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Thermoeconomic Analysis and Diagnosis of Energy Utility Systems

From Diagnosis to Prognosis

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Abstract

In this paper an approach for the complete thermoeconomic diagnosis is proposed. The procedure, initially developed for the location of anomalies, is here extended in order to evaluate the expected energy savings obtained when removing each anomaly found. This is an important task when different anomalies contemporarily occur in a plant, since they can be classified according to their contribution on the reduction in the overall system efficiency. Consequently, maintenance can be more efficiently planned.

Diagnosis is conduced through a thermoeconomic model of the system, built by means of available operating conditions corresponding to the plant without anomalies. The effects induced by the anomalies in the components are progressively removed. This procedure does not need to know in advance the exact location of the anomalies themselves. In this way the direct effect of the anomalies in the components where they occur is isolated, called intrinsic malfunctions. The total fuel impact associated with each malfunction is calculated by reassigning to each intrinsic malfunction their own induced effects.

A simulator is used in order to determine the operating conditions corresponding to the presence of different anomalies. Then the procedure is applied in order to first locate the anomalies and then to quantify them. The results are compared with those that can be obtained by progressively eliminating the malfunctions in the simulator.

Key words: Anomalies, thermoeconomic diagnosis, fuel consumption, induced malfunction

1. Introduction

Necessity of reducing the cost of electricity, also pushed by the liberalization of markets, has determined an increased attention in plant management. This fact involves, in operating plants, the control of fuel consumption, prevention of failures and maintenance programming. This last task should be pursued by considering that the degradation of the components' performance causes an increase in the fuel consumption required to produce the same amount of electricity. On the other hand, maintenance has a cost due to the intervention itself (on average 5% of the investment cost of the system per year [Jelen, Black, 1983]) and to the non-realized production. This means that the optimal programming is found as a compromise between these two contributions.

An effective diagnosis system should allow the plant management to individuate the causes of malfunctions so that possible degradation of the performances could be detected and the anomalies located. In this way, any intervention is more precise. Since these anomalies cause a reduction in the plant efficiency, i.e. additional fuel consumption, a useful information for the management is constituted by the evaluation of each single impact on the plant efficiency. Such information would allow one to estimate the possible economic effect of an intervention, as the component cleaning, in terms of reduction of the fuel consumption. This quantity together with the cost of the maintenance allows deciding whether and when to intervene.

The use of thermoeconomics as a tool for the plant diagnosis has been proposed, having in mind an important principle: anomalies that produce the same degradation in the performance of different components do not necessary produce the same overall impact [Lozano, Valero, 1993]. This means that the same reduction in the efficiency of two components generally produces different additional fuel consumption. Themoeconomics allows over-coming this problem by introducing in the analysis the concept of cost.

The plant model is represented by a *productive structure*, which expresses the productive role of each component by defining the required resources and the provided product. Exergy is usually used to define resources and products [Valero et al., 1986b].

The cost of a flow is defined as the amount of external resources (fuel) needed to produce that flow. Cost can be measured in monetary units as well as purely thermodynamic units, such as exergy.

Structural Theory [Valero et al., 1992] is here adopted for building the thermoeconomic model of the system. In this approach each subsystem or component is identified by a single product but different fuels, provided by as many components. This product feeds other components or constitutes a part of the plant product. As an example, *Figure 1* shows a possible productive structure of a gas turbine. Flow E_{ij} is fuel for the j^{th} component and the product of the i^{th} component. Plant fuels and products are indicated, respectively, as E_{0i} and E_{i0}. In particular, E_{01} is the exergy flow of the natural gas feeding the gas turbine. This flow enters the combustor together with the compressed air, which is provided by the compressor (flow E_{21}). The combustor produces hot gases (flow E_{13}) used by the turbine to produce mechanical power (flows E_{32} and E_{34}). These flows are resources for the compressor and the alternator. Gases leaving the turbine are fuel of the HRSG in a combined cycle (flow E_{30}). Other flows represented in the scheme are E_{40}, E_{20}, $E_{23,}$ respectively the electricity produced by the alternator, the losses associated with the air

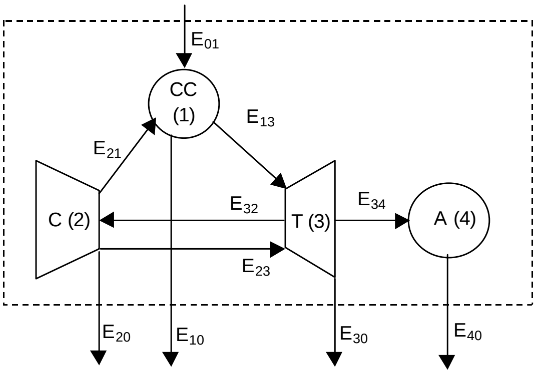

Figure 1 Example of a productive structure

leakage and the air used for the blade refrigeration. Finally E_{10} is the exergy flow lost with the exhaust gases. In thermoeconomics losses are assigned to one or more components in order to charge the cost of their production on that component. Several criteria have been proposed to achieve this objective (see for example [Frangopoulos, 1987] and [von Spa-kovsky, Evans 1990]). Here these losses have been completely assigned to the combustor.

