of byproduct, i. e., the negentropy produced by the recovery boiler is a byproduct, because its main function is to produce useful heat. Thus, the negentropy flow ($S_{4:5}$) assumes the same cost as the negentropy flow produced by the environment ($S_{5:1}$), which is only unit whose function is to produce negentropy only. Equation (6) defines the negentropy flow ($S_{i:j}$) as function of physical flows.

$$S_{i:j} = S_i - S_j = mT_0(s_i - s_j) \quad (6)$$

The specific entropy variation can be defined as shown in Eq. (7).

$$s_i - s_j = c_p\, ln\left(\frac{T_i}{T_j}\right) - Rln(\frac{P_i}{P_j}) \quad (7)$$

3.2.4 E^T&E^M&S Model

This model is a mix between E^T&E^M and E&S Model, because it uses exergy flows together with the negentropy flows as E&S Model. However, the physical exergy is disaggregated into their thermal and mechanical components as the E^T&E^M Model. Figure 7 shows the productive diagram of the Gas Turbine Cogeneration System according to the E^T&E^M&S Model as defined by Lozano *et al.* (1993).

Once that the use of exergy together with the negentropy is a characteristic of the Structural Analysis Approach (SSA), it uses the concept of byproduct, as explained in section 3.2.2 (E^T&E^M Model) and 3.2.3 (E&S Model).

However, Thermoeconomic Functional Approach (TFA) also uses negentropy together with the exergy disaggregated in their thermal and mechanical (Frangopoulos, 1997).In this case, we have not byproducts, i. e., all outlet flows exiting the same subsystem have the same unit cost. This concept is used for the compressor and the recovery boiler outlet flows. In other words, in this paper the E^T&E^M&S Model is applied according to SAA and also according TFA. Thus, both negentropy flow ($S_{4:5}$) and thermal exergy flow ($E^T_{2:1}$) are calculated as byproducts and products, respectively.

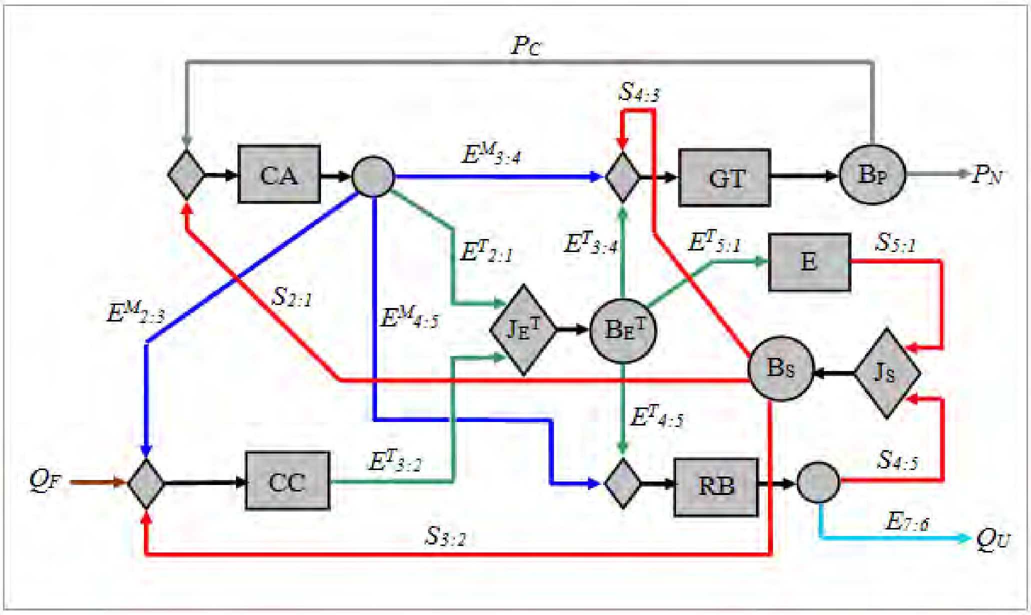

Figure 7. Productive Diagram of the Cogeneration System according to the E^T&E^M&S Model

The thermal and mechanical exergies and the negentropy flows are determined by Eq. (4), (5) and (6), respectively.

3.2.5 H&S Model

This Model defines the productive diagram by disaggregating the physical exergy into enthalpic and entropic components. This kind of physical exergy disaggregation was introduced by Santos *et al.* (2006). Figure 8 shows the productive diagram of the Gas Turbine Cogeneration System according to the H&S Model.

