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ADVANCED EXERGOECONOMIC ANALYSIS OF AN OPTIMIZED COGENERATION SYSTEM

Bruno Seixas Gomes de Almeida
Manuel Ernani de Carvalho Cruz
Federal University of Rio de Janeiro – UFRJ, Mechanical Engineering Department
brunoseixas@poli.ufrj.br; manuel@mecanica.coppe.ufrj.br

Leonardo dos Santos Reis Vieira
Electric Energy Research Center – CEPEL
lsrv@cepel.br

Abstract. Advanced exergoeconomic analysis has been used frequently in numerous recent studies to analyze various thermal systems. The advanced analysis allows, in addition to the quantification of exergetic destruction and investment and destruction costs, the fragmentation of these into avoidable, unavoidable, endogenous and exogenous parts. In this context, the present work sought to compare the results of the advanced exergoeconomic analysis in different operating conditions of an optimized cogeneration system and to evaluate the differences in relation to the conventional analysis. For this, the system operating at the lowest total cost and the system operating at the highest exergetic efficiency were analyzed. There was a significant difference between the results of the advanced exergoeconomic analysis for each operating condition. In addition, it was noted that the advanced exergoeconomic analysis would lead to a different order of equipment prioritization from that obtained with conventional analysis.

Keywords: Exergoeconomic, Exergy, Cogeneration

1. INTRODUCTION

In general, for the design and diagnosis of these thermal systems, thermodynamic formulations and laws are used, such as the first and second laws of thermodynamics individually. However, the use of such concepts singly is not capable to describe the potential of a system to perform work in relation to a given condition. For this, it is appropriate to use the concept of exergy, which results from the combination of the two laws. Basically, exergy will measure the quality of energy and will guarantee a common basis for comparison between different processes.

In general, an exergetic analysis of a thermal system provides information to achieve a better use of the energy resources involved, seeking to reduce the destruction of exergy within the system and/or reducing losses. In addition, it is possible, once the components in which destruction and loss of exergy occur, to classify them in order of importance, allowing greater attention to be given to these components and offering greater opportunities for improvements (Moran, M. J., Shapiro, H. N., 1995).

In addition to checking how much exergy is destroyed in each component of an installation, it is often desirable to know the portion of this destruction that can be avoided, in addition to checking how the efficiency of a given component is influenced by the inefficiencies of the others. For this, an advanced exergetic analysis is carried out, which allows the fragmentation of exergetic destruction into avoidable/unavoidable and endogenous/ xogenous parts. This division allows the exergetic performance of the system, aiming facilitate its improvement (Petrakopoulou, F. et al. 2011). Numerous studies on advanced exergetic analysis have been carried out in recent years and in different applications, as in the works of Fallah, M. et al. (2016), Galindo, J. et al. (2016), Fu, P. et al. (2016) and Balli O. (2017).

Conventional and advanced exergetic analysis can also be combined with economic principles to provide the thermal system designer or operator with information regarding the costs involved in the plant. In this sense, the first and second laws of thermodynamics are combined with economic concepts (forming the field of Exergoeconomics) and represent a powerful tool for the study and optimization of thermal systems (Siahaya Y., 2009).

In this context, the objective of the present work is to evaluate the results of advanced exergoeconomic analysis in different operating conditions of a cogeneration system and to compare the differences in relation to conventional exergoeconomic analysis. The analysis of the chosen thermal system was made in two operating conditions: system operating at a lower total cost and system operating at maximum exergetic efficiency.

2. CONVENTIONAL AND ADVANCED EXERGETIC ANALYSIS

Exergy can be understood as a property that quantifies the potential for use, basically it is a parameter that measures the quality of energy associated with a thermodynamic state. Exergy can also be interpreted as the maximum theoretical work possible to be obtained from a global system, composed of a system and the environment, as this system comes into balance with the environment. Therefore, Exergy is a measure of the deviation from the state of a system when compared to the environment.