The thermoeconomic behavior of com-ponents is expressed by the unit exergy consumption. It is defined as the ratio between each resource of the i^{th} component and its product:

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

The formulation through which it is possible to calculate the additional fuel consumption associated to the anomalies occurring in the plant is called the fuel impact formula ([Reini, 1994] and [Valero et al., 2002]). The aim of this paper is to present a procedure which allows splitting this fuel impact among the occurring anomalies.

The complete procedure presented in this paper consists of two parts: diagnosis and prognosis. In the first one the anomalies are identified and located, while in the second part they are quantified by evaluating the expected effect of their complete removal.

The thermoeconomic approach to diagnosis is particularly interesting just because it allows a rational quantification of effects, while other procedures are limited to the localization of anomalies. This consideration arises clearly in the first applications presented in literature by Prof. Valero and his co-workers [Valero et al., 1986a, Valero et al. 1986b].

2. The Diagnosis Procedure

In this paragraph, the main features of the diagnosis procedure are presented. Additional details can be found in [Verda et al. 2002a], [Verda et al. 2004]. A linear thermoeconomic approach is used since it allows obtaining satisfactory results without complicating the calculation too much. In the last part of the paragraph, a technique for improving the diagnosis is also presented. This technique, based on the use of neural networks to overcome some of the problems caused by non-linearities, allows obtaining a clearer localization of anomalies, nevertheless it requires a larger number of operating data, which is often the main constraint. A simpler procedure for the elimination of some of the non-linearities, called anamnesis, is also presented.

2.1. Thermoeconomic approach to diagnosis

A general diagnosis procedure is conducted by calculating some thermoeconomic quantities, which highlight the behavior of each subsystem, and comparing their values in two operating conditions: an actual condition and a reference condition, where the system works without anomalies. The advantage of such a procedure is a systemic and unique approach to plant analysis, whatever the cause of the malfunction. The reference condition is usually selected characterized by the same production and ambient conditions.

The diagnosis problem is generally not easy to solve, due to the interconnections between the components and the dependence of their efficiencies on the operating conditions. The presence of an anomaly in a component decreases its efficiency. As a consequence, additional resources are required to maintain the product constant (or a lower product is available if the resource is maintained constant). This effect is called the *intrinsic malfunction* [Valero et al., 1999], as it takes place in the malfunctioning component. The intrinsic effect generally is not the only consequence of an anomaly. In fact, other components in the plant have to change their production in order to feed the malfunctioning component with the additional resources required.

The efficiency of the components can depend on their operating condition due to non-flat efficiency curves. This means that when a component moves from an operating condition to another one its efficiency generally changes.

In this way, when a component is malfunctioning, some other components can be forced to change their efficiency. These malfunctions are defined as *induced malfunctions* [Valero et al., 1999].

Moreover if the value of some controlled quantities, like set points or external loads, is changed, the control system intervenes in order to restore the correct values. This intervention also modifies the operating condition of the plant, inducing other malfunctions [Verda et al. 2004].

The diagnosis procedure here described consists of a progressive filtration of the two induced effects: the ones associated with the control system intervention, first, and the ones due to the efficiency curves of the components. In this way the residual effects are all directly associated to the anomalies.

2.2. Filtration of the induced effects

The first effect to be eliminated is the control system intervention. The effect of an anomaly in the ith component of the system can be described as follows.

Assuming $\Delta\tilde{\varepsilon}_i$ to be the reduced efficiency caused by the anomaly, the component production decreases by an amount ΔP_i (see *Figure 2*) at constant fuel consumption. Overall plant production decreases too. Under this condition, the control system intervenes in order to restore the previous production. The plant moves towards the new reliable operating condition characterized by the same production as at the reference condition. The condition that would occur without the intervention of the control system is called the *free condition* [Verda et al. 2004]. In this condition the anomalies are still present; their effects are different with respect to those in operating condition since the system efficiency is generally different (see *Figure 2*).

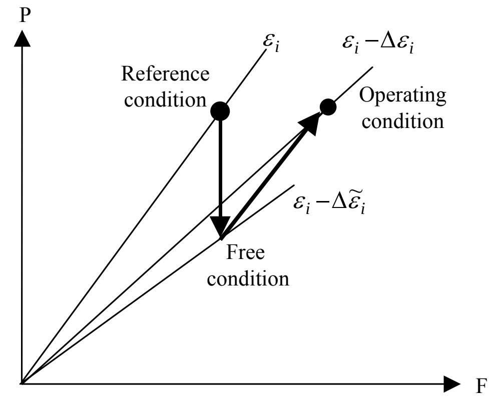

Figure 2. Behavior of the malfunctioning component at different operating conditions

The determination of that condition can be made only mathematically, since it is not a real condition. If the anomalies are small enough, the operating condition is quite close to the reference condition. In this case the effect of every adjustment parameter moved by the control system on the flows can be considered linear. The values of flows in free condition E_{free} can be calculated, starting from the corresponding values in the operating condition E_{op}, as:

$$E_{free} = E_{op} + \sum_{l=1}^{nap} \frac{dE}{dx_l} \cdot \left(x_{l_{ref}} - x_{l_{op}} \right) \qquad (2)$$

where E_{op} is the productive flow at the operating condition, *nap* is the number of adjustment parameters, x, moved by the control system in order to determine an acceptable operating condition. The derivatives can be calculated numerically by using available real conditions corresponding to the plant operating without anomalies, i.e. when it is new (see [Verda et al. 2004]). This is the only information needed to implement the diagnosis approach.

