Int.J. Thermodynamics,
Vol.7, (No.2), pp.61-72, June-2004
ISSN 1301-9724

On the Thermoeconomic Approach to the Diagnosis of Energy System Malfunctions

The Role of the Fuel Impact Formula

Mauro REINI, Rodolfo TACCANI
Department of Energy Engineering,
University of Trieste, ITALY
Fax. (+39) 040 558 3812, E-mail: reini@units.it

Abstract

In this paper, the Productive Structure definition is shortly revised and the deduction of the fuel impact formula is recalled. Then the Combined Cycle Power Plant, proposed previously to demonstrate the practical feasibility of the thermoeconomic approach, is considered and the fuel impact formula is applied for quantifying the effects of degradation. Finally the capability and the limits of the fuel impact approach to perform an accurate diagnosis are discussed.

Keywords: Energy diagnosis, fuel impact, malfunction, thermoeconomics.

1. Introduction

The objects of energy systems' diagnosis are:

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

ii) quantifying energy recovery if design conditions were restored in a particular system component.

To obtain these results, the concept of "fuel impact" was first proposed by Valero et al. (1990), as a tool linking the performance parameters of the components (identified with their exergetic efficiencies) with the resources consumption of the plant. The idea can be summarised as follows: when the exergetic efficiencies of a malfunction components decrease, the effect on the whole resources consumption can be evaluated taking account of the exergetic costs (defined by Valero et al., 1986), of the flows (regarded as internal resources) consumed by that component. The analytical formulation of this concept is the "fuel impact formula" (Reini, 1994; Lozano et al., 1994; Reini et al., 1995).

The expectations are the identification of components affected by any malfunctions through variations in their exergetic efficiencies (or unit exergy consumptions) and the quantification of potential energy recovery through the evaluation of additional resources consumption of the whole plant.

Unfortunately things are not so simple. In fact, also components not affected by any actual malfunctions can show a variation of their exergetic efficiencies (or unit exergy consumptions) because their operating conditions (not their performance characteristics) are modified as a consequence of other components' functional decay. This effect is called "induced malfunction" (see for instance Valero et al., 2002). It can be sad that the development of the fuel impact approach, to improve its diagnosis accuracy, has been mainly devoted to identify strategies and procedures allowing a better evaluation of "induced" and "intrinsic" malfunction effects and to detect the actual origin of induced malfunctions.

In this paper, the Productive Structure definition is shortly revised and the deduction of the fuel impact formula is recalled. Then, the capability and the limits of the fuel impact approach to perform an accurate diagnosis are discussed, Valero et al. (2004).

2. Productive Structure with Single-Product Components

The fuel impact formula is not directly based on the actual exergy flows inside the plant, but on the so called Productive Structure (PS) of the plant, where components are connected by flows describing their "productive relations" with other components and with the outside the plant. In the PS each component is regarded, at local level, as an autonomous production unit, having one output flow named "*Product"* or "*Function*" and one or more input flows named "*Fuels*" or internal resources.

To obtain this kind of structure, a sort of "local model" of each component has to arise from the whole plant thermodynamic model and has to be expressed in analytic form. This can be done as follows.

Each flow E_i describing "productive relations" among components has to be defined on the basis of heat, work and mass flow rates and of thermodynamic conditions of working fluids inside the plant.

From a mathematical point of view, the choice of the analytic formulation is free and is left to the Analyst. Nevertheless, some guideline concepts are widely applied in Literature and they are used in this work also:

- Use exergy to quantify the magnitude of flows **E**, so that heat, work and mass streams can be evaluated taking energy "quality" into account.
- If a material stream, crossing a control
- Volume decreases its exergy content, the component inside the control volume is receiving an exergy flow and the same amount of exergy has to be supplied by some other component of the plant, or by the outside.
- If a material stream, crossing a control volume, increases its exergy content, the component inside the control volume is producing an exergy flow and the same amount of exergy has to be received by some other component of the plant, or by the outside.
- Define, if it is possible, control volumes having a clear purpose inside the plant (increasing pressure, producing mechanical work, dissipating heat).

