THERMOECONOMIC DIAGNOSIS COMPARISON: FUEL IMPACT FORMULA AND RECONCILIATION APPROACH

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Abstract. *Thermoeconomic diagnosis methodologies applied to thermal systems aim to determinate which components are deteriorated; how much these components are deteriorated; and how much gain can be achieved in the thermal system's performance indicator (usually heat rate and net power), by components anomalies elimination. In order to answer these questions several methodologies have been proposed. This paper aims to compare two of the most used thermoeconomic methodologies: the reconciliation approach and the thermoeconomic methodology based on fuel impact formula. Both methodologies are applied to a cogeneration cycle. In the reconciliation approach, models of each component of the thermal cycle are used to predict the components' off-design performance; these models are based on the components' performance curves and they will be considered as the clean state condition in order to avoid the main drawback in thermoeconomic diagnosis, which is the presence of induced malfunctions. This paper shows that the fuel impact formula was effective in the quantification of the main anomaly while the secondary anomalies impact were disguised by induced effects. The reconciliation approach, as applied in this work, was effective to quantify the impact of all anomalies present.*

Keywords*: thermoeconomic diagnosis, induced malfunctions, reconciliation method*

1. INTRODUCTION

The search for a greater efficiency has led to very complex thermal system, where the components relationship is increasingly difficult to be analyzed. Thus it is very difficult to identify components that are not properly working, especially when anomalies are present in several components at the same time. This difficulty is mainly a result of efficiency variation of the components that are working properly due to the variation in the output of the problematic components (this is called induced malfunctions). This facet makes it hard to distinguish between components with induced malfunction and the components where the anomalies are present (called intrinsic malfunctions). In this context, several diagnosis approaches intending to localize the damaged components are been proposed: The dissipation temperature proposed by Royo et al. (1997), Quantitative causality analysis proposed by Usón et al. (2007), heuristic methods as in the work of Toffolo and Lazzaretto (2007), Thermo-characterization approach proposed by Zaleta et al. (2004a), Reconciliation method proposed by Zaleta et al. (2004b), fuel impact formula proposed by Valero and used by Reini and Taccani in 2004.

The fuel impact formula and the reconciliation approach are between the most widespread methods. Both of them, besides localize the damaged components, are used to quantify the fuel that can be saved by the elimination of the anomalies present in the damaged components. This is very useful information, making possible to optimize the maintenance, focusing attention and resources to the components whose repair will lead to a greater quantity of saved fuel.

2. ANALYZED CYCLE

In order to compare the fuel impact formula and the reconciliation methodology a cogeneration cycle was used as a case study. The power plant (gas turbine with a heat recovery boiler) has to provide to its client 26.5 MW of electrical power and 64.3 MW of thermal power, using supplementary firing in the heat recovery steam generator (HRSG), burning natural gas, LHV of 47,597.00 [kJ/kg], at both: gas turbine and supplementary burner. The HRSG has two pressure levels and is composed by two economizers, two evaporators, one superheater and one integral deaerator. An integral deaerator/evaporator is a combined component where the steam for deaeration is supplied solely by the evaporator and the evaporator produced steam goes only to the deaerator. The power plant thermal scheme can be seen in figure 1. Gate Cycle™ software was used to calculate the mass and energy balances. The cycle was considered under steady state condition and it was also considered complete combustion of the fuel.