The second cause of induced malfunctions is associated with the specific behavior of the components and occurs when their resources (inputs) are moved from the reference values. The elimination of such contribution can be obtained by restoring the amount of resources to the reference values, as shown below.

First, each component should be isolated. Under the hypothesis of small anomalies, its off-design thermoeconomic model can be assumed as a linear dependence of the total product on each resource, namely:

$$\hat{E}_j = E_{j_{ref}} + \sum_{l=0}^{n} \left(\frac{\partial E_j}{\partial E_{lj}} \cdot \Delta E_{lj} \right) \tag{3}$$

where *ΔE* is the difference between the resources calculated in the actual condition and in the reference condition.

As an example, the thermoeconomic behavior of the combustion chamber can be expressed as:

$$\hat{E}_{12} + \hat{E}_{10} = \hat{E}_1 = E_{1_{ref}} + \frac{\partial E_1}{\partial E_{01}} \cdot \Delta E_{01} + \frac{\partial E_1}{\partial E_{21}} \cdot \Delta E_{21} \tag{4}$$

It has been shown in [Verda et al. 2002b] that a better result can be obtained by splitting exergy into mechanical and thermal components [Tsatsaronis et al., 1990]. In this case the contribution of the exergy flow of the compressed air becomes:

$$\frac{\partial E_1}{\partial E_{21}} \cdot \Delta E_{21} = \frac{\partial E_1}{\partial E_{21_m}} \cdot \Delta E_{21_m} + \frac{\partial E_1}{\partial E_{21_t}} \cdot \Delta E_{21_t} \tag{5}$$

These derivatives are calculated numerically, by using the same additional operating conditions available for the calculation of derivatives in equation (2).

The elimination of contributions due to the efficiency curves of the components can be made by considering the free condition as the actual condition. This means that the terms ΔE to be considered in equation (3) should be assumed to be the difference between the resources in the free and in the reference conditions. The term E_j calculated through these considerations represents the total product of the component when the resources change, in particular when they assume the same values as in the free condition. Thus, the quantity:

$$\hat{E}_j = E_{j_{ref}} + \sum_{l=0}^{n} \left(\frac{\partial E_j}{\partial E_{lj}} \cdot \left(E_{lj_{free}} - E_{lj_{ref}} \right) \right) \tag{6}$$

is representative of an off-design condition without anomalies in the jth component. The efficiency of the component (or, what is similar, the unit exergy consumption) could be different from the reference efficiency only because of non-flat efficiency curves. Since the thermoeconomic model is based on the use of unit exergy consumptions, the elimination of these induced effects is obtained by calculating the difference between the unit exergy consumption resulting from equation (6) and its value in reference condition, i.e.

$$\Delta \hat{k}_{lj} = \frac{E_{lj_{free}}}{\hat{E}_j} - \frac{E_{lj_{ref}}}{P_{j_{ref}}} \tag{7}$$

Under the formulated hypotheses, the term:

$$\Delta k_{lj_{int}} = \left(k_{lj_{free}} - k_{lj_{ref}} \right) - \Delta \hat{k}_{lj} \tag{8}$$

only includes the variation in the unit exergy consumption directly associated with the anomalies, since all the induced effects have been filtered off. This means that non-zero values of this parameter are a symptom of anomalies in the component where they are located (for additional details see [Verda et al., 2001]).

In thermoeconomic diagnosis other quantities can be introduced for the location of the anomalies. One of the most useful is the so-called *malfunction* [Torres et al., 1999]. It is defined as the product of the variation in the unit exergy consumption between the actual condition and the reference one for the component product, calculated in the reference condition, i.e.

$$MF_{lj} = \Delta k_{lj} \cdot P_{j_{ref}} \tag{9}$$

With respect to the unit exergy consumption, this quantity allows highlighting the variations in the efficiency of components with large production.

2.3. Application to a case of multiple anomalies

In order to better explain this procedure in this section an example is analyzed. For this purpose the TADEUS system is considered [Valero et al., 2002], which is a combined cycle consisting of two gas turbines, two HRSGs and a steam turbine. The total power of this system in design condition is about 350 MW. The operating condition here considered has been obtained by reducing, in one of the gas turbines, the design performances of the compressor and the turbine. This condition has been selected for its significance within this approach. For simplicity, only the data of the two gas turbines are shown in TABLE I.