In any case, flows E_i have to be regarded as a set of dependent variables of the thermodynamic model of the plant (for more details, see Reini et al., 1995) and the "local model" of a component (see *Figure. 1*) can be first formulated as shown in the left hand side below:

In this model each exergy flows in the PS (**E**) can be expressed as a function of an independent variables set (τ_T), made with the output flows of the whole system (ω) and all other independent variables necessary to describe components behaviour (τ).

Let's suppose that each component in the reference condition (not affected by any functional decay or malfunction) has only one degree of freedom. This hypothesis corresponds to the widely applied concept that a component has to have one and only one *"Product"* (the problem of multi-product components will be summarised in the following).

The component degrees of freedom can be expressed, at *local* level, by any variable, not necessarily chosen inside the whole plant independent variable set. In particular, the

$$E_i = f_i(\tau_T) = f_i(\tau_1, \tau_{T-1}) \quad \Rightarrow \quad \tau_1 = f_i^{-1}(E_i, \tau_{T-1})$$

$$E_j = f_j(\tau_T) = f_j\left(f_i^{-1}(E_i, \tau_{T-1}), \tau_{T-1}\right) \Rightarrow \quad E_j = f_j^{+}(E_i, \tau_{T-1})$$

$$E_y = f_y(\tau_T) = f_y\left(f_i^{-1}(E_i, \tau_{T-1}), \tau_{T-1}\right) \Rightarrow \quad E_y = f_y^{+}(E_i, \tau_{T-1})$$

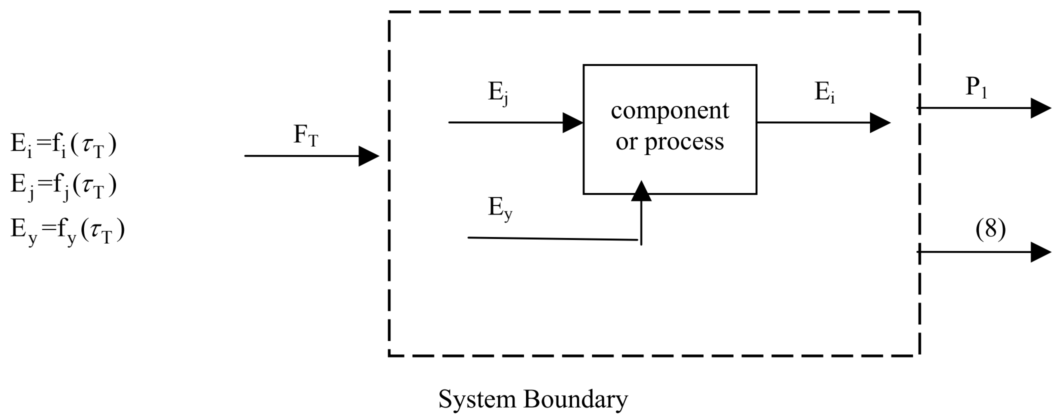


Figure 1: The local model of a generic single-product component.

independent variable substitution shown on the right hand side of the previous equations has to be made when the flow E_i is chosen (von Spakovsky, 1986). To fix ideas, if the system is a simple linear chain, made of components with fixed exergy efficiency, the variable τ_1 can be the final product of the system, and E_i can be the output flow, for each component of the chain.

The choice of an outgoing flow, representing the purpose, or the *"Product"*, of the component, makes easier the economic interpretation of the PS, even if other flows belonging to the productive structure may be used as well to develop the fuel impact formula.

At *local* level, the *unit exergy consumptions* can be easily defined as (see *Figure. 1*):

$$k_{ij} \equiv \frac{E_j}{E_i} = k_{ij}(\tau_T)\;;\; k_{iy} \equiv \frac{E_y}{E_i} = k_{iy}(\tau_T) \quad (1)$$

so that the local model of the component or process in *Figure 1* becomes:

$$E_j = k_{ij}(\tau_T)E_i\;;\; E_y = k_{iy}(\tau_T)E_i\;;\; E_i = \omega_i \quad (2)$$

where the last equation applies to the product flows supplied to the outside the plant.