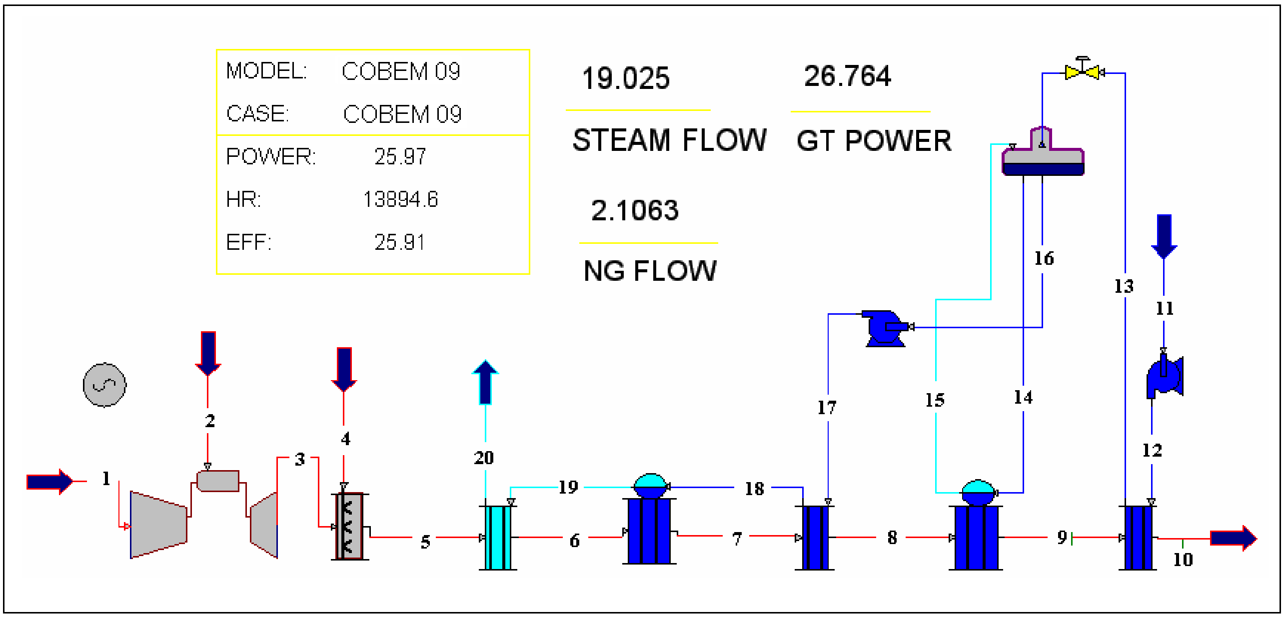

Figure 1. Cogeneration plant used to assess fuel impact formula and reconciliation approach.

In figure 1 the lines: 1 to 10 represent gas streams (air, natural gas or combustion products), the lines: 11, 12, 13, 14, 16, 17 and 18 are water streams, and lines: 15, 19 and 20 represent steam streams. The values of thermodynamic properties of the fluids in these lines are in the table 1.

When the system is under the presence of anomalies, the power plant control systems will react thus more fuel will be furnished to the gas turbine and also to the supplementary fire burner, in order to keep the thermal and electrical power outputs constants. This behavior can be used to simulate anomalies in the power plant components.

Table 1. Thermodynamic properties of the streams numbered in figure 1.

Flow	*Temp. [ºC]*	*Pressure [kPa]*	*Flow [kg/s]*	*Tot.Exergy [kJ/s]*	*Negentropy [kJ/s]*	*Enthalpy [kJ/s]*	*Chemical Exergy [kJ/s*
1	31.89	101.30	82.82	0.00	0.00	0.00	0.00
2	65.09	3,991.68	1.56	78,230.37	-	74,249.98	77,421.01
3	524.54	103.31	84.38	20,202.37	27,093.33	45,879.49	1,416.22
4	27.98	758.80	0.67	33,499.56	-	33,499.56	33,310.02
5	796.90	103.31	85.06	40,504.77	36,985.44	75,138.10	2,352.11
6	687.34	103.06	85.06	32,454.33	33,523.94	63,626.16	2,352.11
7	369.63	102.82	85.06	12,795.36	21,229.74	31,672.99	2,352.11
8	277.04	102.57	85.06	8,450.25	16,665.56	22,763.70	2,352.11
9	243.77	102.54	85.06	7,098.34	14,859.71	19,605.94	2,352.11
10	172.90	102.51	85.06	4,667.18	10,638.03	12,953.10	2,352.11
11	31.89	101.30	19.39	0.00	-	2,592.37	-
12	32.20	1,567.56	19.39	28.58	-	2,643.29	-
13	113.59	1,565.99	19.39	787.17	-	9,262.06	-
14	151.72	498.32	1.52	121.59	-	973.07	-
15	151.72	498.32	1.49	1,005.90	-	4,097.90	-
16	151.72	498.32	19.36	1,548.26	-	12,390.22	-
17	153.14	5,383.21	19.36	1,671.82	-	12,565.17	-
18	254.43	5,377.89	19.36	4,839.04	-	21,386.47	-
19	266.10	5,177.80	18.99	18,651.28	-	53,010.53	-
20	486.12	5,014.72	18.99	24,568.84	-	64,573.25	-
Power (TURBINE)				26,763.66		kW	-
Power (H PP)				223.74		kW	-
Power (L PP)				64.57		kW	-