TABLE I. PRODUCTIVE FLOWS OF THE TWO GAS TURBINES (kW)

	Gas turbine 1			Gas turbine 2		
	op	free	ref	op	free	ref
E_{01}	368312	365450	365450	368312	365450	365450
E_{10}	7251	7286	7160	7265	7034	7160
E_{13}	388679	380278	379134	384300	379247	379134
E_{20}	4352	4149	4122	4221	4122	4122
E_{21}	138018	131572	130712	133967	130712	130712
E_{23}	11548	11016	10953	11214	10953	10953
E_{30}	85587	86316	85128	85282	85254	85128
E_{32}	168868	160820	159148	163324	159149	159148
E_{34}	124986	124146	126263	127181	126269	126263
E_{40}	123736	122905	125000	125909	125006	125000

As a consequence of the anomalies (unknown before the application of the complete diagnosis procedure), the first gas turbine tends to reduce its production, while the second one does not change. These are the free conditions. As indicated before, these conditions are calculated because they are not real, they are fictitious (they could occur only if the anomalies appeared instantaneously, just before the intervention of the control system). The calculation has been made by using equation (2), which requires the knowledge of thermodynamic variables in several additional operating conditions together with the position of the adjustment devices in all the conditions. The productive flows calculated in several additional available operating conditions are shown in TABLE II. These values correspond to the plant in off-design conditions, caused by variations in ambient temperatures, plant load etc., but without anomalies.

TABLE II. PRODUCTIVE FLOWS IN THE ADDITIONAL CONDITIONS (kW)

	add1	add2	add3	add4	add5	add6
E_{01}	364405	368540	363178	363496	365450	365450
E_{10}	6472	7358	7094	7032	7250	7067
E_{13}	373748	384985	376063	377167	378417	380695
E_{20}	3997	4225	4083	4139	4112	4176
E_{21}	126060	134149	128854	130637	129783	131944
E_{23}	10567	11230	10797	10945	10873	11052
E_{30}	85257	85446	84930	84387	85380	85147
E_{32}	153626	163532	156958	159046	158041	160966
E_{34}	126263	127273	125253	125412	126257	125897
E_{40}	125000	126000	124000	124157	124994	124638

The presence of the control system makes the control devices vary in order to restore the setting values of the controlled quantities, such as the total electricity production and the outlet turbine temperature. In particular, plant control is actuated by modifying the fuel mass flow rate and the opening grade of the inlet guided vanes of the compressor. In particular, as described in [Valero et al., 2002], the fuel mass flow rate is modified by the operator in order to vary the plant production, while the *IGVs* modify their angle driven by the outlet turbine temperature, according to the control law. The specific law adopted in the examined plant is indicated in Figure 3.

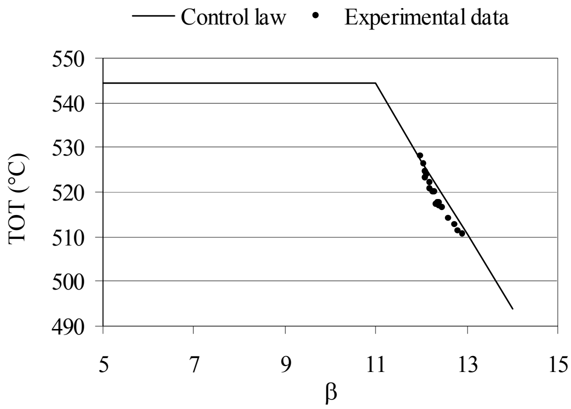

Figure 3. Setting value of the outlet turbine temperature as a function of the pressure ratio

In the modeled operating condition, the fuel mass flow rate is equally split between the two turbines in any operating condition. This means that when the anomalies occur in a single turbine, both fuel mass flow rates are changed. The adjusting parameters in the indicated conditions are shown in TABLE III.

TABLE III. VALUES OF THE ADJUSTMENT PARAMETERS

	Gas turbine 1		Gas turbine 2	
	Fuel (kg/s)	IGV	Fuel (kg/s)	IGV
Operating	8,106	-5,2	8,106	-3,531
Free	8,043	-2,038	8,043	-2,038
Reference	8,043	-2,038	8,043	-2,038
Add1	8,02	0,686	8,02	0,686
Add2	8,111	-3,618	8,111	-3,618
Add3	7,993	-1,104	7,993	-1,104
Add4	8	-2,038	8	-2,038
Add5	8,043	-1,538	8,043	-1,538
Add6	8,043	-2,538	8,043	-2,538

The procedure is completed by applying equations (6) and (7) to each component. Derivatives are calculated by using a linear regression of the productive flows calculated in the additional conditions, such as those shown in TABLE II.

