Int.J. Applied Thermodynamics, **ISSN 1301-9724**
Vol.5 (No.3), pp.127-137, September-2002

Effects of the Productive Structure on the Results of the Thermoeconomic Diagnosis of Energy Systems.

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Abstract

In engineering, the word *diagnosis* identifies procedures for detecting the presence of anomalies in systems, locating where they have occurred and quantifying them.
Thermoeconomic diagnosis procedures are based on the productive representation of systems. This is a mathematical expression of the role played by each component in the whole plant, made by defining its fuels and products in terms of exergy flows. This is called the *productive structure*.
The details of a productive structure are at two different levels, one with respect to the number of components and the other with respect to the number of productive flows. The first one is selected according to the accuracy desired in the location of the anomalies. The higher the number of components is, the higher is the accuracy. Once the components are identified, the number of productive flows can be increased by separating exergy into its components (Tsatsaronis et al., 1990) or by introducing fictitious flows (Frangopoulos 1987, Von Spakovsky and Evans 1990). This decision facilitates the assessment of the nature of the anomaly (thermal, mechanical or chemical), but also affects the results of the thermoeconomic analysis, even when it is adapted for diagnosis purposes.
In this paper the effects of these decisions on the results of the thermoeconomic diagnosis is investigated. A particularly sensitive test, obtained by simulating an anomaly in the HRSG of a combined cycle plant, is considered.

Key words: thermoeconomic diagnosis, productive structure

1. Introduction

In a thermoeconomic diagnosis procedure, such as that one presented in Verda et al. (2002), the analysis is usually conducted at the components' level because the principal aim of diagnosis procedure consists of finding the components where the anomalies have occurred and also quantifying them.

When applying a thermoeconomic diagnosis procedure, systems are described by defining component fuels and products and how they are interconnected, i.e. by the productive structure (Verda et al. 2002, Verda 2001). This is a picture of the system which allows one to highlight the inefficiencies and how they affect the overall efficiency and plant management. In fact, as defined by the principle of the non-equiva-lence of the irreversibilities (Lozano and Valero 1993), the same variation in the efficiency of a process produces a different impact on fuel consumption, depending on the position of the process itself. Thus,

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thermoeconomic analysis gives additional information with respect to the exergy analysis.

The comparison between two pictures of the system - an operating condition compared with respect to a selected reference condition - allows one to investigate the degradation in behavior of the components. Nevertheless, this information is not complete. In fact, when an anomaly occurs in a component, in general not only does its efficiency change but also the efficiencies of other surrounding components. This is due to the dependence of the efficiencies on the operating condition. In this way, when the anomaly occurs, the operating condition moves towards a new equilibrium point to which different efficiencies correspond. This effect in a component is called the induced malfunction.

Induced malfunctions are a problem when diagnosing the behavior of a system, because they hide the real cause of the inefficiencies or anomalies (see Verda et al. 2002 for a more detailed description of the effect of induced malfunctions). In order to filter the disturbing effects of induced malfunctions, the analyst can build a thermoeconomic model of the system that is able to predict the behavior of components. In this way, the anomalies can be more clearly discovered and located.

The proposed thermoeconomic model of a component that should be built by the analyst as a tool for filtering the effect of induced malfunctions is based on the concept of unit exergy consumption, which is defined as the ratio between each resource E_{ji}, consumed by the j^{th} component to develop its productive process, and the product of the process itself, i.e.

$$k_{ji} = \frac{E_{ji}}{P_j} \tag{1}$$

The accuracy of the results increases as the model becomes more detailed, taking into consideration the effect on efficiencies of possible variations in inlet component conditions (pressure, temperature, mass flow, mechanical power). Since the efficiencies depend on the operating conditions, the unit exergy consumptions are functions of the productive flows interacting with the components, i.e.

$$k_{ji} = k_{ji}\left(E_{j0}, E_{j1}, ..., E_{jn}\right) \tag{2}$$

If the variation in the productive flows is sufficiently small, equation (2) can be written as a first order Taylor series, namely

$$\hat{k}_{ji} = k_{ji_{ref}} + \sum_{l=0}^{n}\left(\frac{\partial k_{ji}}{\partial E_{jl}} \cdot \Delta E_{jl}\right) \tag{3}$$

The use of such a model allows one to evaluate the induced effects occurring in a plant when a small anomaly occurs. The sign ^ is adopted to indicate that the effects of the control system have already been considered and filtered out (see Verda et al. 2002, Verda et al. 2001 for details). This is necessary when the presence of the anomaly causes the intervention of the control system, which modifies the natural propagation of the effects of the anomaly itself in order to avoid damage to the components. As explained in Verda et al. (2001), the filtration of the effects of the control system is obtained by considering, instead of the real operating condition, a fictitious condition, called the free condition, which is the state in which the system would operate if the control did not intervene.

In this paper some considerations about the effects of the choice of the productive structure on the diagnosis results are made. The diagnosis procedure presented in Verda et al. (2002) is applied to a combined cycle power plant (see *Figure 1*). The plant is based on two gas turbines, which produce about 125 MW of electricity each at the design condition. The exhausted gases, still hot (about 500 °C), are used to produce steam in two heat recovery steam generators (HRSGs). The steam, produced at two pressure levels (about 55 bar and 6 bar, respectively) is used in a steam turbine, which allows the plant to obtain an additional amount of electricity (about 110 MW).

Different productive structures, characterized by a different detail are analyzed.

2. Problem Definition

The problem of choosing the correct productive structure for the thermoeconomic model definition can be introduced by considering a simple case of malfunction in a gas turbine plant. Let us consider the operating condition corresponding to an anomaly in the compressor, which provokes a decrease in efficiency of the compressor.

The productive structure of the gas turbine is presented in *Figure 2*. Flows E_1 and E_5 are the total exergy components (sum of the mechanical and thermal components) of the air entering the combustor and the turbine (cooling air), while E_2 is the thermal exergy flow of the combustion gases required by the turbine. E_7 and E_8 are shaft power. In TABLE I the components, productive flows, and exergetic unit costs are presented.