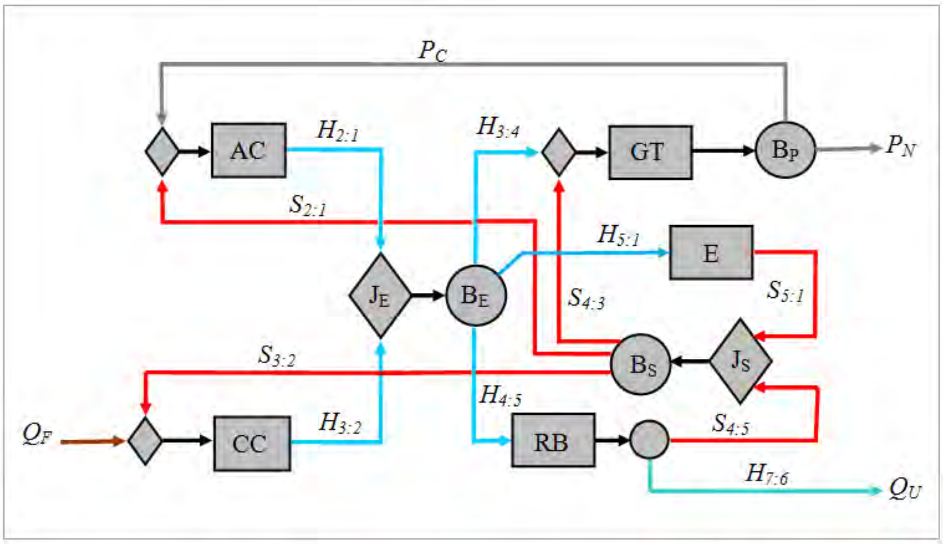

Figure 8. Productive Diagram of the System according to the H&S Model (Santos *et al.,* 2010)

This kind of productive structure is similar to the one that uses the negentropy together with the exergy, because the entropic component and negentropy are the same magnitude ($mT_0\Delta s$) with essentially the same meaning. However, the negentropy is used together with exergy and the entropic term is a physical exergy component, which must be used together with the enthalpic term. The entropic component is determined by Eq. (6) and the enthalpic one by Eq. (8).

$$H_{i:j} = mc_p(T_i - T_j) \tag{8}$$

4. RESULTS AND DISCUSSIONS

Table 3 shows the productive flows, its exergy values and its respective exergetic unit costs for the models that utilize exergy flows together with negentropy as a fictitious flow: E&S and E^T&E^M&S (according TFA and SSA).

Table 3. Exergetic Unit Cost of the Productive Flows obtained by using the Model that use negentropy

Productive Flow	Value (KW)	Exergetic Unit Cost (KW/KW)		
		Model		
		E&S	E^T&E^M&S (TFA)	E^T&E^M&S (SSA)
Q_F	9,761.85	1.00	1.00	1.00
$E_{2:1}$	2,810.41	2.96	----	----
$E_{3:2}$	5,642.60	2.03	----	----
$E_{3:4}/E_{4:5}/E_{5:1}$	5,230.44/2,908.43/314.15	2.34	----	----
$S_{2:1}/S_{3:2}/S_{4:3}$	267.59/3,654.40/539.94	0.47	1.20	0.40
$S_{4:5}$	2,884.57	0.47	1.56	0.40
$S_{5:1}$	1,577.35	0.47	0.55	0.40
$E^M_{2:3}/E^M_{3:4}/E^M_{4:5}$	66.01/1,998.75/9.46	----	4.38	3.98
$E^T_{3:4}/E^T_{4:5}/E^T_{5:1}$	3,231.70/2,898.96/314.15	----	2.74	2.01
$E^T_{3:2}$	5,708.61	----	2.53	2.01
$E^T_{2:1}$	736.19	----	4.38	2.01
P_N/P_C	1,612.50/3,078.00	2.66	3.89	3.13
$Q_U = E_{7:6}$	2,23.59	2.45	1.56	2.11

As shown in Tab. 3 the use of the negentropy together with the exergy presents some inconsistences: some equipments has fuels greater than product, which means efficiency higher than 100%, contradicting the Second Law of Thermodynamics. For all models shown in Tab. 3 the product of the recovery boiler, ($Q_U + S_{4:5}$) is greater than its fuels ($E_{4:5}$ for E&S and $E^T_{4:5} + E^M_{4:5}$ for E^T&E^M&S), and consequently, the exergetic unit cost of the negentropy flows are less than one: 0.47 KW/KW for E&S Model and 0.55/0.40 KW/KW for E^T&E^M&S Model. In addition, these models have some unit cost (exergetic and monetary) less than that of the extenal fuel, for all negentropic flow. Once that ireversiblity is the magnitude generating the cost, the unit cost must increse though the productive diagram.