The location of the anomalies is performed by means of the values assumed by the selected evaluation parameters. Here the total mal-functions in each component, defined as:

$$MF_j = \sum_{l=1}^{n} \Delta k_{lj} \cdot P_{j_{ref}} \qquad (10)$$

are considered. In TABLE IV malfunctions calculated for all the system components are shown. The results in the three columns are different because of the term Δk_{lj} considered for their calculation. In the first column (op-ref), this quantity is calculated as the difference between the value in the operating and reference conditions. The results show large negative malfunctions in the combustors. Positive malfunctions are registered in the compressor and turbine of the first gas turbine, which are the component where the anomalies are located. Some important malfunctions occur in other components having a magnitude of about 200 kW or less. These malfunctions are not anomalies, but when the diagnosis is performed, they can be confused with intrinsic malfunctions.

TABLE IV MALFUNTIONS IN THE COMPONENTS (kW)

		op-ref	free-ref	int
GT 1	Combustor	-2154	-767	-115
	Compressor	799	630	634
	Turbine	751	424	418
	Alternator	0	-1	-1
GT 2	Combustor	-643	16	16
	Compressor	220	1	1
	Turbine	-96	-26	-26
	Alternator	0	0	0
HRSG 1	LP pump	0	0	0
	HP pump	-5	-2	-2
	LP Economizer	-165	-167	-80
	LP Evaporator	-26	63	103
	HP Economizer	83	-33	-133
	LP Super-heater	21	21	26
	HP Evaporator	-24	59	-13
	HP Super-heater	194	93	-52
HRSG 2	LP pump	0	0	0
	HP pump	-5	-2	-2
	LP Economizer	-161	151	-4
	LP Evaporator	92	-86	-65
	HP Economizer	-75	8	-11
	LP Super-heater	32	49	5
	HP Evaporator	16	-174	-102
	HP Super-heater	212	102	85
ST	HP Turbine	72	-41	-41
	LP Turbine	24	-21	-21
	Alternator	-1	-1	-1
	Condenser	201	108	-5

In the second column (free-ref) Δk_{lj} is the difference between the free and reference conditions. With respect to the first column, here the effects of the control system have been eliminated and as a consequence the induced malfunctions generally reduce. The only component where they increase is the high pressure evaporator.

The contribution due to the specific behavior of the components is eliminated in the third column (int). As a result the intrinsic malfunctions should be highlighted. The highest values appear in the compressor and the turbine of the first gas turbine. Nevertheless, several effects are still present in components non-really malfunctioning. As explained in the next paragraph these are due to non-linearities (see also [Verda et al. 2001])

2.4. Improvement of the diagnosis procedure: the analysis of a case history

When this procedure is applied to a real operating condition, it is possible that the values corresponding to some of the occurring anomalies are not sufficiently small. In that case non-linearities can appear in equation (8), though smaller than the intrinsic effects. This means that the diagnosis is still able to locate the main malfunctions, but small anomalies appear due to the non-linearities.

The same problem can occur when estimating the derivatives in equations. (2) and (3) if the operating condition available for this calculation is far from the reference condition. In the proposed example, several operating conditions have been selected far from the reference one to increase the reliability of the results. Thus, some of the non-linearities present in the results are due to the selection of the additional operating condition.

To avoid the problem of non-linearities, a possible approach is constituted by the plant *anamnesis*, i.e. its case history. This proposed approach is taken from the medical field and consists of repeating the analysis during the plant life and comparing the results. This allows distinguishing between real anomalies and 'disturbs' associated with the non-linear behavior of the components.

In TABLE V, the malfunctions, calculated as in the third column of TABLE IV, are shown for several operating conditions ordered chronologically. This information is useful since degradation of the components is supposed to increase with time. In this way, floating values of the malfunctions can be justified through non-linearities.

This approach increases considerably the power of leaving the false anomalies out, isolating all the true ones. In this case the only components where the calculated values of malfunctions do not float are the compressor and the turbine of the first GT.

TABLE V. MALFUNTIONS CALCULATED IN THE ANAMNESIS (kW).

		an1	an2	an3	an4	an5	an6	op
GT 1	Combustor	-30	-108	-58	-137	-37	-115	-115
	Compressor	95	192	336	436	532	634	634
	Turbine	-33	-25	38	155	170	296	418
	Alternator	0	0	0	-1	0	-1	-1
GT 2	Combustor	0	0	0	16	16	16	16
	Compressor	1	1	1	1	1	1	1
	Turbine	-7	-7	-7	-26	-26	-26	-26
	Alternator	0	0	0	0	0	0	0
HRSG 1	LP pump	0	0	0	-2	-2	0	0
	HP pump	-5	-5	13	-4	-9	-8	-2
	LP Economizer	-14	-13	-30	37	18	-70	-80
	LP Evaporator	-4	-7	-17	-15	-85	45	103
	HP Economizer	6	12	19	51	-126	-160	-133
	LP Super-heater	-13	-12	-8	11	16	10	26
	HP Evaporator	-150	-110	33	-176	120	41	-13
	HP Super-heater	109	83	237	139	6	50	-52
HRSG 2	LP pump	0	0	0	-2	-2	0	0
	HP pump	-5	-5	13	-4	-9	-8	-2
	LP Economizer	-10	-5	-12	84	82	1	-4
	LP Evaporator	-34	67	33	-73	-42	-95	-65
	HP Economizer	-13	9	18	104	30	-3	-11
	LP Super-heater	-14	-15	-16	-1	-2	-10	5
	HP Evaporator	-145	-145	33	-200	56	11	-102
	HP Super-heater	86	91	220	96	56	56	85
ST	HP Turbine	-44	67	19	-51	30	-11	-41
	LP Turbine	-31	79	-26	23	48	-91	-21
	Alternator	0	-2	0	0	-1	-1	-1
	Condenser	2	-11	9	-14	-22	13	-5