Equation (2) can take different forms, depending on the detail of the productive structure and, then, on the number of productive flows. For example, the number of productive flows is different depending on whether the exergy flows are separated into their thermal and mechanical components or not. The unit exergy consumptions k_{10} and k_{12}, associated with the exergy flow of the natural gas and the air required by the combustor are particularly sensitive to this choice. Thus, if the thermal and mechanical exergy

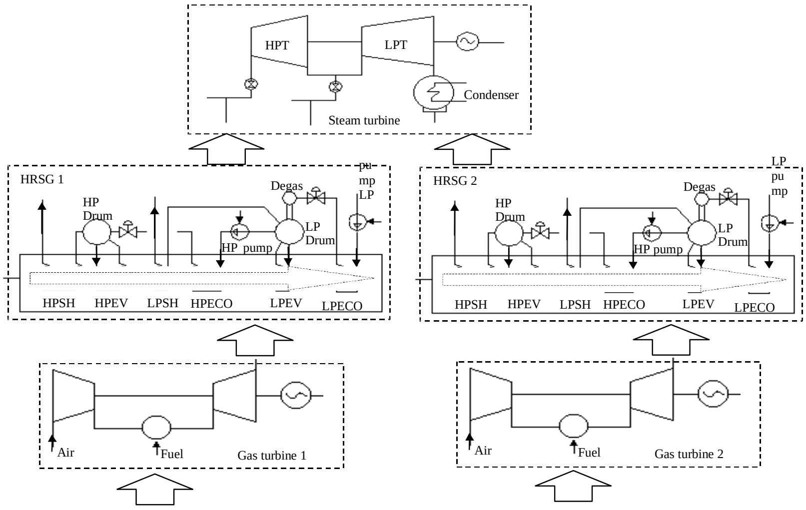


Figure 1. Scheme of a combined cycle.

TABLE I. COMPONENTS AND PRODUCTIVE FLOWS OF THE GT1 GAS TURBINE.

Components	Fuels	Product	Unit exergy consumption
1 Combustor	E_0,E_1	E_2;E_3;E_4	$k_{10}=E_0/(E_2+E_3+E_4)$;$k_{12}=E_1/(E_2+E_3+E_4)$
2 Compressor	E_8	E_1;E_5;E_6	$k_{23}=E_8/(E_1+E_5+E_6)$
3 Turbine	E_2,E_5	E_7;E_8	$k_{31}=E_2/(E_7+E_8)$;$k_{32}=E_5/(E_7+E_8)$
4 Alternator	E_7	E_9	$k_{43}=E_9/E_7$

E_0 (exergy of methane)
E_1 (exergy of compressed air used as comburent)
E_2 (exergy of combustion gases processed in the turbine)
E_3 (exergy combustion gases processed in the HRSG)
E_4 (exergy of exhausted gases)
E_5 (exergy of refrigeration air)
E_6 (exergy of escaped air)
E_7 (shaft power to the alternator)
E_8 (shaft power to the compressor)
E_9 (electricity)

components are considered, then the variation of these unit exergy consumptions can be calculated as follows:

$$\Delta k_{1i} = \frac{\partial k_{1i}}{\partial E_0}\cdot\Delta E_0 + \frac{\partial k_{1i}}{\partial E_{1m}}\cdot\Delta E_{1m} + \frac{\partial k_{1i}}{\partial E_{1t}}\cdot\Delta E_{1t} \quad (4)$$

where i equals 0 and 2.

In the case of our example, the mechanical and thermal components of exergy for an ideal gas are

$$E_{1m} = G_{air}\cdot R_{air}\cdot T_0\cdot\ln\frac{p_{out}}{p_{in}} \quad (5)$$

$$E_{1t} = G_{air}\cdot c_{p_{air}}\cdot\left(T_{out} - T_{in} - T_0\cdot\ln\frac{T_{out}}{T_{in}}\right) \quad (6)$$

The total exergy of a flow is defined by the sum of equations (5) and (6).

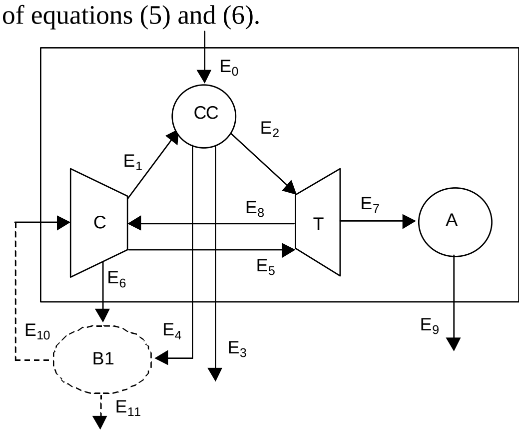


Figure 2. Productive structure of the gas turbine

Variations in mechanical exergy are primarily associated with variations in mass flow rate. Variations in thermal exergy are associated with variations in air mass flow and outlet temperature (the inlet temperature is the same at the design, operating, and free conditions).

The same variation of the exergy flow E_1 can be produced by temperature or mass flow variations. Therefore, the effect on combustor efficiency is different. Assuming constant fuel mass flow rate, an increased air mass flow rate has two opposite effects on the product: it increases the mass flow, but it decreases the specific exergy of the combustion gases. In contrast, if only the thermal component increases, the combustor efficiency increases too, since the outlet gases are at a higher temperature.

The accuracy of the proposed model can be evaluated by comparison with respect to the ideal model, i.e. with respect to a model that would be able to isolate the intrinsic malfunction and completely eliminate the induced effects. In fact, the use of a linear model determines the presence of residual effects if the process is not linear. Thus, the accuracy can be expressed as the ratio between the calculated intrinsic effect and the total effects (intrinsic plus residual effects; see Verda et al. 2002 for details).

If total exergy flows were adopted for the calculation of the induced malfunctions, then the increase of unit exergy consumption would be calculated with the following equation:

$$\Delta k_{1i} = \frac{\partial k_{1i}}{\partial E_0} \cdot \Delta E_0 + \frac{\partial k_{1i}}{\partial E_1} \cdot \Delta E_1 \qquad (7)$$

With this expression, larger errors, than in the case of equation (4), could occur in the calculation of the malfunctions. In this particular example, the use of a more detailed model provides a result with an accuracy of about 92 %. A less detailed model -equation (7)- provides a result with an accuracy of about 60 %.

