On Energy Diagnosis of Steam Power Plants: A Comparison among Three Global Losses Formulations

Mauro REINI*, Rodolfo TACCANI
Dept. of Energy - University of Trieste
via Valerio 10 – Trieste-Italy
Tel: +39 040 558 3823, Fax: +39 040 558 3812
E-mail: reini@univ.trieste.it

Abstract

The objectives of energy systems diagnosis are: i) identifying components responsible for highest losses increments in comparison with design conditions, ii) quantifying energy-efficiency recovery when design conditions are restored in a particular system component. In this paper the energy diagnosis of an existing steam power plant is faced on the basis of three different formulae expressing global losses.

A simulation model of a real 320 MW steam power plant has been implemented with a commercial modular energy systems simulation software (Aspen+). The functional decay of different components of the plant has been simulated using the model. The results show that the components actually responsible for the additional power losses can be identified and the effect of restoring design conditions can be quantified in most cases with sufficient approximation by using the General Formula for the Efficiency or the Lost work Impact Formula (developed in the ambit of thermoeconomics).

Key words: exergy losses, efficiency, diagnosis, malfunction, thermoeconomics

1. Objective of the Work and Methodology

In the paper three different global losses formulations are considered: the components Differential Exergy Balance (DEB), the General Formula for the Efficiency (GFE) (Sorin et al. 1992) and the Lost work Impact Formula (LIF) obtained in the ambit of thermoeconomic analysis.

Tests on a simulation model of an existing steam power plant are carried out with the aim of evaluating the diagnostic accuracy of each of them. In particular the objectives of diagnosis are:

i) identifying components responsible for highest losses increments in comparison with design condition;

ii) quantifying energy-efficiency recovery when design conditions are restored in a particular system component.

The latter objective would require a distinction between the variation of performance parameters caused by functional decay and that induced by modification in system boundary conditions, like a variation of ambient temperature T_0, or an intervention of the control system. Simultaneous perturbations of components and T_0 will be considered in a second paper in this journal following this one; for the effect of regulation system on diagnosis (in the ambit of thermoeconomic analysis) see Verda et al. 2001.

The system is a 320 MW steam turbine unit installed in a power plant located in Monfalcone (Italy). The simulation model has been built on the bases of data acquired during the power plant start up test and it has been implemented using a commercial SW (Aspen+), that allows analyzing in particular industrial and chemical processes, using predefined modules.

The thermodynamic condition inferred during the startup test of the plant has been simulated and considered as reference condition for the subsequent analysis.

The model has been used following four steps:

- perturbation of a performance parameter of a particular plant component (e.g. turbine

---

* Author to whom all correspondence should be addressed.

isentropic efficiency, feedwater heater heat transfer coefficient, etc.);

- simulation of the actions necessary to restore the power output to the reference level (e.g. fuel, steam and air flowrates control);

- evaluation of additional losses allotted to each component according to the three formulations;

- comparison between the additional global losses of the plant, $\Delta(W_{lost})_T$, and those allotted to the component affected by intrinsic malfunction only.

To quantify diagnosis errors, an n-dimensional space is considered. The answer given in a single perturbation test from each considered global losses formulation is represented as a vector, starting from the origin, named the "allocation vector" of the test. The components of this vector are the percentages (positive or negative) of additional global losses allotted to each one of the -n- system components.

For each test, the situation corresponding to the maximum diagnostic accuracy is known: it would be reached if 100% of $\Delta(W_{lost})_T$ were allotted to the component actually affected by the intrinsic malfunction, while there were no additional losses related to the not-affected ones. The vector corresponding to this situation is named the "reference vector" of the test.

The diagnosis error is defined as the module of the difference between the allocation vector and the reference vector; it has the dimension of a percentage. The diagnostic accuracy is defined as 100% minus the diagnosis error.

According to these definitions, the reference vector has a diagnosis error equal to 0% and diagnostic accuracy equal to 100%. As an example, if 100% of additional losses were apportioned on the component actually affected by intrinsic malfunction, while 50% on a different component, -50% on a third component and 0% on the others, the diagnosis error would be equal to 71% and diagnostic accuracy would be equal to 29%.

2. Use of Additional Global Losses Formulations

Diagnosis, local optimization and synthesis are methodologies that can be based on exergy losses analysis. An overview of these methodologies let infer that good results can be generally obtained if the chosen global losses

formulation provides an accurate solution of the basic prognosis problem. The main points of this idea are addressed in the following paragraphs.

What does "global losses formulation" mean?

Let us consider the global exergy balance of a system:

$$\sum_{in,out} W = \sum B_{in} - \sum B_{out} - T_0 S_{gen} \qquad (1)$$

$T_0 S_{gen} \equiv (W_{lost})_T$ expresses the lost work, or global losses, according to the Gouy-Stodola theorem. In a steam power plant (as the test case considered in the paper) the exergy losses related with exhaust gases and condenser cooling may be accounted as internal losses of the system. So that, if the control volume is properly defined, $\sum W = P_T$ (total product), $\sum B_{in} = F_T$ (total fuel), $\sum B_{out} = 0$ and then:

$$(W_{lost})_T = F_T - P_T \Rightarrow \eta_T \equiv \frac{P_T}{F_T} = $$
$$= 1 - \frac{(W_{lost})_T}{F_T} \qquad (2)$$

For other kind of plants, as CHP plants, the total product has to be defined in a different way, for instance including some exergy output, anyway equation (2) holds in that case also.

A global losses formula should provide global efficiency η_T or $(W_{lost})_T$ as a function of a set of components independent performance parameters ($\mathbf{x}$):

$$(W_{lost})_T \equiv f_W(\mathbf{x}) \qquad \text{or} \qquad \eta_T \equiv f_\eta(\mathbf{x}) \qquad (3)$$

The bare exergy balance of components may be regarded as a global losses formula, identifying the losses in each component (S_{gen-i}) as its performance parameter:

$$(W_{lost})_T \equiv \sum_i T_0 S_{gen-i} \qquad (4)$$

Which are global losses formula applications?