3. The Fuel Impact Relation

Eventually, the thermodynamic model can be arranged in matrix form, obtaining the *Characteristic Equation* of the Thermoeconomic Model for the whole plant (see, for instance, Valero et al. 1992, Reini et al. 1995, Valero et al. 2002):

$$\mathbf{E} = {}^t\mathbf{K}\,\mathbf{E} + \boldsymbol{\omega} \Rightarrow E = {}^t\left[U_D - K\right]^{-1}\,\boldsymbol{\omega} \quad (3)$$

Matrix **K** contains the elements k_{ij} related to components and branches of the productive structure, where the latter simply express that exergy input to a branch is the sum of the two outputs. Starting from the expression of **E**, the global consumption of exergy resources (F_T) can be written as:

$$F_T = {}^t k_e^*\;E = {}^t k_e^*\;{}^t\left[U_D - K\right]^{-1}\,\boldsymbol{\omega} \quad (4)$$

where vector $\mathbf{k}_e^*$ contains the unit exergy costs assigned to the energy flows coming from the outside the system (if exergy losses outside the plant are not considered, the unit exergy cost of each external fuel is equal to one).

By differentiating global consumption (F_T) with respect to the whole plant independent variables and putting in evidence the differential of matrix **K**, the Fuel Impact relation (Reini, 1994) is obtained:

$$\begin{aligned} dF_T &= {}^t E\;\; dK\;\; k^* + \sum_i^m k_i^* dw_i \\ &= \sum_i \sum_j k_j^* dk_{ij}(t_T)E_i + \sum_i^m k_i^* dw_i \end{aligned} \quad (5)$$

$$k^* = \left[U_D - K\right]^{-1} k_e^* \quad (6)$$

This relation can be used to evaluate the effect on the external energy flows consumption, of both a variation in the amount of final products, and a variation in the unit exergy consumption of a component. Vector $\mathbf{k}^*$ coincides with the unit exergy cost vector defined by Valero et al. (1986).

Notice that this result cannot be obtained on the basis of pure exergy balance, but it bases on two typical thermoeconomic concepts, like productive structure and exergy cost.

When a component is affected by a functional decay, or a malfunction, one or more unit exergy consumptions inside its local model modifies its value, so that the term MF_i^* (named *cost of malfunction* by Torres et al., 1999)

$$MF_i^* \equiv \sum_j k_j^* dk_{ij}(\tau_T)\,E_i \quad (7)$$

assumes a positive value. If unit exergy consumptions of no other components are affected by the functional decay of the true malfunctioning one, MF_i^* expresses the amount of additional resources consumed because component -i- is not operating in the reference condition, as can be easily verified by comparing the last relation with the Fuel Impact relation.

Unfortunately component functional decay can be described inside the thermodynamic model by some independent variables (τ_i), not by unit exergy consumptions. In fact the latter are defined as dependent variables, depending on the whole set τ_T. So, if a variable from the set τ_T changes, unit exergy consumptions can be affected in various components, and a *cost of malfunction* can arise also in components not affected by any intrinsic malfunction. This is the *induced malfunction* effect, previously outlined.

4. Productive Structure with multi-product components

The procedure bringing in previously, in order to obtain the *Characteristic Equation* of the Thermoeconomic Model, can be applied also to components or processes with two product flows (*Figure 2*). For this kind of component, a change involving two (instead of only one) independent variables (τ_1, τ_2) can be introduced:

$$E_i = f_i(\tau_T) = f_i(\tau_1, \tau_2, \tau_{T-2}) \quad \Rightarrow \quad \tau_1 = f_i^{-1}(E_i, E_h, \tau_{T-2})$$

$$E_h = f_h(\tau_T) = f_h(\tau_1, \tau_2, \tau_{T-2}) \quad \Rightarrow \quad \tau_2 = f_h^{-1}(E_i, E_h, \tau_{T-2})$$

$$E_j = f_j(\tau_T) = f_j\left(f_i^{-1}(E_i, E_h, \tau_{T-2}),\ f_h^{-1}(E_i, E_h, \tau_{T-2}), \tau_{T-2}\right) \quad \Rightarrow \quad E_j = f_j^{+}(E_i, E_h, \tau_{T-2})$$

$$E_y = f_y(\tau_T) = f_y\left(f_i^{-1}(E_i, E_h, \tau_{T-2}),\ f_h^{-1}(E_i, E_h, \tau_{T-2}),\ \tau_{T-2}\right) \quad \Rightarrow \quad E_y = f_y^{+}(E_i, E_h, \tau_{T-2})$$