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For all other models used in this paper the products of the equipments are less than its fuels. Consequently, the exergetic unit costs of all flows are greater than one and the monetary unit costs are greater than that of the external fuel, which is in accordance with the expected for de unit costs of the internal flows and finals products.

Figures 9 and 10 compares the exergetic unit cost and the monetary unit cost, respectively, of the final products (useful heat and net power), obtained by the application of each model used in this paper. The graphic shows that the higher the unit cost of net power, the lower the unit cost of useful heat, and vice-versa.

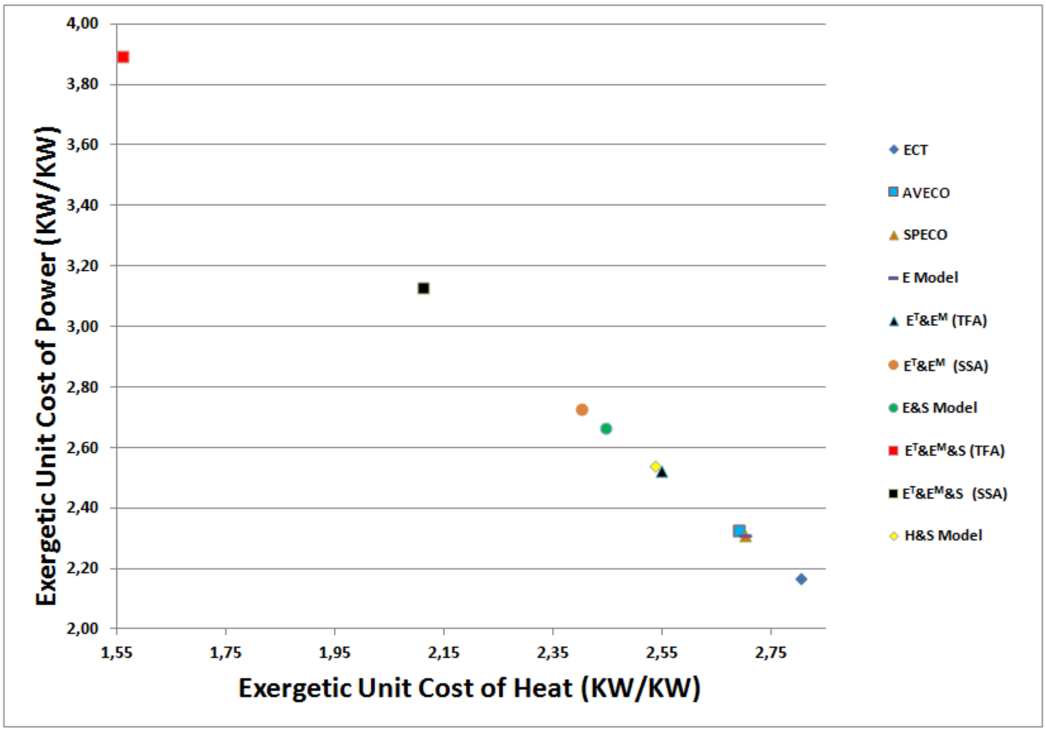

Figure 9. Exergetic Unit Cost of Heat and Power obtained by using Different Models