Four main applications may be identified:

a) Prognosis: system global losses prediction when a component performance parameter (x_i) is modified as a consequence of functional decay or upgrading. On the bases of the global losses formula, a differential relation may be written as:

$$\delta(W_{lost})_T = \frac{\partial f_W(\mathbf{x})}{\partial x_i} \delta x_i,$$
$$x_j = const. \forall j \neq i \qquad (5)$$

b) Diagnosis: allocate additional global losses among components, in such a way that all additional global losses, with respect to a reference condition, each component is responsible for, are allotted to itself. This can be done by differentiating the global losses formula:

$$\delta\left(W_{lost}\right)_T = \sum_i \frac{\partial f_W(\mathbf{x})}{\partial x_i} \delta x_i \equiv \sum_i \delta\left(W_{lost}\right)_i \quad (6)$$

and obtaining that each component is responsible for additional losses equal to $\delta\left(W_{lost}\right)_i$.

c) Local optimization: optimize a plant component with the objective of maximum total efficiency or minimum total cost (see for instance El Sayed, 1996). Seeking simplicity, let's consider the total product - P_T - as a fixed parameter, thus, taking eq. 2 into account, the term $c_F.P_T$ can be omitted in the total cost objective function and the problem can be expressed as:

$$\begin{aligned} \min. f : &\left\{ c_F \left(W_{lost}\right)_T + Z_T \right\} = \\ &= \left\{ c_F f_W(\mathbf{x}) + Z_T(\mathbf{x}) \right\} \\ \mathrm{s.t.}: &\ \mathbf{G}(\mathbf{x,y}) = 0; \quad \mathbf{H}(\mathbf{x,y}) \geq 0; \\ &\ P_T = const; \quad x_j = const., \quad j = 1,...,n_f \end{aligned} \quad (7)$$

where $\{x_j\}$ $j = 1...n_f$ are the performance parameters not involved in the optimization, $\{x_i\}$ $i = n_{f+1}...n$ are the local parameters to be optimized, $\mathbf{G}(\mathbf{x, y})=0$ and $\mathbf{H}(\mathbf{x, y}) \geq 0$ are generic equality and inequality constraints respectively;

d) Synthesis: optimize components size and layout in an energy system.

Different heuristic or Artificial Intelligence-based strategies were proposed in literature for energy systems synthesis (Linnhoff, 1989, Sciubba, 1995, Frangoloulos et al. 2002) that, in principle, may not be based on a global losses formula. Nevertheless, the synthesis problem may be regarded as a generalization of case c), introducing in the Objective Function (O. F.) a set of binary variables expressing the presence or absence of each component inside a "super-system" obtained combining all the layout alternatives of interest (Bruno et al. 1998).

Each of these four problems can be considered as successive extension of the previous case. In fact, this is true for case d), that is an extention of case c). But when the local optimization problem is solved by applying analytic methods, O. F. differentiation is required (von Spakovsky and Evans 1990, Reini and Lozano, 1994), leading to a relation containing Eq. (6) in case b) (Lozano et al. 1994, Reini, 1996). If only one component is modified, Eq. (6) can be simplified into Eq. (5) in case a) (prognosis). Thus, a necessary condition to

obtaining good results when dealing with diagnosis, local optimization or synthesis is that the chosen global losses formulation provides a good diagnostic accuracy in the basic problem of a single component perturbation (prognosis).

3. Three Formulations of Additional Global Losses

Differential Exergy Balance

The first formulation is directly obtained from the bare exergy balance of components, identifying the losses in each component (S_{gen-i}) as its performance parameter; Differential Exergy Balance (DEB), is simply the incremental relation obtained from Eq. (4):

$$\Delta\left(W_{lost}\right)_T \equiv \sum_i \Delta(T_0 S_{gen-i}) \quad (8)$$

where T_0 represents any temperature expressing the external bond of the system (Alefeld, 1990, Bejan, 1982).

General Formula for the Efficiency

The second is obtained from the General Formula for the Efficiency (GFE), proposed by Sorin-Le Goff-Brodyanskii, in 1992:

$$\begin{aligned} &\eta_T = \sum_i \lambda_i \eta_i + 1 - \sum_i \lambda_i \Rightarrow \Delta\eta_T = \sum_i \Delta x_i \\ &\lambda_i \equiv F_i / F_T, \ x_i \equiv \lambda_i(\eta_i - 1) = P_i / F_T - F_i / F_T \end{aligned} \quad (9)$$

where x_i has to be regarded as the performance parameter of component i.

Lost work Impact Formula

The third formulation is obtained differentiating the Gouy-Stodola theorem (Eq. 2) in matrix form and inferring the Lost work Impact Formula (LIF).

Some introductory definitions and remarks have to be introduced to obtain this formulation.

The idea is to develop in this case also, a differential exergy analysis, not on the basis of the bare input-output balance of the components, but introducing a new network of flows, defining the interaction among components and with the environment. These flows are defined on the basis of the heat and work interactions, of the thermodynamic state and of the mass flowrates of working fluids inside the plant, all of them measured in terms of exergy.

The new network is named the productive structure of the plant and does not necessarily contain the physical flows inside the plant, but the concepts of "fuel" and "product" (Valero et al. 1986, Tsatsaronis et al. 1990) have mainly to be followed in the flows definition. The nodes of the productive structure are:

- The considered control volumes, including physical devices or group of them, named as "component units". Each component unit has one and only one product.

- Junctions and branches of flows. They may appear also in the physical plant or being *fictitious* elements (see Frangopoulos, 1987) introduced to isolate flows defined in the productive structure.

Once the productive structure is defined, the first step in the definition of the LIF consists in manipulating the reference thermodynamic model of the plant in order to make the relations among the product obtained and the fuels consumed appear explicitly, for each component unit.

The desired rearrangement is straightforward, taking advantage from the uniqueness of the product for each component unit, by defining the unit exergy consumptions, κ_{ij} (the issue of multi-product components is discussed in Reini and Giadrossi, 1994):

$$\kappa_{ij}(\tau,\omega) \equiv \frac{E_{ij}(\tau,\omega)}{P_j(\tau,\omega)} \qquad (10)$$

where P_j is all the product of *j*-th component and each flow E_{ij} represents the production portion of the *i*-th component that fuels the *j*-th component: they both are new dependent variables introduced in the productive structure definition, while vectors τ and ω contain the actual independent variables of the reference thermodynamic model (for more details, see Reini et al. 1995; Valero et al. 2002). In particular vectors ω (n×1) contain the final products of the plant; in this paper the symbol ω is used instead of P_S (as in other works in literature) to stress the fact that these products are regarded to be independent variables of the reference thermodynamic model.