3. Plant Operating Conditions

The effects of the choice of the productive structure on the results of the thermoeconomic diagnosis is now analyzed by considering a very interesting case study: a reduction in the heat transfer coefficient of the high pressure evaporator of the HRSG due to fouling or any other operational problem The operating condition is obtained by simulating the system when suffering this anomaly in the HRSG of the high pressure evaporator.

When a highly complex system is considered, the location of the anomalies can be made in two steps. The first one consists of dividing the system into macro-components constituting a simpler and sequential productive structure (Verda et al. 2002). In this way, a simple analysis allows one to locate the macro-components where the anomalies have occurred. Next, the more precise location is made by diagnosing these macro-components only.

In the present example, the analysis is focused on the macro-component heat recovery steam generator since it was located in the previous step as the macro-component containing the anomaly (see Verda et al. 2002).

The subsystem is depicted in *Figure 3*.

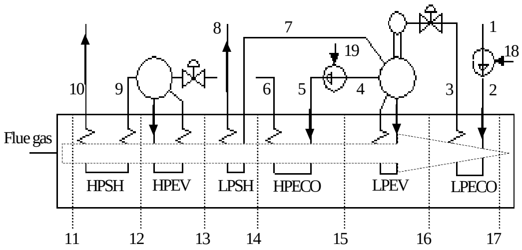


Figure 3. Physical schematic of the HRSG.

The values of thermodynamic quantities at the operating and reference conditions are shown in TABLE II.

TABLE II. OPERATING AND REFERENCE CONDITION FOR THE HRSG.

	Reference			Operation		
Point	G [kg/s]	T [°C]	p [bar]	G [kg/s]	T [°C]	p [bar]
1	61.11	53.5	0.15	61.27	53.5	0.15
2	61.11	53.5	7.84	61.27	53.5	7.85
3	61.11	162.5	6.59	61.27	162.6	6.59
4	48.03	162.5	6.59	47.02	162.6	6.59
5	48.03	163.5	64.92	47.02	163.6	64.33
6	48.03	269.5	54.54	47.02	268.9	54.04
7	13.08	162.5	6.59	14.25	162.6	6.59
8	13.08	273.0	6.39	14.25	277.4	6.40
9	48.03	269.5	54.54	47.02	268.9	54.04
10	48.03	490.0	52.90	47.02	490.0	52.42
11	445.83	505.0	1.02	446.28	505.0	1.02
12	445.83	446.8	1.02	446.28	448.0	1.02
13	445.83	291.4	1.01	446.28	295.9	1.01
14	445.83	284.9	1.01	446.28	288.5	1.01
15	445.83	236.7	1.01	446.28	241.7	1.01
16	445.83	180.1	1.00	446.28	180.1	1.00
17	445.83	120.4	1.00	446.28	120.3	1.00

In the case of the HRSG, the thermoeconomic model required for the thermoeconomic diagnosis and for locating the induced malfunctions should be built by using some additional operating conditions that could simulate the effects of both the control system and the inlet conditions of the components on the behavior of the components themselves. These additional operating conditions must refer to the HRSG without anomalies. Thus, they can be measured when variations in ambient conditions, set-points, or electric load occur. Otherwise, they can correspond to anomalies located in other macro-components, such as the gas turbine or the steam turbine.

4. Base Thermoeconomic Model of Components

The available data (measured or simulated) allows one to built thermoeconomic models containing eight components, which in the HRSG are: 2 economizers, 2 evaporators 2 super-heaters, and 2 circulation pumps. Since the Thermoecono-mic models contain these eight components, it is expected that the diagnosis procedure would be able to locate any anomaly in the corresponding subsystems.

The simplest productive structure that can be obtained corresponds to that which expresses resources and products as exergy flows (*Figure 4*).

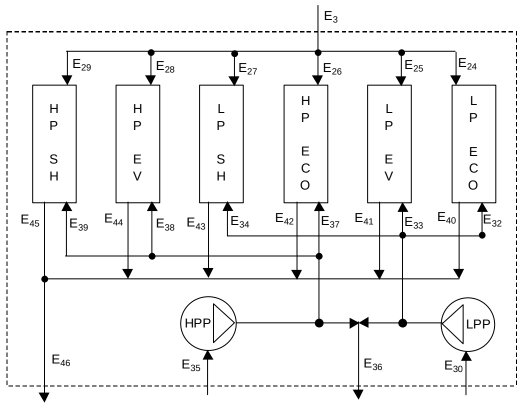


Figure 4. Base productive structure of the HRSG.

In TABLE III, the components and productive flows of the HRSG are shown. E_3 is the total resource of the HRSG macro-component, which has been produced by the gas turbine (see *Figure 1*). Inside the control volume, this flow is split among the heat exchangers according to their demand. For the heat exchanger depicted in *Figure 5*, the corresponding resource, which corresponds to the exergy released by the hot gases, is expressed as

$$E_{F1} = G_{gas} \cdot \left(b_{gas\,in} - b_{gas\,out}\right) \quad (8)$$

The exergy increase of the water flows passing through the pumps is the product of the pumps and it is provided to the heat exchangers (E_{32}-E_{35} and E_{37}-E_{39}) and to the steam turbine (E_{36}). The total product of the pumps is then split among these components according to the pressure drop registered on the water-side, i.e.

$$E_{F2} = G_w \cdot \left(b\left(T_0, p_{w\,in}\right) - b\left(T_0, p_{w\,out}\right)\right) \quad (9)$$

This quantity represents the mechanical exergy of the liquid (Tsatsaronis et al. 1990). This flow is zero when it is calculated for the evaporators since both inlet and outlet pressures correspond to the drum pressure.