The environment is defined as a simple compressible system that is large in extension and uniform in temperature T_0 and pressure P_0, taken under typical conditions. When a system is in balance with the environment, it is said to be in a dead state, so there can be no interaction between the system and the environment. Thus, there is no potential to develop work (Moran, M. J., Shapiro, H. N., 1995). Mathematically the exergy per unit mass, known as specific exergy, can be obtained using the Eq. (1).

$$e = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \qquad (1)$$

where $u, v, s, V^2/2$ and gz represent the specific internal energy, the volume, the entropy, the kinetic energy and the specific potential energy, respectively in the state of interest; u_0, v_0, s_0 are specific properties in the dead state, at T_0 and P_0. Therefore, specific exergy is given in J/kg. In thermal systems, it is convenient to express the exergetic balance by analyzing the exergy portion associated with fuel, products, losses and the destruction of each component (Bejan, A. et al., 1996). In a system, this balance is given by Eq. (2).

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{L,tot} + \dot{E}_{D,tot} \qquad (2)$$

where $\dot{E}_{F,tot}$ is the exergy rate for the fuel, $\dot{E}_{P,tot}$ for the product, $\dot{E}_{L,tot}$ for exergy loss and $\dot{E}_{D,tot}$ for the exergy destruction. It is important to note that there is a difference between lost (or rejected) energy and destroyed energy. Lost exergy refers to the rejected exergy for the neighborhood, while destroyed exergy is due to the irreversibility of the system (Bejan, A. et al., 1996)

To evaluate the use of energy resources and provide an important measure of the performance of an energy system from a thermodynamic point of view, exergetic efficiency is used. Basically this indicates the percentage of fuel exergy that is found in the products. Mathematically, exergetic efficiency is given by Eq. (3).

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F} \qquad (3)$$

It is also common to calculate the exergy destruction ratio that indicates the share of exergetic destruction of that component in the total destruction of the system. The equation is given by Eq. (4).

$$\dot{y}_{D,k}^* = \frac{\dot{E}_{D,k}}{\dot{E}_{D,total}} \qquad (4)$$

In many cases, the simple quantification of exergetic destruction is not enough to better describe the exergetic performance of thermal systems. Sometimes, it becomes interesting to fragment this destruction into different parts that improve the exergetic description of the system. In addition to checking how much exergy is destroyed, it is necessary to know the portion of this destruction that can be avoided and how the efficiency of a given component is influenced by the inefficiencies of the others.

It is known that in all components exergetic destruction occurs, however, part of these destruction is inevitable due to technological and / or economic limitations of the equipment itself (Kelly, S., 2008). In this sense, there is a part of the destruction that is inherent to the component due to such restrictions and cannot be eliminated, even using the best technologies. This parcel is called unavoidable exergetic destruction. The rest refers to preventable exergetic destruction and it is this portion that must be given attention, since this is the fraction that can be reversed improving the efficiency of the component, consequently of the thermal system. Assuming a certain component k, exergetic destruction can be represented mathematically as indicated in Eq. (5).

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{AV} + \dot{E}_{D,k}^{UN} \qquad (5)$$

where $\dot{E}_{D,k}^{UN}$ represents unavoidable exergetic destruction that cannot be reversed and $\dot{E}_{D,k}^{AV}$ refers to the avoidable exergetic destruction that can be preventable. For the determination of the unavoidable part, the ratio between exergy destruction and product exergy $\left(\frac{\dot{E}_D}{\dot{E}_P}\right)$ is calculated by selecting thermodynamic parameters of component k that produce the lowest exergy destruction rate. Therefore, this ratio is calculated considering that the component operates in its best condition, that is, the one that produces the lowest rate of destruction with the technological and economic limitations for

the present period. The inevitable exergetic destruction of a given k component, operating under any "A" condition, is calculated by Eq. (6).

$$\dot{E}_{D,k,A}^{UN} = \dot{E}_{P,k,A} \left(\frac{\dot{E}_D}{\dot{E}_P} \right)_k^{UN} \tag{6}$$

In general, to determine $\left(\frac{\dot{E}_D}{\dot{E}_P} \right)_k^{UN}$ for different components, it is customary to consider them separately. Tsatsaronis, G., Park, M. H. (2002) pay attention to the fact that, although the actual project flow data (those referring to the analyzed condition) are used, temperatures, pressures, mass flow rates and the main design parameters are adjusted to achieve the best performance thermodynamic. The best performance state is found by selecting the most important thermodynamic parameters of the component and adjusting in order to find the best efficiency. There is no single criterion for this selection, therefore, it is made in an arbitrary manner and can be based on the designer's experience.