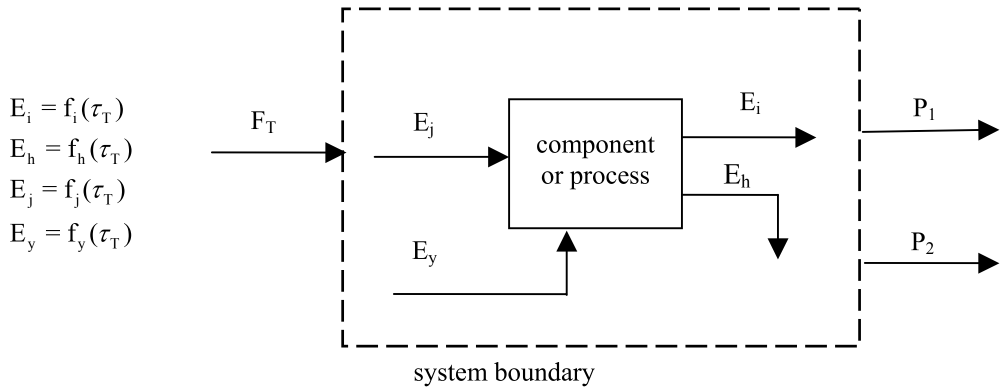


Figure 2. The local model of a generic multi-product component.

To do this, functions f_i, f_h, f_j and f_y in the ideal thermodynamic model must be expressed in terms of at least two independent variables, i.e. the component must have at least two *degrees of freedom*. The problem of multi-product components is discussed in Valero et al. (1992), Reini and Giadrossi, (1994). Unit exergy consumptions have to be defined in this case as derivative quantities:

$$k_{ij} \equiv \left(\frac{\partial E_j}{\partial E_i}\right)_{\substack{\tau_{T-2} \\ E_h}} \qquad k_{hj} \equiv \left(\frac{\partial E_j}{\partial E_h}\right)_{\substack{\tau_{T-2} \\ E_i}}\ ; \qquad k_{iy} \equiv \left(\frac{\partial E_y}{\partial E_i}\right)_{\substack{\tau_{T-2} \\ E_h}} \qquad k_{hy} \equiv \left(\frac{\partial E_y}{\partial E_h}\right)_{\substack{\tau_{T-2} \\ E_i}} \tag{8}$$

They can not be directly obtained any more from a measure of the exergy flows, but they have to be inferred from the actual expressions of functions f_i, f_h, f_j and f_y. This can be regarded as the main reason why multi-product PSs are very uncommon in practical applications of thermoeconomic methodologies. The local model of a multi-product component is supposed to be of the following kind (equivalent hypotheses can be formulated from a mathematical standpoint):

$$E_j = k_{ij}(\tau_T)E_i + \ k_{hj}(\tau_T)E_h \tag{9}$$

$$E_y = k_{iy}(\tau_T)E_i + \ k_{hy}(\tau_T)E_h \tag{10}$$

Therefore the matrix form of the *Characteristic Equation* still holds and, starting from this basis, the same expressions for the Fuel Impact relation and the unit exergy cost vector are obtained. In particular, the unit exergy costs of the two bifurcating co-products are:

$$k_i^* = k_j^* k_{ij}(\tau_T) + k_y^* k_{iy}(\tau_T) \tag{11}$$

$$k_h^* = k_j^* k_{hj}(\tau_T) + k_y^* k_{hy}(\tau_T) \tag{12}$$

Exergy cost results to be a conservative quantity in this case too, even if the unit exergy costs of the two bifurcating co-products may be different.