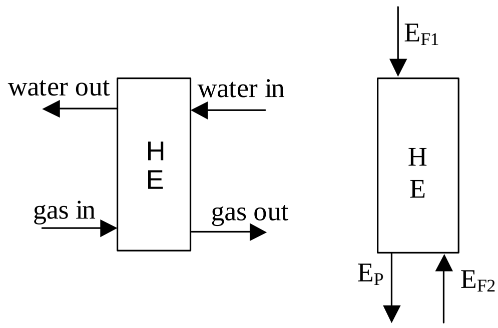


Figure 5. Physical and productive flows of a heat exchanger.

Finally, the product of each heat exchanger is the exergy provided to the water in the heat transfer process, namely,

$$E_P = G_w \cdot \left(b_{w\,out} - b_{w\,in}\right) \quad (10)$$

TABLE III. COMPONENTS AND PRODUCTIVE FLOWS OF THE HRSG.

Components	Fuels	Product	Unit exergy consumption
5 Low pressure economizer	E_{24},E_{32}	E_{40}	$k_{5-1}=E_{24}/E_{40}$;$k_{5-11}=E_{32}/E_{40}$
6 Low pressure evaporator	E_{25},E_{33}	E_{41}	$k_{6-1}=E_{25}/E_{41}$;$k_{6-11}=E_{33}/E_{41}$
7 High pressure economizer	E_{26},E_{37}	E_{42}	$k_{7-1}=E_{26}/E_{42}$;$k_{7-12}=E_{37}/E_{42}$
8 Low pressure super-heater	E_{27},E_{34}	E_{43}	$k_{8-1}=E_{27}/E_{43}$;$k_{8-11}=E_{34}/E_{43}$
9 High pressure evaporator	E_{28},E_{38}	E_{44}	$k_{9-1}=E_{28}/E_{44}$;$k_{9-12}=E_{28}/E_{44}$
10 High pressure super-heater	E_{29},E_{39}	E_{45}	$k_{10-1}=E_{29}/E_{45}$;$k_{10-12}=E_{29}/E_{45}$
11 Low pressure pump	E_{30}	E_{32};E_{33};E_{34};E_{36}*	$k_{11-0}=E_{30}/(E_{32}+E_{33}+E_{34}+E_{36}*)$
12 High pressure pump	E_{35}	E_{37};E_{38};E_{39};E_{36}**	$k_{12-0}=E_{35}/(E_{37}+E_{38}+E_{39}+E_{36}**)$

E_3 (exergy of combustion gases processed in the HRSG)
E_{24}-E_{29} (exergy of combustion gases split among the heat exchangers)
E_{30} (electric power required by LPP)
E_{32}-E_{34} (exergy of feed water split among the low pressure heat exchangers)
E_{35} (electric power required by the HPP)
E_{36} (exergy of feed water tranfered to the steam processed in the steam turbine)
low pressure (*) and high pressure (**) components produced by LPP and HPP respectively
E_{37}-E_{39} (exergy of feed water split among the high pressure heat exchangers)
E_{40}-E_{45} (exergy trasfered to steam by each heat exchanger)
E_{46} (exergy transfered to the steam by all the heat exchanger)

TABLE IV. BASE PRODUCTIVE FLOWS OF THE HRSG.

	Ref	Op	Add 1	Add 2	Add 3	Add 4	Add 5	Free
E24	10490	10522	10484	10474	10609	10532	10752	10505
E25	11888	11837	11765	11900	12032	11942	12196	12993
E26	11403	11462	11454	11379	11536	11452	11691	11173
E27	1644	1638	1630	1645	1667	1653	1693	1864
E28	44100	44347	44253	44027	44485	44241	44933	43399
E29	18911	18656	19161	18840	19088	18974	19297	18515
E30	54.9	55.1	55.0	54.8	55.7	55.2	56.7	55.2
E32	8.3	8.4	8.3	8.3	8.4	8.4	8.6	8.3
E33	0	0	0	0	0	0	0	0
E34	0.43	0.44	0.42	0.44	0.43	0.43	0.42	0.45
E35	424.7	427.3	427.2	423.6	430.9	427.0	438.1	411.0
E36	293.7	295.5	295.4	292.9	298.0	295.3	303.0	283.7
E37	67.7	68.1	68.1	67.5	68.7	68.1	69.8	65.6
E38	0	0	0	0	0	0	0	0
E39	10.7	10.7	10.7	10.6	10.8	10.7	11.0	10.3
E40	7875	7903	7876	7863	7966	7908	8075	7889
E41	10121	10080	10019	10130	10244	10167	10386	11011
E42	10304	10360	10354	10281	10425	10349	10567	10006
E43	1349	1344	1338	1350	1368	1356	1390	1534
E44	38345	38544	38457	38284	38692	38473	39096	37553
E45	16757	16481	16975	16694	16916	16814	17104	16389
E46	84751	84712	85018	84602	85612	85067	86618	84382

The exergy flows calculated at the reference (Ref) and actual operating (Op) conditions are indicated in TABLE III. In this table, the additional operating conditions (Add1 – Add5), used for building up the thermoeconomic model of the HRSG, are also indicated. Add1 and Add2 have been obtained by changing the control settings of the turbine with respect to the reference condition. In particular, Add1 is obtained by reducing the air mass flow rate (position of the IGV +0.5) and Add2 by reducing the fuel mass flow rate (-0.01 kg/s). The operating conditions Add3-Add5 have been simulated by introducing anomalies in the gas turbine. The free operating condition is indicated in the last column of TABLE IV. The free condition, as is explained in detail in Verda et al. (2001), is a fictitious condition characterized by the same regulation as the reference condition but containing the anomalies occurring at the actual operating condition. In this way, the induced effects provoked by the control system can be filtered and avoided (Verda et al. 2001).

The proposed thermoeconomic model must simulate the behavior of a component when no anomalies have taken place in the component itself and when its resources differ from the reference ones. In *Figure 6*, the intrinsic (Δk_{int}) and the induced (Δk_f) effects appearing in the comparison between free and reference conditions are indicated. As already explained, at the free condition, the induced effects provoked by the control system have been filtered and removed. Then, the remaining induced effects are those provoked by the rest of the plant components. l system have been filtered out. Thus, the elimination or filtration of the induced effects Δk_f allows one to highlight the intrinsic inefficiencies, which correspond to the real anomalies occurring in the plant.