2.5. Improvement of the diagnosis procedure: non-linear thermoeconomic model based on neural networks

The use of neural network algorithms to foresee the product of a component corresponding to a particular set of resources is particularly effective due to its easiness to be performed. A neural network is a black box which establishes a relation between inputs (resources) and outputs (products), i.e.

$$\hat{P}_j = P_j\left(E_{0j_{free}}, E_{1j_{free}}, \ldots E_{nj_{free}}\right) \qquad (11)$$

The relation is obtained by means of a learning process, called training, where the network parameters (weights and biases) are calculated through the knowledge of inputs and outputs in several conditions. The only condition necessary for the implementation of the diagnosis procedure is the availability of a sufficiently large number of reliable operating conditions.

In this study, a mathematical model plays the role of the plant. It has been used in order to generate the operating conditions necessary for the training phase. Here, 1000 conditions have been considered for each network. Moreover, 100 additional conditions have been generated in order to verify the accuracy of the results obtained with the networks.

Each network defines the thermoeconomic behavior of a component. The networks are made up of 2 layers of neurons, respectively characterized by sigmoid and linear transfer functions. Each layer is constituted of a number of neurons varying from 11 to 19, depending on the number of its inputs, i.e. the number of resources of the component. In *Figure 4*, a scheme of the network is depicted.

Each neuron applies the transfer function to the inputs p:

$$a = F\left(\{W\} \cdot \{p\}^T + b\right) \qquad (12)$$

where a are the outputs, W the weights, b the biases, and F the functions (F1 is a sigmoid function and F2 a linear function).

The Levenberg-Marquardt algorithm [Hagan, Menhaj, 1994] has been implemented in order to calculate weights and biases of the network in the training process.

As said before, a theoretical advantage offered by the use of neural networks is the relative easiness of implementing the procedure system. In fact, the only decision to be operated is the choice of productive flows that constitute the fuel of each component, i.e. the productive structure. This choice must be made by selecting an opportune desegregation level in the analysis. In particular, in most cases it is necessary to split exergy into mechanical and thermal components, so that the different effects of temperature and pressure on the component production can be considered.

Once this choice is operated, the neural network can be trained by introducing the set of couples fuels-product (in this case 1000) of the components.

An application of neural networks to thermoeconomic diagnosis is presented in [Verda, 2003].

Anamnesis and neural network based thermoeconomic models can be used together in order to increase the reliability of the diagnosis results.

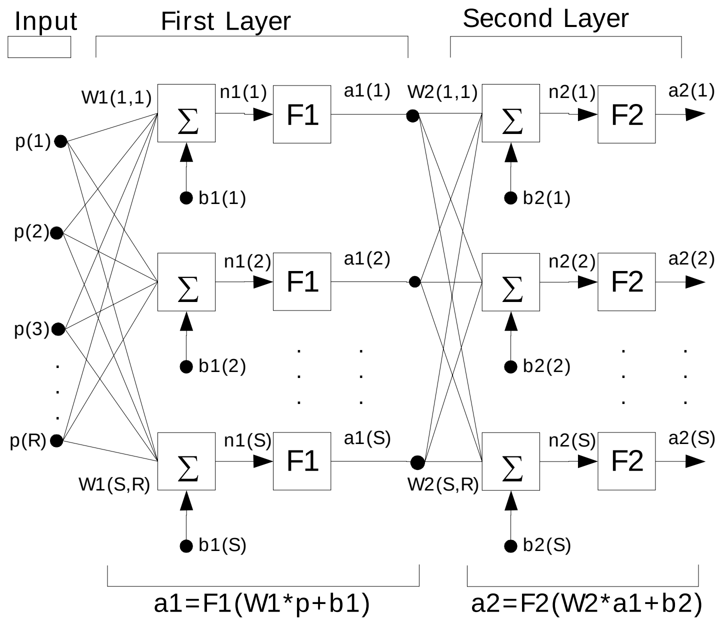

Figure 4. Scheme of the neural network

3. Prognosis

Once all the anomalies have been detected and located any decision about maintenance strategies depends on the economic convenience. In order to help take a correct decision, in this paragraph an additional tool is provided. It consists of a reliable evaluation of the expected fuel saving obtained by completely removing each anomaly. This is called the plant *prognosis*.

The complexity of this goal is high when several anomalies have been detected, in fact, the available information is not sufficient. Known quantities are:

1) the intrinsic malfunctions, calculated in the previous paragraph;

2) the total additional fuel consumption.