If the multi-product component has only *one degree* of freedom, the independent variables change cannot involve two variables, but again only one. The output regarded as the local independent variable is the actual product of the component, while the second (dependent) output can be a *residue* or a *by-product*, according to the consequence that the presence of this flow has on the total plant fuel consumption. In the case of ecological energy systems, a third case can be considered, bringing to the Emergy concept, as discussed in Reini and Valero (2002).

4.1 Residue

In this case a disposal process exists inside the plant, in order to convert the residual flow E_h in a flow that can be discharged into the environment (*Figure 3*).

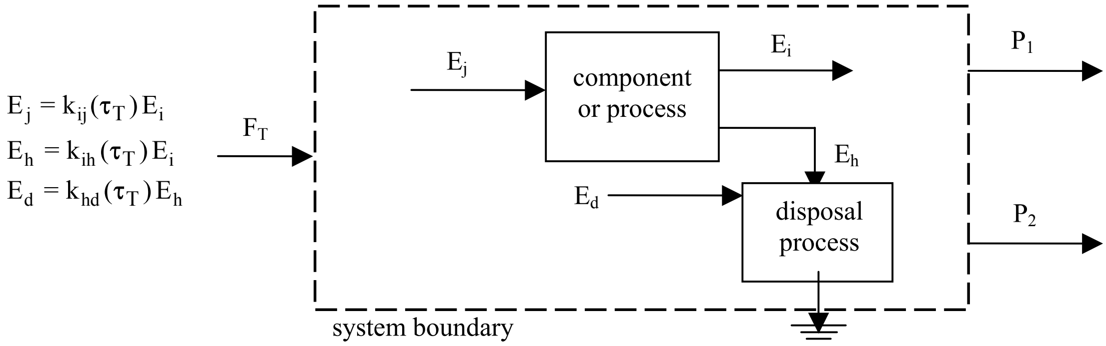


Figure 3. The local model of a multi-product component with a residue.

The flow E_h is introduced as the independent variable of the disposal process. Notice that in this case the cost k_h^* expresses the disposal exergy cost. If k^*_d is supposed to be positive, from the unit exergy cost equation it can be easily obtained that:

$$k_h^* \equiv \left(\frac{\partial F_T}{\partial E_h}\right)_{\tau_{T\text{-}1}} = k_d^* k_{hd} > 0 \tag{13}$$

$$k_i^* \equiv \left(\frac{\partial F_T}{\partial E_i}\right)_{t_{T\text{-}1}} = k_j^* k_{ij} + k_d^* k_{hd} k_{ih} \tag{14}$$

The last equation shows that the cost of the actual component product is charged with the disposal cost of the residual flow.

4.2 By-product:

The idea is that flow E_e is a fuel for a down stream process and it can be partially replaced with the by-product E_h (*Figure 4*). The flow E_h and E_s are introduced as two independent variables of the node where these two flows simply merge, without dissipation, so that E_e is simply the difference $E_s – E_h$. In this case it follows:

$$k_h^* \equiv \left(\frac{\partial F_T}{\partial E_h}\right)_{\tau_{T\text{-}1}} = -k_e^* < 0 \tag{15}$$

$$k_i^* \equiv \left(\frac{\partial F_T}{\partial E_i}\right)_{\tau_{T\text{-}1}} = k_j^* k_{ij} - k_e^* k_{ih} \tag{16}$$

In this case the cost of the actual component product is discharged of the saved cost for the fuel of the down stream process. In other words, the unit exergy costs of the dependent output from a multi-product component has to be inferred from the additional exergy consumed or saved by the component receiving that flow. Notice that this is a result of the local independent variables choice, not an axiom introduced by the Analyst, and can be regarded as the mathematical basis of the *cost formation process of residues and by-products*.

Residue and by-product concepts are widely used when thermoeconomic methods are applied to power plants: notice that if all multi-product components can be described as components with only one actual product and one (or more) residue or by-product, the unit exergy consumptions can still be calculated as simple ratios, i.e. from a measure of the exergy flows, while the expressions for the *Characteristic Equation*, the Fuel Impact relation and the unit exergy cost vector are always the same.