Exergetic destruction can also be divided into endogenous and exogenous destruction. The endogenous destruction ($\dot{E}_{D,k}^{EN}$) of a given component refers to the portion of exergy destruction that is due only to the irreversibility of that component when the others are operating under ideal conditions (Kelly, S., 2008) as long as the exogenous portion is the remainder ($\dot{E}_{D,k}^{EX}$). The equation that describes these parts is presented in Eq. (7):

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX} \tag{7}$$

In this context, there are countless techniques for calculating endogenous destruction, among which: Method Based on Thermodynamic Cycles (Kelly, S. et al., 2009 and Galindo, J. et al. 2016), Exergetic Balance Method (Kelly, S. et al., 2009), Equivalent Component Method (Kelly, S. et al., 2009), Method based on Structural Theory and malfunction analysis (Abreu, A. S., 2013.) and Engineering Method (or Graph Method) (Kelly, S. et al., 2009, Galindo, J. et al., 2016 and Kelly, S. et al., 2009). In the present work, the Graph Method was chosen, since for it it is not necessary to know the ideal functioning of all components, only the determination of some points of operation, varying the efficiency of its components. The method was developed by Morosuk, T. et al. (2006) and consists of obtaining different operating conditions while maintaining the exergetic efficiency of the analyzed component constant and varying that of the others. Then plot the points on a graph in which the x-axis refers to the destroyed exergy of the other components and the ordinate axis refers to the total destroyed exergy of the system. The point where the line intersects the y-axis will be the point at which the exergy of the other components is zero, so the entire exergetic destruction value is due to the component under analysis, as shown in Fig. 1. The advantage of the method is that to obtain the value of endogenous exergetic destruction of a given component, it is not necessary to know which values should be adopted for the parameters of each component so that they operate ideally.
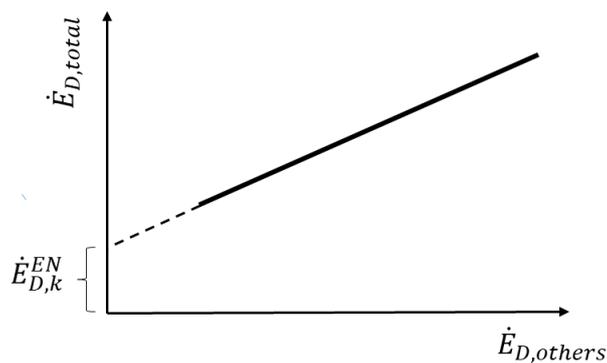

Figure 1. Determination of the endogenous part by the engineering method.

3. CONVENTIONAL AND ADVANCED EXERGOECONOMIC ANALYSIS

Every project and operation of a thermal system involves the application of thermodynamic principles, fluid mechanics and heat transfer, besides materials, manufacturing and mechanical design. In addition, the design of these systems also includes economic factors, since costs are always an important factor to be considered. This analysis aims to apply in the real world the experience of cost assessment in engineering design and project management (Moran, M. J., Shapiro, H. N., 1995). In this context, the field of exergoeconomics emerges, which seeks to combine exergy and economics for optimization studies during the design of new systems and improvements to existing projects. In a

conventional exergoeconomic analysis, a cost balance is usually formulated for the overall system operating at steady state (Bejan, A. et al., 1996.) as presented in Eq. (8).

$$\sum_P \dot{C}_{P,k} = \sum_F \dot{C}_{F,k} + \dot{Z}_k \tag{8}$$

where $\dot{C}_{P,k}$, $\dot{C}_{F,k}$ represent the cost rates associated with the product, the fuel respectively, while $\dot{Z}_k$ represents the costs associated with the investment, operation and maintenance of the system. The average costs per unit of exergy of products and fuels as well as the costs of destruction of each component are determined by Eq. (9), Eq. (10) and Eq. (11), respectively:

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{9}$$

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{10}$$

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{11}$$

where $c_{P,k}$, $c_{F,k}$, $\dot{C}_{D,k}$ represent the average costs per unit of exergy for products, average costs per unit of exergy for products fuels and the cost rates associated with the exergy destruction. Further details of the methodology for calculating average costs and obtaining the remaining installments can be seen in Tsatsaronis, G., Lazzaretto, A. (1997), Lozano, M. A., Valero, A., (1993) and Bejan, A. et al. (1996).