2.1. Anomalies simulation

In order to test both methodologies, the performance decrease in some components was simulated. High pressure evaporator and economizer were selected as the components showing performance degradation caused by fouling, corrosion and aging. So the global heat exchange factors (U) in the high pressure evaporator and in the high pressure economizer were reduced to 90% of their respective values. The gas turbine heat rate was also increased in 600 [kJ/kW.hr] (additive). Thus, to keep the electric power constant the gas turbine fuel flow increased from 1.47 to 1.56 [kg/s], and to keep the steam flow constant, the supplementary firing fuel flow increased from 0.64 to 0.67 [kg/s].

3. FUEL IMPACT FORMULA

The fuel impact formula, see equation (1), is a relation between the unit exergy consumption variation of the cycle's components and the variation of exergy inputs in the cycle. Therefore this formula relates the components' efficiency to the plant's fuel consumption.

In equation (1), Δk_{ji} represents the unit exergy consumption variation of the exergy flows from *j* components that enter in component *i*. The term k^*_p is the unit exergy cost of each flow (this parameter indicates the quantity of external exergy necessary to produce the respective flow). And P^0_i, *is* the exergy product of component *i* at reference operation condition (*ROC*).

$$\Delta F_T = \sum_{i=1}^{n}\left(\sum_{j=0}^{n} k^*_p \Delta k_{ji}\right) P_i^0 \tag{1}$$

Using matrix algebra tools is possible to modify the scalar equation (1) to the matrix equation (2) where $\Delta^t k_e$ is a vector (*n x 1*) containing unit exergy consumption variation of external input ($k_{01}, k_{02}, \dots k_{0n}$) and $\Delta\langle KP\rangle$ is a matrix (*n x n*) containing the unit exergy consumption variation of each cycle's component, for further details see Valero et al. (2006a and 2006b).

$$\Delta F_T = \left(\Delta^t k_e + {}^t k^*_p \Delta\left\langle KP\right\rangle\right) P^0 \tag{2}$$

In order to obtain the necessary data for equation (2) it is necessary to build up the productive structure of the analyzed cycle. Several approaches to elaborate the productive structure of physical cycles have been proposed. The most widespread productive structures uses exergy as the base for cost allocation (*E* model) and exergy joined up with negentropy (*E&S* model). However the *E* model does not permit to isolate dissipative components and *E&S* model has some inconsistencies regarding the second law efficiency of the components. A detailed analysis about this issue can be found in Santos et al. (2006, 2008a, 2008b). Because of that, a new approach, as proposed by Santos and co-workers, which uses enthalpy joined up with negentropy, was used to formulate the productive structure of the analyzed plant (see figure 2).

The following nomenclature was used in figure 2. Note that the flow *E3:1*, for example, means exergy of flow 3 minus exergy of flow 1(*E3 – E1*).

TG: gas turbine
H PP: high pressure pump
L PP: low pressure pump
ENV: environment
SH: superheater
H Evap: high pressure evaporator
H Econ: high pressure economizer
L Econ: low pressure economizer
L Evap: low pressure evaporator
DA: Deaerator
Burner: supplementary firing
M: mixer
S (component): splitter
E: exergy
S (line): negentropy
C: chemical exergy
H: enthalpy

The gas turbine was considered as only one component, i.e., the compressor, the combustion chamber and the turbine itself is represented by a single square. This approach was used by Arena and Borchiellini (1999).