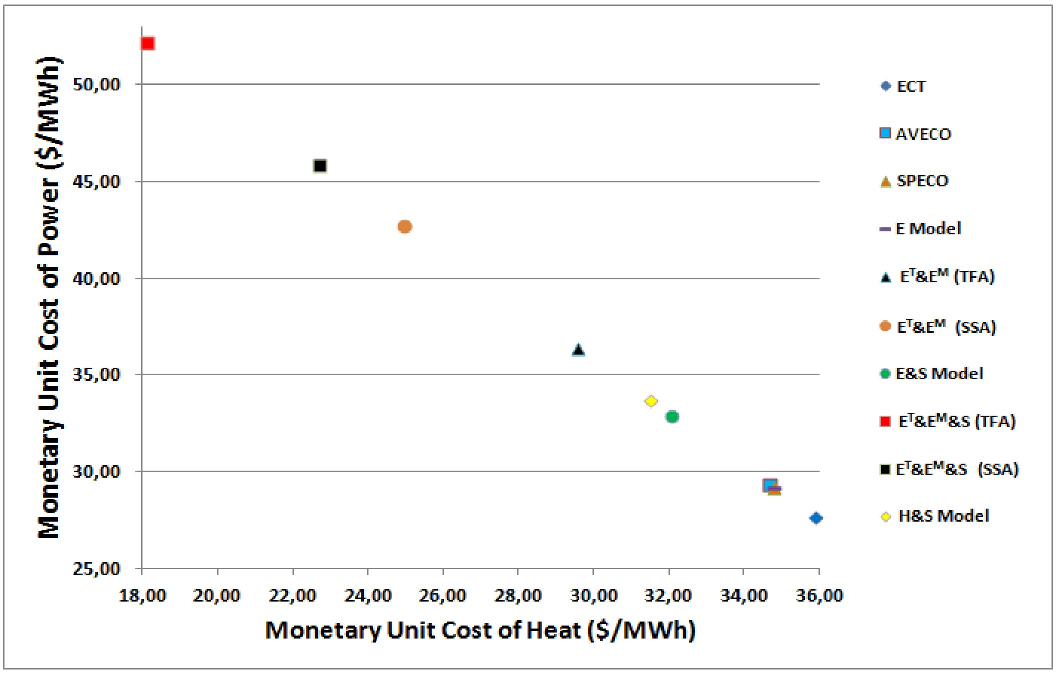

Figure 10. Monetary Unit Cost of Heat and Power obtained by using Different Models

The Exergetic Cost Theory as it was originally formulated presents the highest useful heat unit cost because in this Theory the residues are allocated in the recovery boiler. Thus it costs is allocated to the useful heat only.

The E Model and the SPECO has the same monetary and exergetic unit costs. This result shows that for a Gas Turbine Cogeneration System the unification of these theories is already a reality.

The use of the Structural Theory (SAA) in the E^T&E^M e E^T&E^M&S Models generates different results that obtained with the Thermoeconomic Functional Approach (TFA) because this Theory introduces the concept of byproduct and thus alters the intermediate flows distribution and consequently the final products unit cost.

However, in a general way, the Models that use negentropy flows together with exergy flows (E&S and E^T&E^M&S Models) have the greatest net power unit cost, because they uses the term that defines the negentropy flow twice. This term ($mT_0\Delta s$) is present in the negentropy and already in the exergy flow. This way these models penalize twice the units that increase the work fluid entropy and then overcharge the power cost in the detriment of the heat cost.

By using the entropic term ($mT_0\Delta s$), which has the same meaning as negentropy ($mT_0\Delta s$), the H&S Model takes all the well known and recognized advantages of the negentropy application for residue allocation in thermoeconomics, it is consistent regarding the subsystem fuels and products definition, and avoids the inconsistencies of previous models.

5. CONCLUSIONS

The consistency of the more widespread thermoeconomic methodologies was evaluated by applying them for cost allocation in a Gas Turbine Cogeneration System. The difference between the thermoeconomic methodologies is due to the kind of productive structure, i. e., depend on the kind of the cost flow (physical or productive) and the magnitude used (exergy, enthalpy, negentropy or entropy).

The models that use the physical structure to represent the cost formation process differ mainly with respect to the residues reallocation. The Exergetic Costing Theory as it was originally proposed allocates them in the recovery boiler and overcharges the heat unit cost in detriment of the power unit cost. The SPECO allocates the residues according to most authors agree, i.e., in the equipment in which it were generated.

The use of total exergy flow, E Model, or disaggregated into its components, E^T&E^M Models, obtains coherent results. The Structural Theory introduces the concept of byproduct and thus changes the final products unit cost in relation to the use of the Thermoeconomic Functional Approach.

When the negentropy is applied as a fictitious flow, joined up with the exergy flows (E&S and E^T&E^M&S Models), the term that defines the negentropy is used twice because this term is already present in the exergy flow. Therefore, these models penalize the Gas Turbine (power producer) twice due to the increase of the working fluid entropy, while the subsystems that decrease the working fluid entropy are awarded twice (recovery boiler, which is the heat producer).

Thus in the E&S and E^T&E^M&S Models some equipment (such as the recovery boiler) has products greater than their fuels and, consequently, the product-fuel ratio of this subsystem is greater than 100%, which can be interpreted as an inconsistency. Therefore these Models obtain unreasonable values of monetary and exergetic unit cost.

However, when the advantage of negentropy concept is taken by means of the use of the entropic term of exergy, i.e., by using the entropic terms joined up with the enthalpic term of exergy (H&S Model), the exergetic unit cost of the internal flows and final products is coherent, and there are no subsystems whose products is greater than the fuels.

6. ACKNOWLEDGEMENTS

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