Destruction costs can be divided into avoidable and unavoidable parts in order to indicate the potential for improvement of the component given the technological limitations of the period, as well as in endogenous and exogenous parts in order to show how much destruction costs is due only to irreversibility of the component or due to the inefficiency of the others (Kelly, S., 2008). Knowing the specific fuel costs, it is possible to determine these portions using the Eq. (12-15).

$$\dot{C}_{D,k}^{EN} = c_{F,k}\dot{E}_{D,k}^{EN} \tag{12}$$

$$\dot{C}_{D,k}^{EX} = \dot{C}_{D,k} - \dot{C}_{D,k}^{EN} \tag{13}$$

$$\dot{C}_{D,k}^{UN} = c_{F,k}\dot{E}_{D,k}^{UN} \tag{14}$$

$$\dot{C}_{D,k}^{AV} = \dot{C}_{D,k} - \dot{C}_{D,k}^{UN} \tag{15}$$

As with destruction costs, investment rates can also be divided into avoidable unavoidable, endogenous/exogenous parcels with the same purpose, only now associated with investment rates. Equations (16-19) indicates how to calculate these parts.

$$\dot{Z}_k^{EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{Real} \tag{16}$$

$$\dot{Z}_k^{EX} = \dot{Z}_k^{Real} - \dot{Z}_k^{EN} \tag{17}$$

$$\dot{Z}_k^{UN} = \dot{E}_{P,k}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN} \tag{18}$$

$$\dot{Z}_k^{AV} = \dot{Z}_k^{Real} - \dot{Z}_k^{UN} \tag{19}$$

As seen, in order to obtain the endogenous part of the investment rate, it is necessary to obtain $\dot{E}_{P,k}^{EN}$, which represents the exergy rate of the products of component k when all other components operate theoretically (Petrakopoulou, et al., 2012). Such part is obtained when the behavior of all other components is approached to the ideal and the exergy of the products for component k is calculated. Then, $\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{Real}$ is calculated for the system operating in the analyzed real condition.

For the unavoidable part of the investment, the ratio of the investment rate to the exergy of the products $\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN}$ must be calculated, choosing the thermodynamic variables considering the most inefficient version of the component. This investment represents the lowest investment rate to be spent, since it will be related to the purchase of the component with the lowest performance. As in the calculation of unavoidable exergetic destruction, the choice of these variables is made in an arbitrary manner, and can be guided by the designer's experience (Tsatsaronis, G. and Park, M. H., 2002).

4. DESCRIPTION OF THE CGAM SYSTEM

The system studied in this work is a reference system called the CGAM System and was developed by Frangopoulos, C. et al. (1993) and it is a benchmark among researchers. The CGAM system is a cogeneration system consisting of an air compressor (AC), a combustion chamber (CC), a gas turbine (GT), an air preheater (APH) and a Heat Recovery Steam Generator (HRSG). The purpose of such a cycle is the generation of 30MW of electrical energy and 14 kg/s of saturated steam at a pressure of 20 bar. More details of the model as well as the investment costs of each component can be seen in (Frangopoulos, C. et al, 1993). Figure 2 illustrates this system.
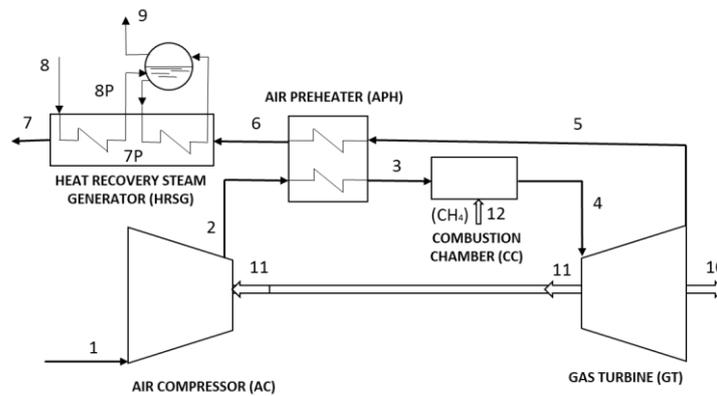

Figure 2. CGAM System.