This quantity can be calculated by means of the *fuel impact formula* ([Reini, 1994], [Valero et al., 2002] and [Torres et al., 1999]):

$$\Delta F_T = \sum_{i=1}^{n} k_{p_i}^* \cdot \Delta P_{e_i} + \sum_{i=1}^{n}\left(\sum_{j=0}^{n} k_{p_j}^* \cdot \Delta k_{ji}\right) \cdot P_{i_{ref}} \quad (13)$$

where:

ΔF_T is the fuel impact.

$k_{pj}*$ is the unit exergy cost of the product of the j[th] component, calculated at the operating condition. The cost of a flow indicates the amount of overall fuel required to produce it. The unit exergy cost is obtained as a ratio between the cost of the flow and its exergy.

ΔP_{ei} is the variation in overall plant production provided by the i[th] component, which occurs between operating and reference conditions.

Δk_{ji} is the variation in unit exergy consumption k_{ji}, which occurs between operating and reference conditions.

P_{iref} is the total product of the i[th] component at the reference condition.

The first term on the right-hand side is associated with a different plant production, while the second with a change in behavior of the components.

This equation is particularly helpful for multi-product systems; in fact it is easier to compare the operating and reference conditions, also if characterized by different overall production. In order to eliminate the effect associated with a different production in the operating and reference condition, the total fuel impact is corrected by subtracting the first term at the right-hand side of equation (13):

$$\Delta F_{T_{corr}} = \Delta F_T - \sum_{i=1}^{n} k_{p_i}^* \cdot \Delta P_{e_i} \quad (14)$$

or

$$\Delta F_{T_{corr}} = \sum_{i=1}^{n}\left(\sum_{j=0}^{n} k_{p_j}^* \cdot \Delta k_{ji}\right) \cdot P_{i_{ref}} \quad (15)$$

The fuel impact formula highlights the difficulties of the prognosis problem. In fact, in order to calculate the additional fuel consumption associated with an anomaly, it is necessary to know not only the intrinsic component of the malfunction but also its induced effects. The induced effects are known but it is not possible to distinguish their origin, i.e. it is not possible to understand which anomaly has provoked which.

The approach proposed here is based on the use of the same operating conditions considered for the anamnesis. For each condition it is possible to distinguish the intrinsic components of the fuel impact, one for each detected anomaly. For the general anomaly in the jth component this term is:

$$\Delta F_{\mathrm{int}_j} = k^*_{p_l} \cdot \Delta k_{lj_{\mathrm{int}}} \cdot P_{j_{\mathrm{ref}}} \qquad (16)$$

$\Delta k_{lj\mathrm{int}}$ being the significantly non-null terms defined by equation (8) still present after consideration from the anamnesis.

The total corrected fuel impact can be written as:

$$\Delta F_{T\mathrm{corr}} = \sum_j \Delta F_{\mathrm{int}_j} - \Delta F_{\mathrm{ind}} \qquad (17)$$

The additional fuel consumption caused by each anomaly must be obtained by splitting the induced term among all the anomalies. Through a linear regression it is possible to find a correlation between the intrinsic and the corresponding induced term of the fuel impact. The operating conditions available for the anamnesis are considered for achieving this objective. In TABLE VI all the terms are indicated.

TABLE VI. COMPONENTS OF THE FUEL IMPACT (kW)

	An1	An2	An3	An4	An5	An6	Op
ΔF_T	455	1365	2912	4096	4732	5188	5734
$k_l^* \Delta P$	149	25	45	-15	221	-67	-53
$\Delta F_{T\,corr}$	306	1340	2867	4111	4512	5255	5787
ΔF_{ind}	147	1020	2243	3135	3349	3720	4057
$\Delta F_{int\text{-}2}$	158	320	563	730	891	1064	1064
$\Delta F_{int\text{-}3}$	0	0	61	246	271	471	666

The expression adopted for this calculation is:

$$\Delta F_{T\mathrm{corr}} = (1 + i_2) \cdot \Delta F_{\mathrm{int}_2} + (1 + i_3) \cdot \Delta F_{\mathrm{int}_3} \qquad (18)$$

where i_2 and i_3 are the coefficients determined through the linear regression. In fact, not all the coefficients need to be specified, one of them is calculated from the knowledge of the total impact in the operating condition. The calculated value for i_2 is 4.70.

The use of such approach in the example proposed before does not produce satisfactory results. In fact the additional fuel consumption calculated for the two anomalies is, respectively, 5006 kW and 781 kW. In contrast, the residual fuel impact that would be determined by simulating an operating condition corresponding to the removal of the anomaly in the compressor is 3366 kW, while the same operation for the turbine would have produced a result of 3868 kW.

This result is only due to the failure of the hypothesis of linearity. This is demonstrated by the failure of the principle of superposition of the effects for the fuel impact; in fact the total fuel impact in the operating condition (5787 kW) is different from the summation of the two fuel impacts corresponding to single anomalies (7234 kW). If the same calculations were repeated with lower anomalies, the results would have been much better. In *Figure 5*, the anomaly in the turbine is varied while the anomaly in the compressor is maintained. The calculated and real values of the total fuel impact are represented. The graph shows that the principle of superposition of the effects tends to fail as the malfunction increases.