In this kind of productive structure the chemical exergy that goes to the environment is re-allocated as fuel to the burner and TG (components in which chemical exergy is generated). In the same way the negentropy generated by the heat exchangers in the heat recovery steam generator (HRSG) is proportionally re-allocated as fuel to the components responsible for gas entropy increasing (TG and Burner).

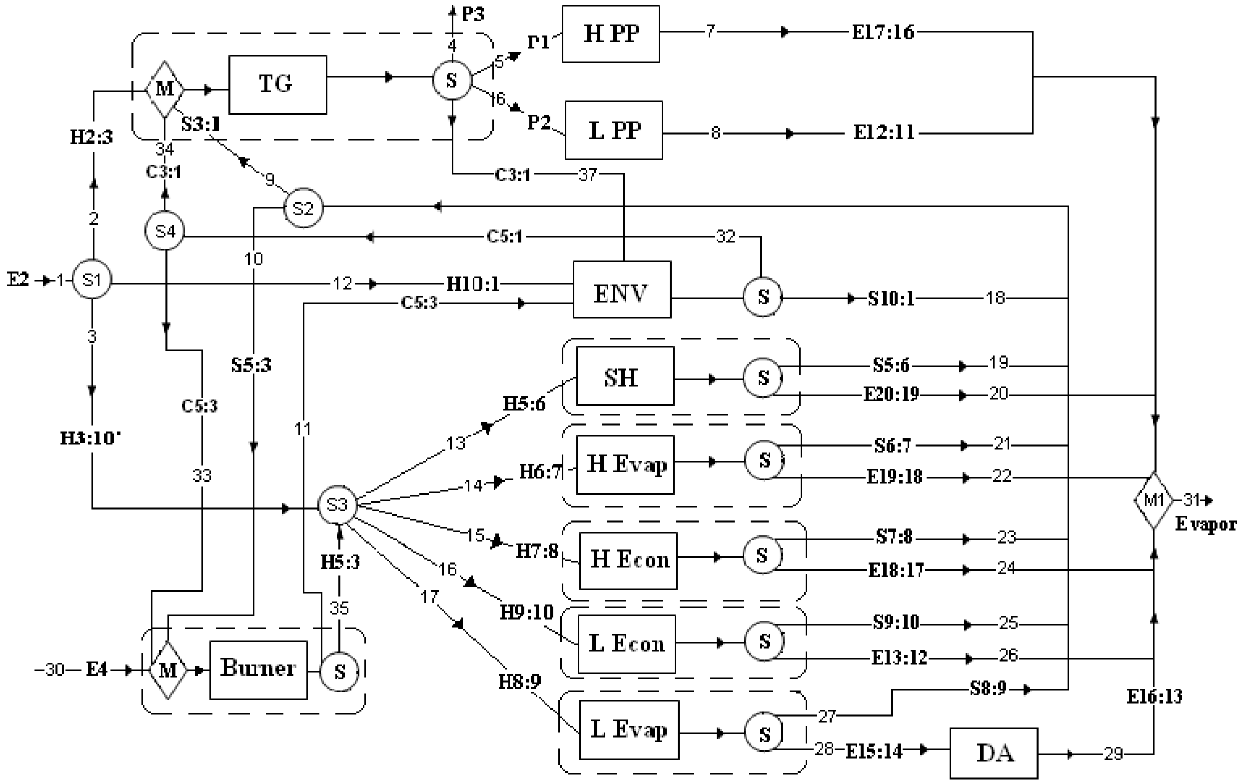

Figure 2. The productive Structure of the analyzed cycle using *H&S* model,.

Once the productive structure is defined, the next step for the use of fuel impact formula is the definition of the unit exergy cost of each flow (k^*). This parameter indicates how much each component uses the cycle external exergy inputs.