The system is described according to five variables: the compression ratio (P_2/P_1), the isentropic efficiency of the compressor (η_{AC}), the isentropic efficiency of the turbine (η_{GT}), the temperature of the air at the exit of the preheater (T_3) and the temperature of the flue gas at the entrance to the turbine (T_4). The system was modeled at IPSEpro which is a professional process simulator used to model and simulate different thermal systems, through its thermodynamic equations.

5. METHODOLOGY FOR ADVANCED EXERGOECONOMIC ANALYSIS

Advanced exergoeconomic analysis involves, in addition to conventional exergoeconomic analysis, the determination of exergetic destruction of components, destruction costs and investment rates, all divided into avoidable, unavoidable, endogenous and exogenous parts. With the conventional exergoeconomic analysis, the Exergic of Fuel $(\dot{E}_F)$, Product $(\dot{E}_P)$ and Exergy Destroyed $(\dot{E}_D)$ of the components are obtained, in addition to the costs of fuel $(\dot{C}_F)$, product $(\dot{C}_P)$ and destruction $(\dot{C}_D)$ and the investment rates of each component $(\dot{Z})$ according to the work of Frangopoulos, C. et al. (1993), Tsatsaronis, G., Lazzaretto, A. (1997), Lozano, M. A., Valero, A., (1993) and Bejan, A. et al. (1996).

For the advanced exergoeconomic analysis, the avoidable and unavoidable parts of Exergetic destruction are determined. For the calculation of the term $\left(\frac{\dot{E}_D}{\dot{E}_P}\right)$ and the definition of the thermodynamic parameters that provide a better efficiency, as well as the values attributed to them, the works of Kelly, S. (2008) and Tsatsaronis, G. and Park, M. H. (2002) were used, in addition to analysis on the IPSEpro simulator. Thus, each component was simulated in separately and the thermodynamic parameters chosen were changed and the ratio between the destruction of exergy and the exergy of the product was obtained. Table 1. indicates the variables and values chosen for conditions of greater efficiency.

To determine the endogenous and exogenous portions of the exergetic destruction of each component, the Engineering Method was used. To determine the points on the graph, the thermal system was simulated in IPSEpro, keeping the exergetic efficiency of the component of interest constant and varying the efficiencies of the others. From this procedure, the graph line was determined and the point of the line that intersects the ordinate axis was obtained, which is related to the endogenous plot of destruction. Subtracting the endogenous portion from the total exergy destroyed, the exogenous portion was determined. Table 2 presents the changed variables for each component to plot the graph and determine the endogenous part of destruction.

As seen, the unavoidable part of the investment rate involves calculating the investment ratio with the exergy of the products $\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN}$ by choosing the thermodynamic variables considering the most inefficient version of the component. The procedure for determining this ratio is similar to that used in calculating the unavoidable part of the exergy destruction. The difference, however, is that the value assigned to the thermodynamic variables of the chosen component must be such that its efficiency is the lowest. Thus, the components were also simulated separately and the thermodynamic variables and their values were chosen based on the same bibliographic references and analyzes in the IPSEpro simulator. Table 1. indicates the variables and values chosen for conditions of lower efficiency.

For the endogenous portion of the investment rate, it is necessary to obtain $\dot{E}_{P,k}^{EN}$ which represents the exergy rate of the products of component k when all other components operate ideally. For this, the whole system is simulated separately and the behaviors of all components, except component k, are approximated to the ideal operating condition, and then the exergy of the products for component k is obtained for that point. In addition, for the system operating in the analyzed condition, $\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{Real}$ is calculated.

Table 1. Variables and values chosen for conditions of greater and lesser energy efficiency.

	Variables	Greater Efficiency	Lower efficiency
Air Compressor	η	90%	70%
Air Preheater	ΔT_{min}	30°C	227°C
Combustion Chamber	T_3	723°C	-
	ΔP	-	3 bar
Gas Turbine	η	90%	70%
HRSG	ΔP	0.02%	-
	T_6	-	700°C

Table 2. Changed variables to determine endogenous parts.

	Changed Variables
Air Compressor	η_{GT} ; T_3
Air Preheater	η_{AC} ; η_{GT} ; ΔP_{CC}
Combustion Chamber	η_{AC} ; η_{GT}
Gas Turbine	η_{AC} ; T_3
HRSG	*All endogenous*

The working conditions of the system for analysis are the lowest cost and highest exergetic efficiency and were taken from Almeida B. S. G. (2018). These points are shown in Tab. 3.