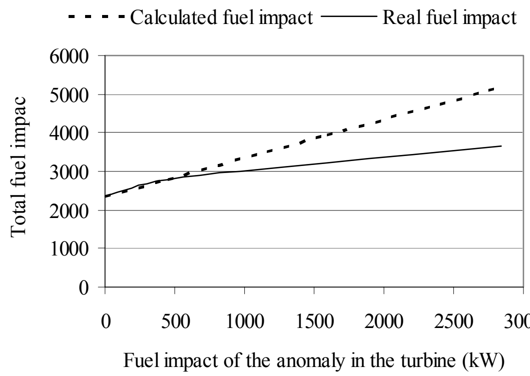

Figure 5. Calculated and real fuel impact as the anomaly in the turbine increases

4. Application of the Diagnosis Procedure to a Test Case

In TABLE VII, the results obtained by applying the complete procedure to the operating condition are defined in the introductive paper of this issue. This condition has been obtained by simulating three anomalies, respectively, in the filter of GT1 (fouling), in the turbine of GT1 (erosion) and in the HP super-heater of HRSG1 (fouling).

The values in columns 1-3 are the malfunctions corresponding to three conditions representative of the case history, while those in the last column are the malfunctions calculated for the actual operating condition.

TABLE VII. MALFUNCTIONS CALCULATED IN THE TEST CASE ANAMNESIS (kW).

		an1	an2	an3	op
GT 1	Combustor	-22	-355	-58	-294
	Compressor	34	253	315	336
	Turbine	284	453	518	888
	Alternator	-1	-2	0	0
GT 2	Combustor	16	14	15	10
	Compressor	1	1	1	0
	Turbine	-26	-25	-26	-24
	Alternator	0	0	0	0
HRSG 1	LP pump	0	-2	0	0
	HP pump	-4	-8	-2	0
	LP Economizer	8	-8	0	-13
	LP Evaporator	-22	33	134	119
	HP Economizer	-36	-17	-53	-18
	LP Super-heater	-4	42	45	32
	HP Evaporator	51	-19	-117	-395
	HP Super-heater	173	190	206	260
HRSG 2	LP pump	0	-2	0	0
	HP pump	-4	-8	-3	0
	LP Economizer	27	20	27	31
	LP Evaporator	-99	-72	-62	-8
	HP Economizer	36	71	93	75
	LP Super-heater	-17	20	24	-11
	HP Evaporator	167	-10	175	-45
	HP Super-heater	-36	-71	-43	-39
ST	HP Turbine	-90	-51	-23	-69
	LP Turbine	14	76	-44	17
	Alternator	-1	-1	-2	-1
	Condenser	14	-9	10	-18

The simple diagnosis procedure without the anamnesis process does not allow filtering off some of the induced effects. In particular, non-negligible malfunctions are determined in the LP evaporator of HRSG1 and in the HP economizer of HRSG2 (the negative values can be immediately eliminated since they are surely induced). It is known that these malfunctions are provoked by anomalies in other components (induced), since the operating condition has been determined by using a simulator. When the diagnosis is applied to a real plant, this is not known. As explained before, these effects, due to non-linearities, are a sort of disturbance that impedes clear detection of all the causes of the additional fuel consumption.

The anamnesis procedure allows overcoming this problem and allows distinguishing between intrinsic (anomalies) and induced malfunctions. In particular, it shows that the malfunctions in the LP evaporator and in the HP economizer are induced by anomalies in other components. In fact, their values present an oscillating trend, while the intrinsic malfunctions should increase progressively. In contrast, the malfunctions in the three components characterized by anomalies present a progressive increasing, so that they can be detected as intrinsic malfunctions.

5. Conclusions

In this paper, a thermoeconomic based approach for diagnosing efficiency reductions in energy systems is proposed. It consists of a successive removal of disturbances that impede identifying where the anomalies have originated. The procedure, theoretically correct for the localization of small malfunctions, is extended to possible real cases by analyzing the case history of the plant operating conditions, called the anamnesis.

The approach is then elaborated for prognosis purposes, i.e. in order to evaluate the expected fuel saving that could be obtained by removing each of the detected anomalies. As happens for the diagnosis, the procedure produces good results when it is applied to small malfunctions. Its application to real cases could pass through the use of neural network algorithms in order to overcome the limits of linear models. This topic is an object of actual research.

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Nomenclature

E_{ij}	Flow of the productive structure [kW]
k_{ij}	Unit exergy consumption
k_p*	Unit exergy cost of the product
MF	Malfunction [kW]
P_i	Product of the i^{th} component [kW]
x	Operating parameter of the control system

Greek

β	Pressure ratio
ΔF_T	Fuel impact [kW]
ε	Efficiency

Subscripts

corr	Corrected term (fuel impact)
free	Free condition
ind	Induced effect
int	Intrinsic effect
op	Operation condition
ref	Reference condition.

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