The procedure for k^* calculation consists in solving the equations that relates the unit exergy consumption of each component to the external exergy inputs, as in equation(3), using matrix properties. The figure 3 shows the fuel / product matrix, while figure 4 shows (U_D - ‹KD›) matrix. The (U_D - ‹KD›) matrix contains the coefficients of equation(3), k_j .

$$k_i^* - k_j k_j^* = 0 \quad (3)$$

By inverting matrix (U_D - ‹KD›) and multiplying it by the unit exergy consumption of the external inputs vector it is possible to calculate the k^* of each productive structure component, as can be seen in figure 5.

	F0	S1	S2	S3	S4	Burner	HPP	LPP	ENV	SH	H.Evap	H.Econ	L.Econ	L.Evap	DA	M1	TG
P0		78230				33500											
S1				33029					12953								28370
S2						9892.1											27093
S3										11512	31953	8909.3	6652.8	3157.8			
S4						935.89											1416.2
Burner				29259					935.89								
HPP																123.56	
LPP																28.582	
ENV			10638		2352.1												
SH			3461.5													5917.6	
H.Evap			12294													13812	
H.Econ			4564.2													3167.2	
L.Econ			4221.7													758.59	
L.Evap			1805.9												884.31		
DA																781.45	
M1	24569																
TG	26475						223.74	64.567	1416.2								

Figure 3. Fuel / Product matrix of analyzed productive structure

	P S1	P S2	P S3	P S4	11,35	7	8	18, 32	19,20	21, 22	23, 24	25,26	27,28	29	31	4,5,6,37
1 S1	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2 S2	0.00	1.00	0.00	0.00	0.00	0.00	0.00	-0.29	-0.09	-0.33	-0.12	-0.11	-0.05	0.00	0.00	0.00
3 S3	-0.53	0.00	1.00	0.00	-0.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 S4	0.00	0.00	0.00	1.00	0.00	0.00	0.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5 Burner	0.00	-0.33	0.00	-0.03	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6 HPP	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.81
7 LPP	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.26
8 ENV	-1.00	0.00	0.00	0.00	-0.07	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.11
9 SH	0.00	0.00	-1.23	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 H.Evap	0.00	0.00	-1.22	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
11 H.Econ	0.00	0.00	-1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
12 L.Econ	0.00	0.00	-1.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
13 L.Evap	0.00	0.00	-1.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
14 DA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.13	1.00	0.00	0.00
15 M1	0.00	0.00	0.00	0.00	0.00	-0.01	-0.001	0.00	-0.24	-0.56	-0.13	-0.03	0.00	-0.03	1.00	0.00
16 TG	-1.01	-0.96	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Figure 4. (U_D - ‹*KD*›) matrix for the analyzed productive structure (used to calculate k^*)

k^*1		1.0522
k^*2		1.5985
k^*3		1.3486
k^*4		1.4611
k^*5		1.6784
k^*6		4.834
k^*7		6.0306
k^*8	=	1.4611
k^*9		1.6552
k^*10		1.6506
k^*11		1.554
k^*12		1.8015
k^*13		1.583
k^*14		1.7913
k^*15		1.6709
k^*16		2.6696

Figure 5. Unit exergy cost of the productive structure's components

Once that k^* is calculated for each component, it is necessary to compare the unit exergy consumption of the analyzed plant components at the reference operation condition (*ROC*), that is the state without the simulated anomalies, and in test operation condition (*TOC*), that is the state with the anomalies. The differences between unit exergy consumption in both states are the Δks used to form the matrix Δ‹*KP*›. The results of the equation (2) can be seen in table 2.

Table 2. Calculated ΔF for the cycle components.