Table 3. Optimized conditions for advanced exergoeconomic analysis.

	Lowest Cost	Highest Efficiency
P_2/P_1	9.46	19.80
η_{AC}	0.83	0.891
T_3	600.43	517.71
η_{GT}	0.88	0.900
T_4	1210.95	1222.07
Cost($/s$)	0.33948	0.48228
Exergetic Efficiency	0.55485	0.58113

6. RESULTS

Tables 4, 5 and 6 show the results for the lowest cost condition and Tables 7, 8 and 9 the results for the highest exergetic efficiency condition.

Table 4. Exergy destruction for lowest cost condition.

	$\dot{E}_F$ [MW]	$\dot{E}_P$ [MW]	$\dot{E}_D$ [MW]	ε	y_D	$\dot{E}_D^{AV}$ [MW]	$\dot{E}_D^{UN}$ [MW]	$\dot{E}_D^{EN}$ [MW]	$\dot{E}_D^{EX}$ [MW]
Air Compressor	31.61	28.86	2.75	0.91	0.08	1.18	1.58	1.46	1.30
Combustion Chamber	124.87	101.41	23.46	0.81	0.65	3.96	19.50	13.87	9.59
Gas Turbine	64.23	61.61	2.62	0.96	0.07	0.50	2.12	1.97	0.65
HRSG	17.68	12.77	4.91	0.72	0.14	0.27	4.64	4.91	0.00
Air Preheater	18.27	16.03	2.24	0.88	0.06	1.51	0.73	2.20	0.04

Table 5. Destruction costs for lowest cost condition.

	$\dot{C}_F$ [\$/s]	$\dot{C}_P$ [\$/s]	$\dot{C}_D$ [\$/s]	$\dot{C}_D^{AV}$ [\$/s]	$\dot{C}_D^{UN}$ [\$/s]	$\dot{C}_D^{EN}$ [\$/s]	$\dot{C}_D^{EX}$ [\$/s]
Air Compressor	773.4	761.4	67.3	28.8	38.5	35.6	31.7
Combustion Chamber	2304.1	2307.2	432.8	73.1	359.7	255.9	176.9
Gas Turbine	1461.3	1507.4	59.7	11.4	48.3	44.8	14.8
HRSG	402.2	422.5	111.7	6.1	105.6	111.7	0.0
Air Preheater	415.7	432.0	51.0	34.3	16.7	50.1	0.9

Table 6. Investiments for lowest cost conditions.

	$\dot{Z}$ [\$/s]	$\dot{Z}^{AV}$ [\$/s]	$\dot{Z}^{UN}$ [\$/s]	$\dot{Z}^{EN}$ [\$/s]	$\dot{Z}^{EX}$ [\$/s]
Air Compressor	27.4	18.6	8.9	25.8	1.6
Combustion Chamber	3.1	2.7	0.5	2.7	0.4
Gas Turbine	46.1	35.0	11.1	42.1	3.9
HRSG	20.3	9.6	10.8	20.3	0.0
Air Preheater	16.3	0.1	16.2	15.3	1.0

Table 7. Exergy destruction for highest exergetic efficiency.

	$\dot{E}_F$ [MW]	$\dot{E}_P$ [MW]	$\dot{E}_D$ [MW]	ε	y_D	$\dot{E}_D^{AV}$ [MW]	$\dot{E}_D^{UN}$ [MW]	$\dot{E}_D^{EN}$ [MW]	$\dot{E}_D^{EX}$ [MW]
Air Compressor	36.41	34.75	1.67	0.95	0.05	0.13	1.53	0.93	0.73
Combustion Chamber	114.03	91.18	22.86	0.80	0.69	5.73	17.12	15.84	7.02
Gas Turbine	69.16	66.41	2.75	0.96	0.08	0.20	2.55	2.03	0.71
HRSG	17.77	12.77	5.00	0.72	0.15	0.21	4.79	5.00	0.00
Air Preheater	3.63	2.92	0.71	0.80	0.02	0.26	0.45	0.43	0.28

Table 8. Destruction costs for highest exergetic efficiency.