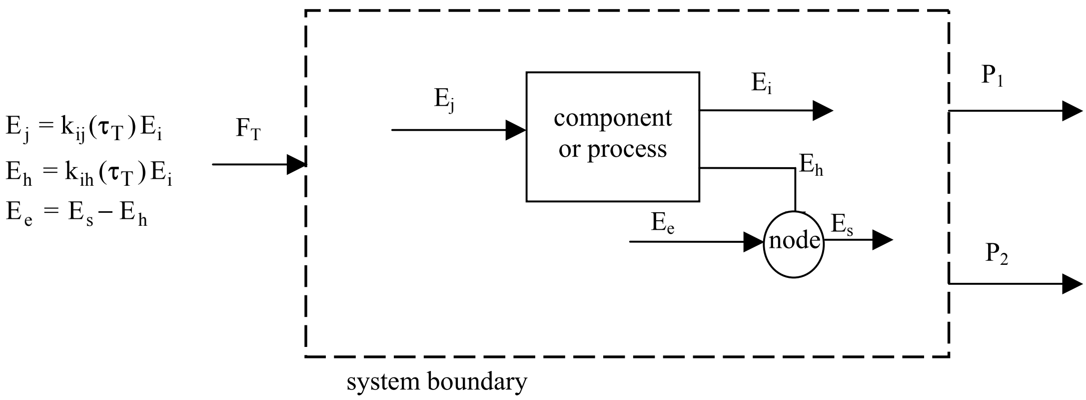


Figure 4. The local model of a multi-product component with a by-product.

5. Diagnostic Procedure

When the Fuel Impact relation is used as a diagnostic tool, the goal is to obtain that:

- The costs of malfunction of components with no functional decay are all equal to zero.
- The cost of malfunction of each component affected by a functional decay is equal to the actual additional fuel consumption the component is responsible for, i.e. to the potential exergy saving obtained if the reference condition were restored in that component.

To approach this objective, proper definition of control volumes and of productive structure flows are required, as well as a correct definition of reference condition for the plant.Unfortunately this is not enough to prevent induced malfunction, so that induced malfunction evaluation becomes a crucial step in the use of the Fuel Impact relation as a diagnostic tool to detect the true causes of malfunction.

To detect induced malfunction, let's think to the global model of the plant and to the local models of its components, previously outlined, and to fix ideas, let's consider single-product components only inside the PS (the same considerations still holds, with simple formal extensions, for multi-product components too).

From the point of view of the global model, induced malfunction is the effect of independent variables τ_T, affecting the *cost of malfunction* of one or more components, besides the one in which the anomaly has appeared.

Nevertheless, from the point of view of the local model of a component, induced malfunction is the effect of *local* independent variables. Let's recall that one of these local independent variables has been replaced with the "product" E_i of the component. If this is the only degree of freedom (let's name this hypotheses as hypotheses i) of the component in the reference condition, being all further degrees of freedom related to the functional decay of that component, induced malfunction can be completely evaluated by means of the partial derivatives:

$$\frac{\partial k_{ij}(E_i, \tau_{T\text{-}1})}{\partial E_i} \equiv \partial_P k_{ij} \Rightarrow (MF_i^*)_P = \sum_j k_j^* \partial_P k_{ij} E_i \quad (17)$$

In the formulation of the Thermoeconomic Theory the hypothesis (named hypotheses ii) that k_{ij} does not depend on E_i is often implicitly or explicitly introduced, so that the dependence of k_{ij} on the product E_i is neglected.

If this couple of hypotheses (i + ii) were true, all partial derivatives in the previous equation would be equal to zero and the induced malfunction effect would disappear. In this case all additional exergy losses, induced inside the control volumes of the no-malfunction components, would be taken into account through the set of unit exergy costs $\mathbf{k}^*$ appearing into the expression of the *cost of malfunction* MF_i^*.

For the plant in hand, k_{ij} depends not only on the product E_i, but the local model of each component has more that one degree of freedom. In fact a material stream of fixed composition has typically three degrees of freedom (for instance h, s, m). This means that a complete detection of induced malfunction can be performed only by introducing for each component a number of local independent variables equal to the number of actual degrees of freedom and by evaluating their effects on each *cost of malfunction* MF_i^*.