Equip.	k@TOC	k@ROC	Δk (TOC-ROC)	k*@TOC	ΔF[kW]	ΔF [kg/s]
TG	2.02	1.87	0.15	2.67	4,535.05	0.0904
Burner	1.47	1.47	0.00	1.68	-25.16	-0.0005
SPHT	1.23	1.23	0.00	1.66	19.86	0.0004
H Evap	1.22	1.21	0.01	1.65	360.33	0.0072
H Econ	1.15	1.14	0.01	1.55	76.06	0.0015
L Evap	1.17	1.17	0.01	1.58	19.67	0.0004
L Econ	1.34	1.31	0.02	1.80	133.54	0.0027
H PP	1.81	1.82	-0.01	4.83	-5.43	-0.0001
L PP	2.26	2.26	0.00	6.03	-0.01	0.0000
DA	1.16	1.17	-0.01	1.79	-2.48	0.0000

As can be seen in table 2 the gas turbine is the component responsible for the greater impact in the fuel consumption, in exergy basis it corresponds to 4,535.05 kW. This value can be easily converted in saved fuel flow regarding *TG* anomaly elimination. It is possible to observe in figure 1 that the flow 2 (fuel input in *TG*) provides 78,230.37 kW to the plant. Thus the anomaly present in the *TG* is responsible for an increase of 0,0904 kg/s in the fuel mass flow. The same analysis is done for the others components. The *H Evap* is responsible for an increment of 0,0072 kg/s in the fuel flow entering in the burner (figure 1, flow 4). *H Econ*, which was considered to be the third and last component with malfunction (section 2.1), is only the forth in importance for anomalies elimination, since anomalies are disguised by the induced effects. Besides that, Table 2 also shows that the *L Econ* is the third component in importance for anomaly elimination; however no anomaly was simulated in this component, as stated in section 2.1.

4. RECONCILIATION APPROACH

In order to use the reconciliation approach, an off-design model of each component, individually, was used to simulate the clean state condition (CC). These models permit to evaluate each component under current conditions inputs. In this way the effects of being working out of project point (off-design), will also be present at the clean state condition, once that the component will be running on the performance curves used in the models.

The performance indicator (PF) used, is the relation between any given thermodynamic (TD) output at current condition (TOC) and the respective thermodynamic output at the clean state condition, both under the same inlet conditions. As the induced effects are present in both cases, it is not present in the performance indicator when no anomalies are present. It happens because the TD output at TOC will be equal to TD output at CC and that will provide a PF = 1, which indicates that no anomalies are present. Any value different from “one” indicates the presence of anomalies.

$$PF = \frac{TDoutput_{TOC}}{TDoutput_{CC}} \tag{4}$$

One component can have more than one performance indicator. Usually the performance indicators of the components are based on the values of the performance curves provided by the manufactures. The pumps, for example, used two *PFs:* one for output pressure and one for efficiency. The heat exchangers present in the HRSG have three *PFs:* one for global heat exchange coefficient *U*, one for pressure drop in the cold side (PDC) and one for pressure drop in the hot side (PDH). The table 3 shows a list with the types (forms) of performance curves used.

Table 3. Performance curves used to make the off-design models

Component	Curves / Equations
Gas Turbines	Heat Rate x Load
	Heat Rate x Temperature
	Exhausting flow x Load
	Exhausting flow x Temperature
	Exhausting Temperature x Load
	Exhausting Temperature x Temperature
Pumps	Head x flow
	Efficiency x flow
Economizers	PDC x Flow
	PDH x Flow, temperature and pressure
	U x Flow
Evaporators	PDH x Flow, temperature and pressure
	U x Flow
Super-Heaters	PDC x Flow, specific volume
	PDH x Flow, temperature and pressure
	U x Flow

Once that all *PFs* have been calculated, the curves used in the clean state condition (CC) are corrected by the *PFs*. These curves corrected by *PFs* are used in the off-design model of the whole thermodynamic cycle, representing the current condition. An example of a CC pump's head curve correction can be seen in figure 6.

In order to provide the information of how much fuel can be saved by the elimination of the simulated anomalies, the performance factors representing the current condition, that are used in corrected curves, are replaced, component by component, by "one" (value that represent no anomaly). This procedure represents the elimination of the anomalies present in the components. After each PF replacement, the mass and energy balance are carried out, and the values of net power and heat rate are calculated. After this, the value of the performance factor of the component being analyzed is restored to its original value and the analysis can proceed to another component, through its performance factor replacement by 1. If a component has two or more PFs, they are analyzed at the same time in order to indicate the component recuperation.