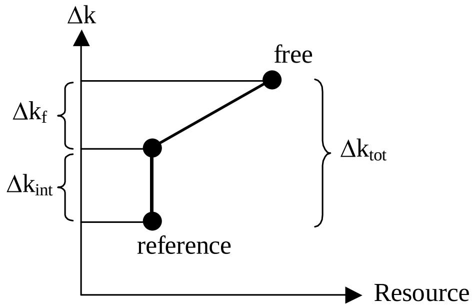


Figure 6. Unit exergy consumption variation in the comparison between free and reference conditions.

The linear model expressed by equation (3) can be adopted to evaluate the malfunctions induced by small anomalies.

As shown before, the induced malfunctions occur when the components operate at conditions different from the reference state. They can be estimated by isolating the components and successively forcing their resources to be equal to the values determined at the free condition. Since the thermoeconomic model of components is built by using data corresponding to operating conditions where no anomaly has occurred, all the variations in efficiency and, therefore, in unit exergy consumptions are due to induced effects. The induced effects expressed in terms of variations in the unit exergy consumptions are, thus, obtained by considering variations of unit exergy consumptions when resources move from the reference to the free condition, i.e.

$$\Delta k_{f_{ji}} = \hat{k}_{ji} - k_{ji_{ref}} = \sum_{l=0}^{n} \left(\frac{\partial k_{ji}}{\partial E_l} \cdot \Delta E_l \right) \tag{11}$$

where E_l is the general fuel of the component, and ΔE_l is its variation between free and reference conditions.

The derivatives are calculated by using the operating conditions Add1-Add5, as indicated below. As illustration, let us consider once again the heat exchanger depicted in *Figure 5*. Its thermoeconomic behavior is described by two values of the unit exergy consumption, namely,

$$k_{P-F1} = \frac{E_{F1}}{E_P} \tag{12}$$

$$k_{P-F2} = \frac{E_{F2}}{E_P} \tag{13}$$

The linear model of the heat exchanger is such that

$$\Delta \hat{k}_{P-F1} = \frac{\partial k_{P-F1}}{\partial E_{F1}} \cdot \Delta E_{F1} + \frac{\partial k_{P-F1}}{\partial E_{F2}} \cdot \Delta E_{F2} \tag{14}$$

$$\Delta \hat{k}_{P-F2} = \frac{\partial k_{P-F2}}{\partial E_{F1}} \cdot \Delta E_{F1} + \frac{\partial k_{P-F2}}{\partial E_{F2}} \cdot \Delta E_{F2} \tag{15}$$

Five operating conditions (Add1-Add5) are available for the calculation of two derivatives, which can be expressed, under the hypothesis of small perturbations, as

$$\frac{\partial k_{P-F1}}{\partial E_{F1}} \approx \left(\frac{\Delta k_{P-F1}}{\Delta E_{F1}} \right)_{F2} \tag{16}$$

$$\frac{\partial k_{P-F1}}{\partial E_{F2}} \approx \left(\frac{\Delta k_{P-F1}}{\Delta E_{F2}} \right)_{F1} \tag{17}$$

where the Δ indicates the difference between values at each additional operating condition (Add1-Add5) with respect to the reference condition. A similar hypothesis is considered for the derivatives in equation (15).

When the evaporators are considered, flow F2 is zero, since no pressure drop is registered between the inlet and outlet cross-section. This means that the derivatives with respect to F2 expressed by equation (11) are zero. Thus, equations (14) and (15) applied to the evaporators become

$$\Delta \hat{k}_{P-F1} = \frac{\partial k_{P-F1}}{\partial E_{F1}} \cdot \Delta E_{F1} \tag{18}$$

$$\Delta \hat{k}_{P-F2} = \frac{\partial k_{P-F2}}{\partial E_{F1}} \cdot \Delta E_{F1} \tag{19}$$

Such a model does not allow one to obtain good results (see TABLE IX in the *Results* section), since the correlation between variations in fuel and variations in unit exergy consumption is very poor. A different productive structure should be adopted.

5. Detailed Thermoeconomic Model of Components

A more detailed productive structure can be obtained by splitting the exergy components associated with the mass flows into mechanical and thermal components (see *Figure 7*). The split of gas exergy allows one to better consider the different effects on heat exchanger production of variations in pressure, temperature or mass flow rate of the gases exiting the turbine. The exergy associated with water flows has been divided into mechanical and thermal components, too.

Formulae for the calculation of these components are suggested in Tsatsaronis et al. (1990).

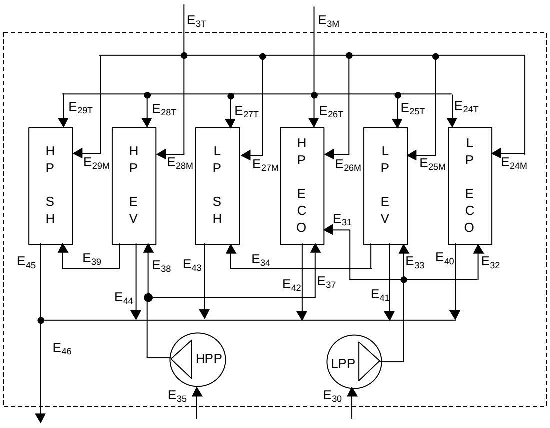
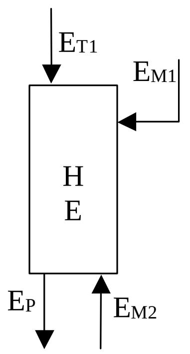


Figure 7. Detailed productive structure.