Starting from these definitions, the thermodynamic model can be rearranged into equations of the type:

$$P_i = \omega_i + \sum_{j=1}^{n} \kappa_{ij} P_j; \quad \kappa_{ij} = \kappa_{ij}(\tau,\omega) \quad i = 1,...,n \qquad (11)$$

or, in matrix notation:

$$\mathbf{P} = \omega + \langle \mathbf{KP} \rangle \mathbf{P} \qquad (12)$$

The above expression represents the characteristic equation of the thermoeconomic model (Valero et al. 1992), where $\langle \mathbf{KP} \rangle$ is a (n×n) matrix, whose elements are the unit exergy consumption κ_{ij}; then, in this formulation, the performance parameters of a component are all the κ_{ij} related to its product $\mathbf{P}_j$.

From equation (2):

$$d(W_{lost})_T = d(F_T - P_T) = d\left({}^t\kappa_e \mathbf{P} - {}^t\mathbf{u}\,\omega \right) \qquad (13)$$

where ${}^t\kappa_e \equiv (\kappa_{01},...,\kappa_{0n})$ is a (1×n) vector whose elements contain the unit consumption of the system-input resources. By isolating vector P from the Eq. (12) and by combining the previous equations, the differential of $d(W_{lost})_T$ becomes:

$$d(W_{lost})_T = d^t\kappa_e \mathbf{P} + {}^t\mathbf{k}_P^* d\langle \mathbf{KP} \rangle \mathbf{P} + {}^t\left(\mathbf{k}_P^* - \mathbf{u} \right) d\omega$$
$$\mathbf{k}_P^* = {}^t\left(\mathbf{U}_D - \langle \mathbf{KP} \rangle \right)^{-1} \kappa_e \qquad (14)$$

where $\mathbf{U}_D$ and u are the unit matrix and vector respectively, while vector $\mathbf{k}_P^*$ (n×1) contains the unit exergetic (or structural) costs of the products considered in equation (12).

Expressing Eq. (14) in scalar form, a summation is obtained, where each term is related to a single unit consumption κ_{ij} or κ_e, or to one of the final products of the plant. The terms containing the unit consumptions associated to the same component can be grouped together, giving the *impact term* of that component. In this way it is possible to allot additional losses to all the components affected by a perturbation in theirs performance parameters, because of functional decay, different ambient condition or other causes.

In the following, Eq. (14) and its integral formulation for $\Delta(W_{lost})_T$ will be defined as the Lost work Impact Formula (LIF), by analogy to the "Fuel Impact" relation (Lozano et al. 1994; Reini et al. 1995).

If the perturbation from the reference condition is not "small" the differential formulation should be replaced with an integral one; Torres et al. (1999) has demonstrated that the last one is formally equal to Eq. (14), but it is necessary to use the exergetic costs $\mathbf{k}_P^*$ in the perturbed condition. Using index "1" for the perturbed condition, "0" for the reference one:

$$\Delta(W_{lost})_{T01} = \Delta^t\kappa_e \mathbf{P}_0 + {}^t\mathbf{k}_{P1}^* \Delta\langle \mathbf{KP} \rangle \; \mathbf{P}_0 +$$
$$+ (k_{PT1}^* - 1)\Delta P_T \qquad (14)$$

4. The Power Plant and the Model

The model is made up of 72 Aspen+ modules, connected with more than 100 streams. The tests on the model have been carried out grouping the modules in a limited numbers of components, as shown in *Figure 1*; note that the combustion chamber control volume includes also the losses related to the ancillary steam flows and to the stack.

The exergy flows in the adopted characteristic equation (Eq. 11) are represented in Reini, Taccani (2002) as a productive structure.
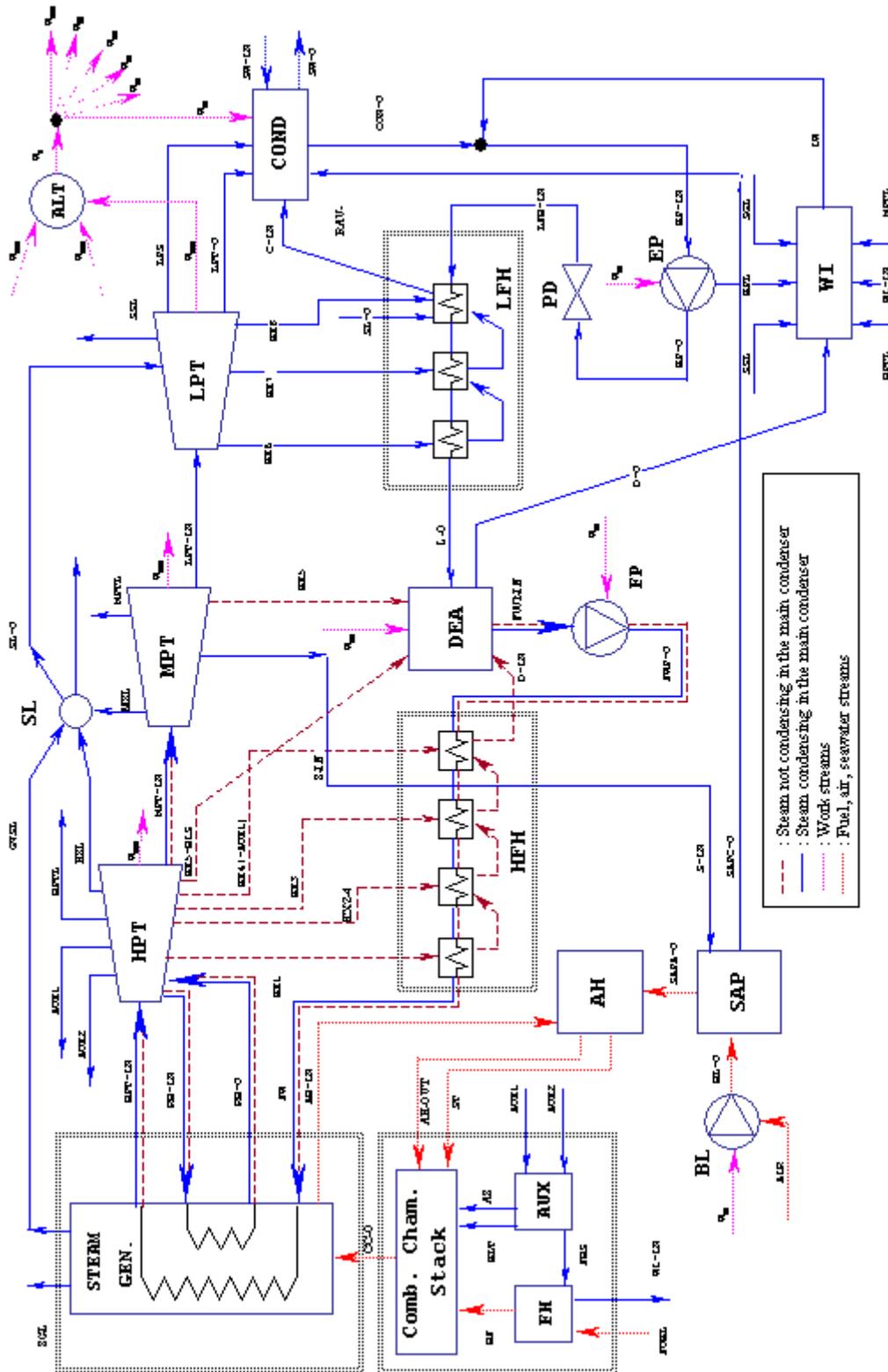