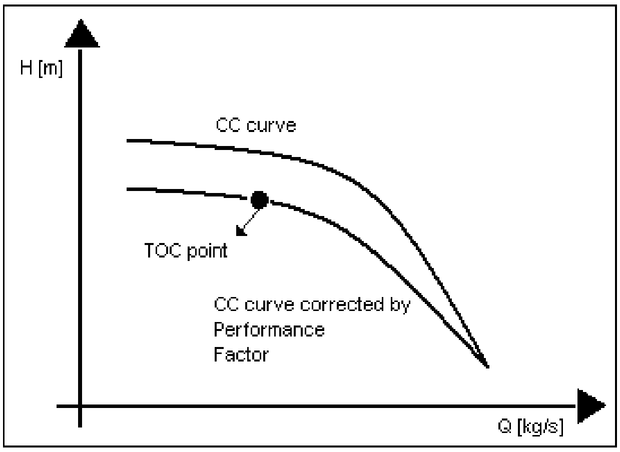

Figure 6. An example of *CC* curve corrected by its *PF* in order to represent the off-design model at current condition

The values obtained by the reconciliation approach can be seen in the table 4. This table clearly shows that the three components responsible for the anomalies simulated were localized and the values of the gain that can be obtained (saved fuel) by the anomalies elimination were quantified. For all the other components (without anomalies) the values for ΔF are zero. It also can be seen that the values of ΔF obtained by reconciliation method are higher than the values obtained by fuel impact formula. It happens because when the component has its anomalies eliminated the effects of this elimination in the others components behavior are also taken into consideration.

Table 4. Results obtained using the reconciliation approach

Equip.	PF@TOC	PF@CC	ΔF [kg/s]
TG	*1.0639*	*1.00*	*0.0937*
Burner	*1.0000*	*1.00*	*0.0000*
SPHT	*1.0000*	*1.00*	*0.0000*
H Evap	*0.9000*	*1.00*	*0.0224*
H Econ	*0.9000*	*1.00*	*0.0123*
L Evap	*1.0000*	*1.00*	*0.0000*
L Econ	*1.0000*	*1.00*	*0.0000*
H PP	*1.0000*	*1.00*	*0.0000*
L PP	*1.0000*	*1.00*	*0.0000*
DA	*1.0000*	*1.00*	*0.0000*

5. CONCLUSION

The fuel impact formula shows its effectiveness to localize the main anomaly present in the cycle, however this approach has induced effects present in its anomalies indicator, Δk. This happens because the comparison in this approach is performed between the current state (*TOC*), where the anomalies are present, and the reference state (*ROC*). As the components are under different conditions, their efficiencies are also different, even in the components without anomalies. The different conditions are caused by induced effects and lead to difficulties in finding the secondary anomalies.

Besides the presence of induced malfunctions or effects, the fuel impact formula uses a non-dynamic external fuel distribution, k^*(unit exergy cost), calculated using the values at current state (*TOC*). This distribution supposes to change at each anomaly elimination until the whole cycle reaches the new stable thermodynamic state. The error regarding this simplification tends to increase when the difference between the current state and the reference state increases.

As the reconciliation approach uses an off-design model of each component to simulate the clean state condition (*CC*), no induced effects are present in the anomaly indicator (*PF*), so the comparison between components behavior are performed under the same conditions.

In the reconciliation approach the prediction of the fuel saved by the anomalies elimination, usually called prognostic, is done using an off-design model of the whole cycle that uses the components performance curves corrected by the performance factors. Using such a model it is possible to reach the new thermodynamic state of the cycle when each anomaly is eliminated. In this way it is possible, accurately, to calculate the fuel that can be saved by each anomaly elimination. Thus, the reconciliation approach results were the expected ones: anomaly in the high pressure evaporator and economizer and in the gas turbine. Besides that, the quantification of the fuel that can be save math with the values provided in section 2.1.

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8. ACKNOWLEDGMENTS

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