The definition of fuels and products must be heavily modified. In particular, it is opportune to distinguish between the exergy associated with liquid and vapor. In this way, pumps increase the mechanical exergy of a liquid. This exergy is partially consumed in the economizers, in order to compensate for the pressure drops. The residual quantities correspond to the mechanical exergy of the liquid entering the evaporators. These are resources for the two evaporators where liquid is completely transformed into vapor. This process involves increases in both the thermal and mechanical components of exergy. A part of the mechanical exergy of the steam is lost in the super-heaters due to friction. These quantities, E_{34} and E_{39}, are provided to the corresponding super-heater by the low-pressure and the high-pressure evaporators. Note, that when an isobaric change of phase of a fluid takes place, not only the thermal component of exergy is involved but also its mechanical component, although fluid pressure does not vary. Since mechanical exergy increases when water evaporates, the evaporators produce mechanical exergy (Tsatsaronis et al. 1990).

TABLE V. DETAILED PRODUCTIVE FLOWS OF THE HRSG.

	Ref	Op	Add 1	Add 2	Add 3	Add 4	Add 5	Free
E24T	10419	10450	10413	10402	10537	10460	10679	10433
E25T	11711	11659	11588	11723	11852	11764	12015	12815
E26T	11372	11430	11422	11347	11504	11421	11659	11142
E27T	1550	1543	1536	1550	1571	1558	1597	1770
E28T	43921	44168	44074	43848	44304	44062	44749	43219
E29T	18774	18518	19024	18703	18949	18836	19157	18377
E24M	71.5	71.5	71.2	71.5	72.3	71.8	73.1	71.5
E25M	177.6	177.6	176.7	177.6	179.4	178.3	181.5	177.6
E26M	31.3	31.3	31.2	31.3	31.7	31.5	32.0	31.3
E27M	94.5	94.5	94.0	94.5	95.5	94.9	96.6	94.5
E28M	179.1	179.1	178.3	179.1	181.0	179.8	183.1	179.1
E29M	137.6	137.6	137.0	137.6	139.0	138.2	140.7	137.6
E30	54.9	55.2	54.9	54.8	55.7	55.2	56.5	55.0
E31	8.9	8.9	8.8	8.9	9.0	8.9	9.2	9.7
E32	7.9	7.9	7.9	7.9	8.0	7.9	8.1	7.9
E33	32.6	32.8	32.7	32.6	33.1	32.8	33.6	31.9
E34	42.6	42.4	42.1	42.6	43.0	42.7	43.6	46.3
E35	427.4	429.8	429.3	426.5	432.4	429.2	438.3	415.9
E36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E37	59.0	59.4	59.3	58.9	59.8	59.3	60.8	57.2
E38	272.4	274.0	274.0	271.6	276.3	273.8	280.9	263.5
E39	53.3	53.4	53.0	53.3	53.0	53.2	52.7	53.7
E40	7875	7903	7876	7863	7966	7908	8075	7889
E41	10089	10048	9987	10098	10212	10135	10353	10976
E42	10402	10458	10452	10379	10525	10447	10668	10101
E43	1392	1386	1380	1393	1411	1399	1434	1580
E44	38564	38765	38678	38503	38915	38694	39324	37763
E45	16810	16534	17028	16748	16969	16867	17157	16443
E46	85132	85095	85401	84982	85999	85449	87011	84752



$$k_{P-T1} = \frac{E_{T1}}{E_P}$$

$$k_{P-M1} = \frac{E_{M1}}{E_P}$$

$$k_{P-M2} = \frac{E_{M2}}{E_P}$$

Figure 8. Detailed productive representation of a heat exchanger.

The flows corresponding to this productive structure are indicated in TABLE V. The thermoeco-nomic model of the components built by using this productive structure is more detailed than that considered in the previous section. In fact, as shown in *Figure 8*, all heat exchangers are characterized by three values of the marginal exergy consumptions. These refer to the use of the thermal and mechanical exergy of the gas (E_{T1} and E_{M1}) and the mechanical exergy of the water (E_{M2}). E_P is the total product of the heat exchanger, which can be supplied to the steam turbine or to other heat exchangers.

With this model the different effects of the three resources on each marginal exergy consumption can be evaluated as follows:

$$\Delta\hat{k}_{P-T1} = \frac{\partial k_{P-T1}}{\partial E_{T1}} \cdot \Delta E_{T1} + \frac{\partial k_{P-T1}}{\partial E_{M1}} \cdot \Delta E_{M1} + \frac{\partial k_{P-T1}}{\partial E_{M2}} \cdot \Delta E_{M2} \tag{20}$$

$$\Delta\hat{k}_{P-M1} = \frac{\partial k_{P-M1}}{\partial E_{T1}} \cdot \Delta E_{T1} + \frac{\partial k_{P-M1}}{\partial E_{M1}} \cdot \Delta E_{M1} + \frac{\partial k_{P-M1}}{\partial E_{M2}} \cdot \Delta E_{M2} \tag{21}$$

$$\Delta\hat{k}_{P-M1} = \frac{\partial k_{P-M2}}{\partial E_{T1}} \cdot \Delta E_{T1} + \frac{\partial k_{P-M2}}{\partial E_{M1}} \cdot \Delta E_{M1} + \frac{\partial k_{P-M2}}{\partial E_{M2}} \cdot \Delta E_{M2} \tag{22}$$

The calculation of the derivatives is made by using the operating conditions Add1-Add5 in a similar way to that explained in the previous section for the other productive structure.

TABLE VI. VARIATION IN UNIT EXERGY CONSUMPTIONS BETWEEN THE OPERATING AND REFERENCE CONDITIONS.

	LPP	HPP	LP ECO	LP EV	HP ECO	LP SH	HP EV	HP SH
Ambient	0.000	0.000	0	0	0	0	0	0
TGA	0	0	-0.046	0.523	0.989	-0.123	0.553	0.098
TV	0	0	0	0	0	0	0	0
LPP	0	0	0.000	-0.032	0.010	0	0	0
HPP	0	0	0	0	-0.001	0	-0.004	0
LP ECO	0	0	0	0	0	0	0	0
LP EV	0	0	0	0	0	-0.128	0	0
HP ECO	0	0	0	0	0	0	0	0
LP SH	0	0	0	0	0	0	0	0
HP EV	0	0	0	0	0	0	0	0.009
HP SH	0	0	0	0	0	0	0	0

6. Results

The diagnosis procedure is now carried out through the analysis of the variation of the unit exergy consumption. The objective consists of locating the anomaly in the high-pressure evaporator of the HRSG.