Figure 1. Control volumes of the plant.

In the simulation of perturbed conditions, the extracted steam flowrates are assumed to vary proportionally to the main steam flowrate: this assumption is consistent (for limited perturbations) with available historical data. The plant is operated in order to maintain the reheated and superheated steam thermodynamic conditions at a constant value and to maintain the net power output at the reference value. The cooling water flowrate in the condenser has been considered constant, even in cases of relevant water temperature variation.

TABLE I.: STREAMS PROPERTIES IN THE REFERENCE CONDITION

Net electrical power output	331500	kW
Steam flowrate	1052	ton/h
Cooling water temperature (T_0)	12.9	°C
Cooling water flowrate	44550	ton/h
Reheated steam temperature	540	°C
Reheated steam pressure	34	bar
Superheated steam temperature	536	°C
Superheated steam pressure	169	bar

5. Perturbations and Results

Whatever the global losses formulation, to obtain a diagnostic accuracy equal to 100% is not a realistic expectation, for the reasons introduced in the following points:

- Although a single independent variable τ is conceptually related to a component, it can affect at the same time the unit exergy consumption (κ_{ij}) of other components in the characteristic equation. The result is that components that have not been actually perturbed may show a non-zero impact term; this effect is named *induced malfunctions* (Torres et al. 1999; Valero et al. 2002).

- In order to restore the reference power output, it is necessary to correct the operation parameters of different components, agreeing with the control system of the plant: this action also can cause *induced malfunctions* in the same components (particularly evident in the steam generator, Verda et al. 2001).

- It has not been always possible to match accurately the reference power output with the plant affected by functional decay of some components. This approximation may introduce a small difference in the losses that cannot be distributed among the components. Nevertheless this difference (ΔP_T rows in TABLE II) is negligible with respect to the total amount of additional global losses, so that it does not affect the comparison that is the aim of the work.

The results obtained for some of the considered perturbations are shown in TABLES IIa, IIb, IIc and analyzed in the following. For each perturbation additional global losses apportioned on each component agreeing with DEB and LIF formulations are presented first, jointly with the corresponding percent rate. Then the percent rate of global efficiency decrease agreeing with Eq. (9) is presented in column GFE.

High and Low Pressure Turbines (HPT, LPT)

In both cases a 2% loss in the isentropic efficiency has been simulated (high pressure turbine: from 90% to 88%, low pressure turbine: from 67% to 65%).

The diagnosis performed with LIF obtains the best accuracy. In fact it associates a part of the additional global losses equal to 93.1% (HPT) and 104.6% (LPT) to the turbine actually affected by intrinsic malfunction, while the losses related to the non-affected components are one or two orders of lower magnitude. Following the definition previously introduced, the diagnostic errors are 18.4% and 10.9% for the high and low pressure turbine decay, respectively. The diagnosis based on GFE shows similar errors (25%, 11.7%). But only 40% of the additional losses are inside the turbines control volume, as DEB shows.

It should be noted that the LIF data column contains also the nodes where two or more exergy flows merge in a single homogeneous product (junction); the exergy balances of these nodes (not to be confused with the "mixing" modules) do not show exergy losses. But if a perturbation causes a different load distribution among the components that produce the merging flows, the junction output may be obtained with a different efficiency if compared to the reference state. For example, if a component with a lower efficiency undergoes a load increase, the LIF allocates the global losses increase on the junction. This is exactly the case of the shaft power junction (J27) when the HPT is perturbed.

If the shaft power junction impact term were reallocated on the actually perturbed turbine, the LIF diagnosis error would be lower: 14.5% and 6.2% for the high and low pressure turbines respectively.

Condenser

It has been considered a 12% reduction in the global heat transfer coefficient (due to fouling), that implies a condensation pressure increase from 0.038 to 0.041 bar.

TABLE IIA. ADDITIONAL LOSSES (AND CORRESPONDING PERCENTAGE) CHARGED ON THE MAIN COMPONENT OF THE STEAM POWER PLANT, FOLLOWING THE THREE GLOBAL LOSSES FORMULATIONS, WHEN A SINGLE PERFORMANCE PARAMETER IS AFFECTED BY FUNCTIONAL DECAY. RESULTS FOR THE DIRECTLY RELATED COMPONENTS ARE IN BOLD CHARACTER. FOR THE GFE, ONLY THE PERCENTAGES OF ADDITIONAL LOSSES ARE CALCULATED. MINOR COMPONENTS ARE 1-WATER INTEGRATION, 2-EXTRACTION PUMP AND 3-PRESSURE DROP.