	$\dot{C}_F$ [\$/s]	$\dot{C}_P$ [\$/s]	$\dot{C}_D$ [\$/s]	$\dot{C}_D^{AV}$ [\$/s]	$\dot{C}_D^{UN}$ [\$/s]	$\dot{C}_D^{EN}$ [\$/s]	$\dot{C}_D^{EX}$ [\$/s]
Air Compressor	1172.9	1490.1	53.7	4.3	49.4	30.0	23.7
Combustion Chamber	2666.7	2669.6	534.5	134.1	400.4	370.4	164.1
Gas Turbine	2025.0	2139.2	80.4	5.8	74.5	59.5	20.9
HRSG	520.3	545.3	146.4	6.3	140.2	146.4	0.0
Air Preheater	106.3	116.2	20.8	7.7	13.1	12.7	8.2

Table 9. Investiments for highest exergetic efficiency.

	$\dot{Z}$ [\$/s]	$\dot{Z}^{AV}$ [\$/s]	$\dot{Z}^{UN}$ [\$/s]	$\dot{Z}^{EN}$ [\$/s]	$\dot{Z}^{EX}$ [\$/s]
Air Compressor	523.8	504.5	19.2	519.5	4.3
Combustion Chamber	2.9	1.6	1.3	2.9	0.1
Gas Turbine	114.2	99.5	14.7	112.3	1.9
HRSG	25.0	14.8	10.2	25.0	0.0
Air Preheater	9.9	0.0	9.8	9.8	0.1

Analyzing the results of the conventional exergoeconomic analysis, it was observed that in both conditions the combustion chamber is the component that most destroys the system's exergy, about 69% of the exergetic destruction for the most efficient condition and 65% for the lowest cost point. Most of the destruction of exergy that occurs in the chamber is associated with the combustion process, which is a highly irreversible process. As it is possible to notice, the investment costs of the compressor and gas turbine increased significantly with the increase of its efficiencies.

Regarding the advanced exergoeconomic analysis, it was possible to verify that the potential for improvement of the components was different in the analyzed cases. Analyzing in absolute values, it is possible to notice that the components with the greatest potential in both conditions is also the combustion chamber followed by the preheater. It is interesting to note that, as at the condition of highest exergetic efficiency, the components are operating with higher individual efficiency, so all components, except the combustion chamber, presented a very small avoidable part (less than 0.5 MW). It was found that the CGAM system operating in the lowest cost condition can avoid 7.42 MW of loss from exergetic destruction and in the highest exergetic efficiency condition, 6.55 MW, about 11.6% less.

With respect to endogenous and exogenous parts of destruction, it was found that the components most affected by the inefficiencies of the others in both cases were the compressor and the combustion chamber. As seen, 68% of the total destroyed exergy in the lowest cost condition is caused by the inefficiencies of the individual components, whereas for the highest exergetic efficiency condition this share is 73%.

Regarding the parts of destruction costs and avoidable and unavoidable investment rates, it was possible to note that the contribution fractions of each share for the same component were very different under different conditions, especially for the compressor. At the lowest cost point, it was found that 219.5 \$/s can be avoided, while for the arbitrary point 778.7 \$/s can be avoided, 254% more than the lowest cost. This great difference can be explained by the fact that, in the condition of highest exergetic efficiency, the components presented very high investment costs, such as the compressor and the turbine, due to their high efficiencies, which considerably increased the total costs.

Analyzing the endogenous and exogenous parts of the destruction costs and investment rates, it was noted that the fractions of the parcels for each component were different. As seen, for the lowest cost condition 604 \$/s are due to the inefficiencies of the individual components, representing 72% of the total costs, while for the system operating in the highest exergetic efficiency, 1288.5 \$/s are due to the inefficiencies of the individual components, which represents 85% of the total costs.

As seen, there was a significant difference between the lowest cost and the highest exergetic conditions. Although in both conditions the combustion chamber is a prominent component, the results of conventional and advanced exergoeconomic analysis have been very different. As noted, the exergoeconomic analysis proved to be a particular picture for each operating condition.