The first possible analysis, the simplest one, is made by comparing the unit exergy consumptions calculated at the operating and reference conditions. The results are shown in TABLE VI.

In this table, rows represent the components (or macro-components, such as the gas turbine TGA or the steam turbine TV) providing the resources to each HRSG component. Columns correspond to the HRSG components. Thus, each term Δk_{ij} of the table expresses how the efficiency, in the use of the resource provided by the i^{th} plant component to the j^{th} HRSG component, varies, when the system moves from the reference to the operating condition, i.e. when the anomaly occurs.

The largest variation takes place in the high-pressure economizer (element $k_{2,5}$), but important variations also occur in the evaporators (low-pressure evaporator, element $k_{2,4,}$ and high-pressure evaporator, element $k_{2,7}$).

TABLE VII. VARIATION OF UNIT EXERGY CONSUMPTIONS BETWEEN THE FREE AND REFERENCE CONDITIONS

	LPP	HPP	LP ECO	LP EV	HP ECO	LP SH	HP EV	HP SH
Ambient	0.000	0.000	0	0	0	0	0	0
TGA	0	0	-0.045	0.526	0.992	-0.120	0.562	0.101
TV	0	0	0	0	0	0	0	0
LPP	0	0	0.000	-0.032	0.010	0	0	0
HPP	0	0	0	0	-0.001	0	-0.005	0
LP ECO	0	0	0	0	0	0	0	0
LP EV	0	0	0	0	0	-0.127	0	0
HP ECO	0	0	0	0	0	0	0	0
LP SH	0	0	0	0	0	0	0	0
HP EV	0	0	0	0	0	0	0	0.010
HP SH	0	0	0	0	0	0	0	0

A first improvement on the diagnosis can be obtained by comparing the free and reference conditions, i.e. by filtering out the effects of the control system intervention. In this case the effect is very small, since the governing system operates directly on the gas turbine by varying the fuel mass flow and the inlet guide vanes angle. The results are shown in TABLE VII.

TABLE VIII. EFFECTS INDUCED BY THE EFFICIENCY CURVES ON THE UNIT EXERGY CONSUMPTIONS.

	LPP	HPP	LP ECO	LP EV	HP ECO	LP SH	HP EV	HP SH
Ambient	0.000	0.000	0	0	0	0	0	0
TGA	0	0	-0.043	0.236	0.663	-0.325	-0.074	-0.024
TV	0	0	0	0	0	0	0	0
LPP	0	0	0.000	-0.033	0.010	0	0	0
HPP	0	0	0	0	-0.003	0	-0.009	0
LP ECO	0	0	0	0	0	0	0	0
LP EV	0	0	0	0	0	-0.132	0	0
HP ECO	0	0	0	0	0	0	0	0
LP SH	0	0	0	0	0	0	0	0
HP EV	0	0	0	0	0	0	0	0.009
HP SH	0	0	0	0	0	0	0	0

Finally, the last step of the malfunction analysis can be obtained by eliminating the malfunctions induced by the different plant components, i.e. the malfunctions induced due to the dependence of the components' efficiency curves on the operating condition. This evaluation is obtained by subtracting the terms $\Delta\hat{k}_{i,j}$, calculated by means of equation (3), from the corresponding elements in TABLE VII. The elements $\Delta\hat{k}_{i,j}$ corresponding to the choice of the more detailed productive structure are shown in TABLE VIII, while the results of the application procedure are shown in TABLE IX.

The results highlight the high-pressure evaporator as the main component responsible for the malfunctioning behavior of the plant since the principal variation in unit exergy consumption takes place in it. Residual effects are still present due to the presence of non-linearities.

TABLE IX. VARIATION IN UNIT EXERGY CONSUMPTIONS ONCE THE INDUCED EFFECTS HAVE BEEN ELIMINATED.

	LPP	HPP	LP ECO	LP EV	HP ECO	LP SH	HP EV	HP SH
Ambient	0.000	0.000	0	0	0	0	0	0
TGA	0	0	-0.002	0.290	0.330	0.205	0.636	0.125
TV	0	0	0	0	0	0	0	0
LPP	0	0	0.000	0.001	0.000	0	0	0
HPP	0	0	0	0	0.002	0	0.005	0
LP ECO	0	0	0	0	0	0	0	0
LP EV	0	0	0	0	0	0.005	0	0
HP ECO	0	0	0	0	0	0	0	0
LP SH	0	0	0	0	0	0	0	0
HP EV	0	0	0	0	0	0	0	0.000
HP SH	0	0	0	0	0	0	0	0

The use of a different productive structure would have determined a different free condition, different values for the terms $\Delta\hat{k}_{i,j}$, and then for the final results. The diagnosis results obtained by using the base productive structure are shown in TABLE X.

TABLE X. VARIATION IN UNIT EXERGY CONSUMPTIONS ONCE THE INDUCED EFFECTS HAVE BEEN ELIMINATED WITH THE BASE PRODUCTIVE STRUCTURE.

	LPP	HPP	LP ECO	LP EV	HP ECO	LP SH	HP EV	HP SH
Ambient	0.000	0.000	0	0	0	0	0	0
TGA	0	0	-0.045	0.271	0.926	-0.219	0.651	0.124
TV	0	0	0	0	0	0	0	0
LPP	0	0	0.000	0	0	0.000	0	0
HPP	0	0	0	0	0.040	0	0	0.001
LP ECO	0	0	0	0	0	0	0	0
LP EV	0	0	0	0	0	0	0	0
HP ECO	0	0	0	0	0	0	0	0
LP SH	0	0	0	0	0	0	0	0
HP EV	0	0	0	0	0	0	0	0
HP SH	0	0	0	0	0	0	0	0

The main variation in unit exergy consumption occurs in the high-pressure economizer, which is an induced effect. This result shows that the detail of the productive structure can be very important when diagnosing a complex system. A rough productive structure can provide misleading information and, as a consequence, a wrong diagnosis. In the example presented in this paper, the more detailed productive structure, which took into account the different impacts of variations in the mechanical and thermal components of exergy, provided a correct diagnosis of the anomaly occurring in the plant.