Component affected by intrinsic malfunctions		High Pressure Turbine					Low Pressure Turbine					Condenser				
		DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]
123	**minor components**	1	0	0.0	0.0	0.0	3	0	0.0	0.0	0.0	0	-6	0.0	-0.2	-0.1
4	**Low pressure FH**	28	42	3.2	2.7	3.2	28	12	0.8	0.4	0.1	-38	-135	-1.2	-4.3	-4.4
5	**Deareator**	10	11	0.8	0.8	1.4	3	-8	0.0	-0.2	-0.2	38	72	1.2	2.3	2.4
6	**Feed Pump**	2	0	0.2	0.0	0.1	4	0	0.1	0.0	0.0	3	0	0.1	0.0	0.0
7	**High pressure FH**	52	72	3.9	5.5	7.3	80	116	2.4	3.5	3.7	34	29	1.1	0.9	0.9
8	**Steam Generator**	197	-166	14.9	-12.6	-18.4	747	-52	22.2	-1.6	-3.4	647	-18	20.9	-0.6	-3.2
9	**High Pressure T**	**535**	**1230**	**40.5**	**93.1**	**88.8**	74	-2	2.2	-0.0	-0.3	63	-2	2.0	-0.0	-0.3
10	**Middle Pressure T**	4	-4	0.3	-0.3	0.2	6	-2	0.2	-0.0	0.0	5	-2	0.2	-0.0	0.0
11	**Steam Leakage**	0	-1	0.0	-0.0	-0.1	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1
12	**Low Pressure T**	88	-36	6.7	-2.7	5.8	**1473**	**3517**	**43.8**	**104.6**	**91.6**	**-591**	**-860**	**-19.1**	**-27.8**	**-53.9**
13	**Condenser**	60	-4	4.5	-0.3	3.9	160	-23	4.8	-0.7	4.2	**2114**	**4131**	**68.3**	**133.5**	**152.3**
14	**Blower**	1	0	0.0	0.0	0.0	3	0	0.0	0.0	0.0	3	0	0.1	0.0	0.0
15	**Steam Air Preheat.**	8	-3	0.6	-0.2	0.6	13	1	0.4	0.0	0.0	11	1	0.4	0.0	0.0
16	**Air PreHeater**	31	14	2.3	1.1	2.3	69	25	2.1	0.7	1.5	75	40	2.4	1.3	2.5
17	**Comb. Chamber**	290	58	22.0	4.4	6.4	734	75	21.8	2.3	4.4	657	93	21.2	3.0	5.8
18	**Alternator**	0	0	0.0	0.0	-1.5	1	0	0.0	0.0	-1.5	0	0	0.0	0.0	-1.5
J27	**Shaft Power Junc.**	0	108	0.0	8.2	0.0	0	-296	0.0	-8.8	0.0	0	-248	0.0	-8.0	0.0
	Components	1308	1321	99.0	100.0	100.0	3397	3362	101.0	100.0	100.0	3020	3094	97.6	100.0	100.0
	ΔP_T	13	0	1.0	0.0	0.0	-35		-1.0	0.0	0.0	73	0	2.4	0.0	0.0
	Add. Losses	1321	1321	100.0	100.0	100.0	3362	3362	100.0	100.0	100.0	3093	3094	100.0	100.0	100.0

Pressure drop increase in the cooling water circuit has not been taken into account. The functional decay in the condenser affects directly the discharge condition of the LPT, so that this malfunction has to be regarded as affecting both components.

Summing up the terms related to the condenser and the low pressure turbine, it follows that the diagnosis errors are 11.5% and 9% on the bases of LIF and GFE, respectively. On the other hand DEB shows that only half of the additional global losses are physically inside the control volumes of the two components directly related to the functional decay. If the shaft power junction impact term were reallocated on the turbine (as it is suggested in the previous point), the LIF diagnosis error would be 6.4%.

Feed Pump (FP)

Two different malfunctions have been considered: a 3% loss in the isentropic efficiency (88% to 85%) and a 3.3% loss in the mechanical efficiency (97% to 93.7%). In the latter case, the diagnoses based on LIF and GFE show modest errors (5.8% and 9.4), while only about 40% of the additional global losses is physically inside the pump control volume. On the contrary, in the former case, the errors are not so little (24% and 33% for LIF and GFE, respectively); this suggests that a re-examination of the characteristic equation may lead to a diagnosis improvement.

Taking into account that only 30% of the additional global losses is physically inside the pump control volume, the LIF diagnostic accuracy (76%) may be considered good enough.

Blower

The mechanical efficiency has been lowered from 90% to 87%. In this case too the additional losses in the considered control volume are approximately 50% of the total, while both LIF and GFE results show similar errors (13.1% and 18.5%, respectively).

TABLE IIB. ADDITIONAL LOSSES AS IN TABLE IIA RELATED TO THE FUNCTIONAL DECAY OF OTHER COMPONENTS

Component affected by intrinsic malfunctions		Feed Pump (η-is)					Feed Pump (η-m)					Blower				
		DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]
123	minor components	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
4	Low pressure FH	12	14	2.0	2.3	2.7	6	3	0.9	0.4	0.3	2	1	0.9	0.5	0.6
5	Deareator	42	78	7.0	12.9	15.6	2	1	0.3	0.1	0.3	2	3	0.9	1.4	1.6
6	Feed Pump	**188**	**487**	**31.1**	**80.6**	**72.1**	**279**	**647**	**41.2**	**95.6**	**95.5**	0	0	0.0	0.0	0.0
7	High pressure FH	16	24	2.6	4.0	4.5	8	7	1.2	1.0	1.0	-4	-11	-1.8	-5.0	-5.5
8	Steam Generator	135	-12	22.4	-2.0	-2.3	148	-8	21.9	-1.1	-4.2	37	-19	16.7	-8.5	-14.2
9	High Pressure T	15	0	2.5	0.0	0.3	15	-1	2.2	-0.1	-0.3	5	0	2.3	0.0	0.4
10	Middle Pressure T	1	0	0.2	0.0	0.1	1	-1	0.1	-0.1	0.0	0	0	0.0	0.0	0.0
11	Steam Leakage	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1
12	Low Pressure T	28	0	4.6	0.0	0.6	28	-1	4.1	-0.1	-0.5	10	0	4.5	0.0	0.8
13	Condenser	13	-11	2.2	-1.8	-1.7	18	-3	2.7	-0.4	-0.7	6	-2	2.7	-0.9	-0.2
14	Blower	1	0	0.2	0.0	0.0	1	0	0.1	0.0	0.0	**102**	**238**	**46.2**	**107.7**	**107.8**
15	Steam Air Preheat.	2	0	0.3	0.0	0.0	3	0	0.4	0.0	0.0	1	0	0.5	0.0	0.0
16	Air PreHeater	15	8	2.5	1.3	2.5	17	9	2.5	1.3	2.4	5	3	2.3	1.4	2.2
17	Comb. Chamber	134	17	22.2	2.8	5.5	154	21	22.7	3.1	6.5	49	7	22.2	3.2	6.4
18	Alternator	4	0	0.7	0.0	0.1	4	0	0.6	0.0	-0.1	2	1	0.9	0.5	0.1
J27	Shaft Power Junc.	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0
	Components	607	604	100.5	100.0	100.0	684	677	101.0	100.0	100.0	219	221	99.1	100.0	100.0
	ΔP_T	-2	0	-0.3	0.0	0.0	-7	0	-1.0	0.0	0.0	1	0	0.5	0.0	0.0
	Add. Losses	**605**	**604**	**100.2**	**100.0**	**100.0**	**677**	**677**	**100.0**	**100.0**	**100.0**	**220**	**221**	**99.5**	**100.0**	**100.0**