In order to compare the difference between conventional and advanced exergoeconomic analysis, an order of priority for system improvement was established by adopting two criteria: a criterion based on destroyed exergy and a criterion based on total costs. For the criterion based on the destroyed exergy, the conventional analysis will provide the magnitude of the destroyed exergy, while the advanced analysis will indicate how much of the destroyed exergy can, in fact, be avoided for that particular component. Table 10 indicates the comparison of the prioritization order between conventional and advanced exergoeconomic analysis for each operating condition using this criterion.

Table 10. Comparison between advanced and conventional exergoeconomic analysis using the criterion based on destroyed exergy.

	Highest Efficiency		**Lowest Cost**
	Conventional Analysis - Criterion: $\dot{E}_D$		
1°	Combustion Chamber	1°	Combustion Chamber
2°	HRSG	2°	HRSG
3°	Gas Turbine	3°	Air Compressor
4°	Air Compressor	4°	Gas Turbine
5°	Air Preheater	5°	Air Preheater

Advanced Analysis - Criterion: $\dot{E}_D^{AV}$			
1°	Combustion Chamber	1°	Combustion Chamber
2°	Air Preheater	2°	Air Preheater
3°	HRSG	3°	Air Compressor
4°	Gas Turbine	4°	Gas Turbine
5°	Air Compressor	5°	HRSG

As senc, the first position in both analyzes and in all operating conditions is occupied by the combustion chamber. This result, as already discussed, is due to the fact that the irreversibilities in this component are very high due to the combustion process, therefore, the magnitude of the destruction of exergy is very high.

It is also possible to notice that, for the same operating condition, there is a significant difference in the order of improvement between conventional and advanced analysis. This result indicates that the conventional analysis would lead to a prioritization of the components that is not very adequate, as it would not notice how much of the destroyed exergy is likely to be reduced. Therefore, the fragmentation of exergetic destruction into avoidable parts represents a good strategy for determining the prioritization of components.

Regarding the prioritization criteria involving the total costs, the conventional analysis will provide the magnitude of the costs of destruction and total investments for each component, while the prioritization by the advanced analysis will use only the avoidable parts of the costs of destruction and investment. Table 11 indicates the comparison of the prioritization order between the conventional and advanced exergoeconomic analysis for each operating condition using this criterion.

Table 10. Comparison between advanced and conventional exergoeconomic analysis using the criterion based on costs of destruction and investment.

	Highest Efficiency		Lowest Cost
Conventional Analysis - Criterion: $\dot{C}_D + \dot{Z}$			
1°	Air Compressor	1°	Combustion Chamber
2°	Combustion Chamber	2°	HRSG
3°	Gas Turbine	3°	Gas Turbine
4°	HRSG	4°	Air Compressor
5°	Air Preheater	5°	Air Preheater
Advanced Analysis - Criterion: $\dot{C}_D^{AV} + \dot{Z}^{AV}$			
1°	Air Compressor	1°	Combustion Chamber
2°	Combustion Chamber	2°	Air Compressor
3°	Gas Turbine	3°	Gas Turbine
4°	HRSG	4°	Air Preheater
5°	Air Preheater	5°	HRSG

Comparing the results, it is noted that, for the same type of analysis, conventional or advanced, the results depend on the operating conditions. This result points again to the sensitivity of the analysis results in relation to the operating conditions of the system. It is also noticed that, for the same condition, there was a difference in relation to the results of the conventional and advanced analyzes, except for the condition of greater efficiency where the prioritization between both was similar, possibly due to the fact that the component costs increased a lot and its avoidable plots followed that growth. In general, it is possible to verify that the prioritization involving advanced analysis, since it is focused only on the parcels that can actually be avoided, leads to a more adequate prioritization from the practical point of view for the components of the system.

7. CONCLUSIONS

From these comparisons, it was possible to verify that the exergoeconomic performance of a system is a particular picture of the operating condition. Therefore, each case must be analyzed separately, with its share of exergetic destruction, destruction costs and investment rates obtained in order to adopt the best measures for improvement in each case. Then, a comparison was made between the conventional and advanced exergoeconomic analysis in relation to the order of prioritization of the components to improve the system. It was found that, for the same operating condition,

advanced exergoeconomic analyzes would lead to a different prioritization than that obtained with a conventional analysis for the two conditions analyzed, both for the criterion based on destroyed exergy and for the criterion based on total costs. It has been proven that fragmentation of exergetic destruction and investment and destruction costs into avoidable part represents a good strategy for determining the prioritization of components.

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