7. Conclusions

Thermoeconomic analysis is a systemic energy analysis tool that, based on the data measured in a plant, provides new information related to the costs, the efficiency of energy conversion processes, and the interactions among the different plant devices.

Due to its simplicity, thermoeconomic analysis is able to deal with highly complex systems. In fact, the behavior of devices is described by only a few parameters, the unit exergy consumptions, which are obtained by grouping together physical magnitudes, such as temperatures, pressures, mass flow rates, and so on. Thus, with a relatively small set of variables, the behavior of a very complex energy system and the interactions of its components can be analyzed.

In this paper, attention was focused on the use of Thermoeconomics for the diagnosis of energy systems. Diagnosing an energy system consists of comparing an actual state with a reference one in order to locate the final causes of its deviation. This implies identifying how, where, and how much of additional consumed resources can be saved. However, the physical interactions among components are highly complex and the task of locating and quantifying them is a major task.

It is apparent that such detailed information, due to its complexity, cannot be obtained with a conventional simulator. A conventional exergy analysis comparing the irreversibilities at the component level is also not adequatel. This is because many irreversibilities occurring in a system component are not due to an actual malfunction of that component but to the influence of other components.

Thermoeconomics has two characteristics that make it suitable for diagnosis:

1) It allows one to quantify the effects of each modification at a plant's operating conditions, for instance, in terms of additional fuel consumption with respect to the design condition. This is possible since not only the efficiency of the processes is considered in the analysis but also the other parameters that determine the total impact, such as the position of the components where they take place and the components' production.

2) It makes comparable the effects associated with different physical phenomena, such as variations in pressure and temperature.

Nevertheless, it is necessary to not forget that when the thermoeconomic model is built, physical quantities are substituted with thermoeconomic quantities, such as the unit exergy consumption. The number of unit exergy consumptions, which constitute the thermoeconomic model of each component, depends on the detail adopted in the analysis, i.e. the number of flows considered in the definition of fuels and products. If the detail is too low, some physical information and sensitivity about the processes occurring in components is lost. In contrast, a more detailed productive structure allows one to conserve the information required for a correct diagnosis.

Nomenclature

c_p Specific heat [kJ/kgK];
b Specific exergy [kJ/kg];
E Flow of the productive structure [kW];
F Fuel of a component [kW];
G Mass flow [kg/s];
k_{ij} Unit exergy consumption;
k_{pi}^* Exergetic unit cost of the product of the i^{th} component;
MF Malfunction [kW];
MF* Cost of the malfunction [kW];
p Pressure [bar]
P Product of a component [kW];
R_g Specific gas constant [kJ/kgK];
T Temperature [K];
T_0 Reference temperature [K];
x Operating parameter of the control system;

Greek

$\Delta\hat{k}$ Calculated variation of unit exergy consumption due to variations in component resources;
Δk_f Variation of unit exergy consumption due to variations in component resources;
Δk_{int} Variation of unit exergy consumption due to anomalies in the component;

Subscripts

add Operating condition corresponding to the macro-component without anomalies
free Free condition;
gas Combustion gas flow;
M Mechanical component of exergy;
op Actual operating condition;
ref Reference condition;
T Thermal component of exergy;
w Water flow.

References

Tsatsaronis G., Pisa J. and LIN L. 1990, “The Effect of Assumptions on the Detailed Exergoeconomic Analysis of a Steam Power Plant Design Configuration - Part I: Theoretical Development. Part II: Results and Discussion”, *Proceedings of FLOWERS 90*, Florence, May 28 - June 1, 1990.

Frangopoulos C. A., 1987, “Thermoeconomic Functional Analysis and Optimization”, *Energy - The Int. J.* 7, pp.563-571.

Von Spakovsky, M. R., and Evans R. B., 1990. “The Foundations of Engineering Functional Analysis (Part I and II)”, A Future for Energy, FLOWERS 1990, Stecco and Moran, Florence.

Verda V., Serra L., Valero A., 2002, “Zooming Procedure for the Thermoeconomic Diagnosis of Highly Complex Energy Systems” *International Journal of Applied Thermodynamics*, vol. 5, no. 2, International Center of Applied Thermodynamics, Istanbul, Turkey.

Valero, A., Correas, L., and Serra, L., 1999, “On-Line Thermoeconomic Diagnosis of Thermal Power Plants” NATO ASI on Thermodynamics and Optimization of Complex Energy Systems, Bejan and Mamut ed., Kluwer Academic Publishers, pp. 117-136.

Torres, C., Valero, A., Serra, L., and Royo, J., 1999, “Structural Theory and Thermoeconomic Diagnosis. Part I: On Malfunction and Dysfunction Analysis” *Proceedings of the ECOS’99*, pp. 368-373, ASME, Tokyo, Japan.

Lerch, F., Royo, J. and Serra, L., 1999, “Structural Theory and Thermoeconomic Diagnosis. Part II: Application to an Actual Power Plant” *Proceedings of the ECOS’99* Conference, pp. 374-379, ASME, Tokyo, Japan.

Valero A., Torres, C., and Lerch, F., 1999, “Structural Theory and Thermoeconomic Diagnosis. Part III: Intrinsic and Induced Malfunctions” *Proceedings of the ECOS’99* Conference, pp. 35-41, ASME, Tokyo, Japan.

Verda, V., 2001, *Thermoeconomic Diagnosis of an Urban District Heating based on Cogenerative Steam*. Ph. D. Thesis. Polytechnic of Turin and University of Zaragoza.

Lozano, M.A., Valero, A. (1993). “Theory of the Exergetic Cost”. *Energy, The International Journal*, Vol. 18, no 9, pp. 939-960.

Verda, V., Serra, L., Valero, A. 2001, “The effects of the regulation system on the thermoeconomic diagnosis of a power plant. Part 1: The diagnosis procedure” *ECOS 2001*. Efficiency, Costs, Optimization, Symulation and Environmental Impact of Energy Systems. July 4-6. Istanbul. Turkey.