TABLE IIC. ADDITIONAL LOSSES AS IN TABLE IIA RELATED TO THE FUNCTIONAL DECAY OF OTHER COMPONENTS

Component affected by intrinsic malfunctions		Steam Generator					HFH n.3					HFH n.1				
		DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]	DEB [kW]	LIF [kW]	DEB [%]	LIF [%]	GFE [%]
123	minor components	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1
4	Low pressure FH	0	-1	0.0	-0.2	-2.0	0	2	0.0	1.2	-1.4	-11	-21	-2.0	-3.9	-6.5
5	Deareator	-3	-5	-0.6	-1.1	-1.7	1	1	0.6	0.6	0.7	86	169	16.0	31.5	36.9
6	Feed Pump	0	0	0.0	0.0	-0.3	0	0	0.0	0.0	-0.3	0	0	0.0	0.0	-0.3
7	High pressure FH	14	29	3.0	6.1	5.1	**82**	**173**	**50.0**	**105.5**	**113.8**	192	422	35.8	78.6	81.3
8	Steam Generator	**370**	**464**	**78.4**	**98.4**	**128.4**	38	-21	23.2	-12.8	0.8	127	-68	23.6	-12.7	0.5
9	High Pressure T	0	0	0.0	0.0	-5.3	0	0	0.0	0.0	-5.2	0	0	0.0	0.0	-5.4
10	Middle Pressure T	0	0	0.0	0.0	-0.4	0	0	0.0	0.0	-0.4	0	0	0.0	0.0	-0.4
11	Steam Leakage	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1	0	0	0.0	0.0	-0.1
12	Low Pressure T	0	0	0.0	0.0	-9.9	0	0	0.0	0.0	-9.8	0	-1	0.0	-0.2	-9.8
13	Condenser	1	1	0.2	0.2	-6.3	2	3	1.2	1.8	-4.0	7	12	1.3	2.2	-3.6
14	Blower	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	1	0	0.2	0.0	0.0
15	Steam Air Preheat.	0	3	0.0	0.6	-0.7	0	1	0.0	0.6	-0.7	0	3	0.0	0.6	-0.7
16	Air PreHeater	155	-22	32.8	-4.7	73.3	1	4	0.6	2.4	-2.0	6	11	1.1	2.0	-0.8
17	Comb. Chamber	-68	3	-14.4	0.6	-78.5	39	2	23.8	1.2	10.3	130	10	24.2	1.9	10.6

18	Alternator	0	0	0.0	0.0	-1.6	0	0	0.0	0.0	-1.6	0	0	0.0	0.0	-1.6
J27	Shaft Power Junc.	0	0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	0	1	0.0	0.2	0.0
	Components	470	472	99.6	100.0	100.0	162	164	98.8	100.0	100.0	539	537	100.4	100.0	100.0
	ΔP_T	1	0	0.2	0.0	0.0	2	0	1.2	0.0	0.0	-2	0	-0.4	0.0	0.0
	Add. Losses	471	472	99.8	100.0	100.0	164	164	100.0	100.0	100.0	537	537	100.0	100.0	100.0

Steam generator

An average reduction of 4% in the global heat transfer coefficient has been simulated in the high temperature heat exchangers of the steam generator. Taking into account the hypotheses about the unit off-design operation, briefly summarized in section 4, it follows that this malfunction affects in practice the steam generator only, having modest effects on the steam cycle thermodynamic states. A consistent result is obtained through DEB, showing that 78% of additional global losses are inside steam generator control volume (the diagnosis error is equal to 47%). LIF results show a little diagnosis error (8%); on the contrary, GFE results apportion the steam generator with 128% of the additional global and various components with negative contributions, so that the diagnosis error is greater than 100%.

High pressure Feedwater Heaters (HFH)

The HFH control volume contains four high pressure feedwater heaters; two of them have been perturbed independently: the first one (i.e. the one directly connected to the deareator) and the third one. In both cases, a 5% decrease in the global heat transfer coefficient has been considered.

The first case presents an important induced malfunction affecting the deareator (16% of additional global losses), so that the diagnosis error on the bases of LIF is not small (40%) and the matter is about the same on the bases of GFE (45%). In the second case errors are significantly lower (21% for the GFE), in particular if the LIF is considered (14%). In both cases, less than 50% of additional global losses are inside the HFH control volume, as is shown by DEB.

Steam Air Preheater (SAP)

It has been considered a 13% reduction in the global heat transfer coefficient, while the preheated air temperature has been kept constant by increasing the mass flowrate of the steam extracted from the turbine as a fuel of the SAP.

DEB shows that additional losses arise in various control volumes. Also LIF and GFE results do not show a single main contribution to the additional global losses so that, on the opposite of the previous cases, the component affected by intrinsic malfunction cannot be identified. Numerical results for this kind of functional decay are reported in Reini, Taccani (2002), where a modification of the productive structure is considered to improve the diagnostic accuracy.

6. Discussion

TABLE II shows how numeric results provided by GFE are not generally far from those obtained with LIF. This is not true when using DEB. The opposite situation only happens when the steam generator is perturbed. This can be explained if a linear chain is considered, where each component yields a single product that is completely used as a fuel by the subsequent component.

Let us consider the component exergetic efficiecies to be independent of one another and the total product (i.e. the last component product) kept constant. In this ideal system let us first perturb the last component only (named component - n -); in this case $P_i = P_n = P_T$ and from equation (9):

$$x_n = \frac{P_T}{F_T} - \frac{F_n}{F_T} \Rightarrow$$

$$\Delta x_n = \frac{P_T^1}{F_T^1} - \frac{P_{(n-1)}^1}{F_T^1} - \left(\frac{P_T^0}{F_T^0} - \frac{P_{(n-1)}^0}{F_T^0} \right) \quad (15)$$

Because the total efficiency of the linear chain, made of the first n-1 components (i.e. made of all components but the last one), is not modified by hypothesis:

$$\frac{P_{(n-1)}^1}{F_T^1} = \frac{P_{(n-1)}^0}{F_T^0} \Rightarrow \Delta x_n = \frac{P_T^1}{F_T^1} - \frac{P_T^0}{F_T^0} \equiv \Delta \eta_T \quad (16)$$

In this case the diagnostic accuracy would be 100% with GFE, while it would be lower with DEB, because of non-equivalence of losses (see for instance, Valero et al. 1992). If we perturb the first component only, the DEB diagnostic accuracy is 100%, as can be easily inferred from Eq. (8), while Eq.(16) does not hold anymore and we have simply:

$$\Delta x_i = \Delta x_1 = \Delta \eta_1 \neq \Delta \eta_T = \Delta \eta_1 \eta_2 \quad (17)$$

From Eq. (17) it can be inferred that, following the GFE, also components not affected by any intrinsic malfunction are wrongly regarded as responsible for the global efficiency variation.

The steam generator can be regarded as the first component of the production chain so that the good result with DEB and the lower accuracy with GFE may be justified. On the contrary, the turbines and the feedwater heaters may be regarded to some extent as components consuming in parallel exergy mainly produced in the steam generator, that is to say as the "last" components of the production chain, justifying the GFE results.

In both the considered perturbations of an ideal linear chain, LIF would obtain a 100% diagnostic accuracy. On the other hand the LIF application is more complex if compared to the other global losses formulations. In fact LIF contains information about energy interactions among components, as the characteristic equation does, while DEB and GFE are based only on internal losses and on each component efficiency, respectively and they do not consider the component position in the productive structure.

7. Conclusions

In the paper a simulation model of an existing steam power plant has been developed through Aspen+ and used in a set of simulation tests; in each of these a single component has been perturbed with the aim of evaluating the diagnostic accuracy of three different global losses formulations.

The results obtained show that the components actually responsible for the additional power losses can be identified and the effect of their functional decay can be quantified in most cases with sufficient approximation on the bases of the Lost work Impact Formula. The components Differential Exergy Balance provides a detailed measure of additional power losses that may be a useful help in energy systems diagnosis. But the numerical results obtained in this way are far to quantify with sufficient approximation the energy-efficiency recovery, when design conditions were restored in a particular system component.

On the contrary, for the plant considered, numerical results obtained on the bases of the general formula for the efficiency are in most cases not so far from the ones provided by the Lost work Impact Formula. Moreover the former only needs the fuel and the efficiency of each component to be calculated, while the latter needs a bigger effort to define the complete characteristic equation of the system.

On the other hand, through the Lost work Impact Formula further improvements can be achieved, in fact it may be manipulated by the analyst (Reini and Giadrossi 1996) to reduce errors: two examples are reported in a second paper in this journal following this one.

Nomenclature

Variables

B	Exergy
b	Specific exergy
c	Unit cost
DEB	Differential Exergy Balance
E	Generic flow in the productive structure
f	Generic function
F	Fuel Exergy
G=0	Generic equality and inequality constraints
GFE	General Formula for the Efficiency
H=0	Generic equality and inequality constraints
k_P^*	Unit cost of product
LIF	Lost work Impact Formula
m	Number of flows
n	Number of component units
P	Product exergy of a component
S_{gen}	Entropy generated because of irreversibility
T	Temperature
T_0	Ambient Temperature
W	Work
W_{lost}	Lost work
x	Generic perfomance parameter
y	Generic variable
Z	Capital cost function

Plant components

AH	Air heater
ALT	Alternator
AUX	Auxiliaries
BL	Blower
Com. Cham.	Combustion chamber and stack
COND	Condenser
DEA	Deareator control volume
EP	Extraction pump
FH	Fuel heater
FP	Feed water pump
HFH	High pressure feed water heater
HPT	High and medium pressure turbine
LFH	Low pressure feed water heater
LPT	Low pressure turbine
MPT	Medium and low pressure turbine
PD	Pressure drop
SAP	Air-steam heater
SL	Steam leagakes collector
St. Gen.	Steam generator
WI	Water integration system

Matrix and Vector

(**KP**)	Matrix (n×n) of unit exergy consumption
P	Product vector
u	Unit vector
U$_D$	Unit matrix
x	Perfomance parameter vector
ω	external products vector

Subscripts and Superscripts

0	Reference conditions
D	Diagonal matrix
e	Inlet
F	Fuel
h,i,j	Generic indices
P	Product
T	Total
t	Transposed
W	Work
η	Efficiency

Greek

τ	Independent variable
ω	External products
κ	Unit exergy consumption
η	Efficiency
λ	GFE coefficient eq. (9)

Streams in *Figure 1*

AH-O	Air heater outlet
AH-IN	Air heater inlet
AIR	Ambient air
AS	Fuel atomization steam
AUX1	Auxiliary steam
AUX2	Auxiliary steam
BL-O	Blower outlet
CC-O	Combustion outlet
C-IN	Condenser inlet
CON-O	Condenser outlet
D-IN	DEA inlet
D-O	Deareator outlet
ELT	Steam to gas cleaning unit
EP-0	Extraction pump outlet
EP-IN	Extraction pump inlet
EPL	Extraction pump losses
EX1	Extraction steam
EX2-4	Extraction steam
EX5-BIS	Integration to extraction steam n. 5
FHS	Fuel heating steam
FUEL	Fuel
FW	Feedwater
FWP-IN	Feedwater pump inlet
FWP-O	Feedwater pump outlet
GVSL	Governor valves steam leakages
HF	Heated fuel
HSL	High pressure steam leakages
HPT-IN	High pressure turbine steam inlet
HPTL	High pressure turbine losses
IW	Integration water
LFH-IN	Low pressure heater inlet

L-O	LFH outlet
LPS	Low pressure seals steam
LPT-IN	Low pressure turbine inlet
LPT-O	Low pressure steam outlet
MPT-IN	Medium pressure inlet
MPTL	Medium pressure turbine losses
MSL	Medium pressure steam leakages
RH-IN	Reheater steam inlet
RH-O	Reheater steam outlet
SAPA-O	Steam-air preheater outlet (air)
SAPC-O	Steam-air preheater outlet (conden.)
SGL	Boiler losses
S-IN	SAP inlet
SL-O	Steam leakages collector outlet
SS	Steam seals
SSL	Seals steam leakages
ST	Flue gas to stack
SW-IN	Seawater inlet
SW-O	Seawater outlet
WI-IN	Integration water inlet
W_{BL}	Blower power consumption
W_{CP}	Condenser pump power consumption
W_E	Total electrical power output
W_{EP}	Extraction pump power consumption
W_{FP}	Feedwater pump power consumption
W_{HPT}	Med. and high pres. turb. p. output
W_{LPT}	Low pressure turbine power output
W_{MPT}	Medium pres. turbine power output
W_{NET}	Net electrical power output
W_{RP}	Recirculation pump power consump.

References

Alefeld, G., 1990, "What are Thermodynamic Losses and How to Measure Them?", *Proceedings of FLOWERS 1990*, Florence, May 28 - June 1 1990.

Bejan, A., 1982, *Entropy Generation through Heat and Fluid Flow*, Wiley, New York.

Bruno, J. C., Fernandez F., Castells F. and Grossmann I. E., 1998, "A Rigorous MINLP for the Optimal Synthesis and Operation of Utility Plant", *Inst. of Chem. Eng*, Vol. 76, Part. A March 98.

El Sayed Y. M., 1996, "A Second-Low Based Optimization: Part 1 – Methodology", *J. of Eng. for Gas Turbine and Power*, 118, 693-697.

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

Frangopoulos C. A., Spakovsky von M. R., Sciubba E., 2002, "A Brief review of Methods for the Design and Synthesis Optimization of

Energy Systems" Proceedings of ECOS 2002, Berlin, July 2002.

Linnhoff B., 1989, "Pinch Technology for the Synthesis of Optimal Heat and PowerSystems", *J. of Energy Resources Technology*, 111, 137-147.

Lozano M. A., Bartolomé J. L., Valero A., and Reini M., 1994, "Thermoeconomic Diagnosis of Energy Systems", *Proceedings of FLOWERS 1994*, Florence, July 1994.

Reini M. and Lozano M. A., 1994, "Local Optimization of Components inside an Energy Systems (in Italian)", *Proceedings of 46° ATI Symposium*, Perugia, Sept. 1994.

Reini M., 1996 "Losses Differential Analysis of a Steam Cycle with Internal Regeneration (in Italian)", *Proceedings of 51st ATI Symposium*, SGE Padova. Udine, Sept. 16-20 1996.

Reini M., Giadrossi A., 1994, "On the costs of products in multi-task systems: theoretical development and application to a cogeneration engine", *Proceedings of FLOWERS 1994*, Florence, July 6-8 1994.

Reini M., Taccani R., 2002, "Improving the Energy Diagnosis of Steam Power Plants Using the Lost Work Impact Formula", this issue of IJAT.

Reini M., Giadrossi A., 1996, "Local and Global Losses in Multi-component Energy System", *Proceedings of the ASME Conf. ESDA 1996*, Montpellier, July 1996.

Reini M., Lazzaretto A. and Macor A., 1995, "Average Structural and Marginal Costs as Result of a Unified Formulation of the Thermoeconomic Problem", *Proceedings of "Second Law Analysis of Energy System: Towards the 21st Century"*, Rome, July 5 - 7, 1995.

Sciubba E., 1995, "Artificial Intelligence Applications to the Synthesis of Thermal Processes", *Proceedings of "Second Law Analysis of Energy System: Towards the 21st Century"*, Rome, July 5 - 7, 1995.

Sorin M. V., Le Goff P. and Brodyanskii V. M., 1992, "Thermodynamic Optimization and Integration of Processes Using a General

Formula for the Efficiency", *Proceedings of ECOS 1992* (ASME Book No. I00331), Zaragoza, June 1992.

Spakovsky von M. R. and Evans R. B., 1990, "The foundations of Engineering Functional Analysis", *Proceedings of FLOWERS 1990*, Florence, May 28 - June 1, 1990.

Torres C., Valero A., and Serra L., 1999, "Structural Theory and Thermoeconomic Diagnosis - Part I: On Malfunction and Dysfunction Analysis", *Proceedings of ECOS 1999*, Tokyo, July 1999.

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 1990*, Florence, May 28 - June 1, 1990.

Valero A., Lozano M. A. and Muñoz, M., 1986, "A General Theory of Exergy Savings- Part I: On the Exergetic Cost, Part II: On the Thermoeconomic Cost", *Computer-Aided Engineering of Energy System*, pp. 1-21, A.S.M.E. W.A.M. 1986, AES-Vol. 2-3.

Valero A., Serra L. and Lozano M. A., 1993, "Structural Theory of Thermoeconomics", AES-V. 30/HTD-V. 266, Thermodynamics and the Design, Analysis and Improvement of Energy System.

Valero A., Torres C., Serra L. and Lozano M. A., 1992, "A. General Theory of Thermoeconomics - Part I: Structural Analysis, - Part II: The Relative Free Energy Function", *Proceedings of ECOS 1992* (ASME Book No. 100331), Zaragoza, June 1992.

Valero A., Correas L., Zaleta A., Lazzaretto A., Verda V., Reini M. and Rangel V., 2002, "On the Thermoeconomic Approach to the Diagnosis of Energy System Malfunctions Part-2 Malfunction Definitions and Assessment", *Proceedings of ECOS 2002*, Berlin, July 2002.

Verda V., Serra L. and Valero A., 2001, "Effects of the Regulation System on the Thermoeconomic Diagnosis of a Power Plant – Part 1: The Diagnosis Procedure" *Proceedings of ECOS 2001*, Istanbul, Turkey, June 4-6 2001.