Nevertheless, the expectation is that the use of exergy flow E_i, instead of the mass flow m, or of the product h•m related to some material stream inside each component, leads to more complete (or less incomplete) information about off design components behaviour.

In this application, only the dependence of MF_i^* on the product E_i is considered in order to identify induced malfunction inside the fuel impact terms.

In practical cases, the dependence of MF_i^* on the product E_i is not known analytically for each component. It can be inferred from an historical data base of the plant monitoring system, by extracting a set of operating conditions characterized by: i) the same ambient conditions of the analyzed case, ii) various production level for each component, iii) all components in non-malfunctioning conditions.

Note that, following this approach, the production level measured in the malfunctioning condition may be not-possible for some components. This fact can limit the size of component degradation that can be dealt with historical data only. Larger degradations would be dealt with if the dependence of MF_i^* on the product E_i were not obtained from plant behaviour, but from separate simulation of each component.

From all these consideration jointly with Authors' experience, the following "rules" can be inferred:

1) If MF_i^* is negative, it is probably an effect of induced malfunction.

2) If MF_i^* is very close to / smaller than $(MF_i^*)_P$, it is the effect of induced malfunction.

3) If MF_i^* related to a Junction is not equal to zero, it is the effect of induced malfunction because inside Junctions control volumes there are no exergy losses.

6. Example and Results

As an example, the TADEUS test case is considered, three different component malfunctions are simulated and the related three fuel impacts are calculated.

The TADEUS test case is based on a combined cycle power plant made up of two gas turbines, two HRSG and one steam turbine. Details about the plant and its control system are given in Valero et al. (2003), in *Figure 5* a partial schematic of the plant.

Three fuel impacts are calculated as a consequence of functional decay of three different components inside the first group of the Tadeus model:

- Filter Fouling at compressor inlet, causing a decrease of compressor inlet pressure;
- (B)Gas turbine efficiency degradation;
- High pressure super heater fouling, causing a decreased heat transfer between flue gas and steam. To avoid the need of separate component simulations, the size of the each degradation has been limited, obtaining a cost of malfunction always lower to 500 kW.

The numerical results are shown in TABLES I to III, where components are grouped in blocks. The columns show the cost of malfunction if the component production level, measured in the malfunctioning condition, were reached with all components in non-malfunctioning conditions, $(MF_i^*)_P$, the actual cost of malfunction obtained from the fuel impact relation MF_i^*, and some comments according to the rules a, b, c discussed above.

The total of terms $(MF_i^*)_P$ is not considered because they can be related to different operating conditions of the plant.

In the case (A) the intrinsic malfunction is detected inside the block TG1 and its amount is evaluated in 166 kW. All other blocks show induced malfunctions only; in addition the sum of all these induced malfunctions is about zero. In particular intrinsic malfunction is originated inside the stack control volume, where the pressure losses across the filter are located, whereas in the other components of the block malfunctions are classified as induced, according to the rules discussed above.

These results clearly detect the functional decay simulated in the test.

Case (B) is not very different from (A): the intrinsic malfunction is detected inside only one block (TG1) and its amount is evaluated in 424 kW. All other blocks show induced malfunctions only and the sum of all these induced malfunctions is about 21 kW. In particular intrinsic malfunction is originated inside the gas turbine control volume, which is the component affected by functional decay in the simulation test.

In case (C), three blocks show a possible intrinsic malfunction. But HRSG1 only presents an important value at both component and block levels (65 kW). The block TG1 shows a small possible intrinsic malfunction (15 kW), which is completely due to the stack control volume.

Inside the block STEAM, the low pressure turbine only shows a small possible intrinsic malfunction (14 kW). From this situation it can be inferred that the actual malfunction component is a heat exchanger of the high pressure circuit inside the HRSG1 control volume, while total malfunction inside other blocks (33 kW) has to be regarded as induced.

7. Conclusions and Perspectives

The fuel impact formula is a thermoeconomic tool for identifying components responsible for losses increments, in comparison with reference or design condition, and for quantifying energy- recovery if design conditions were restored in a particular component.

Starting from the three malfunction tests presented here, the following conclusions can be inferred:

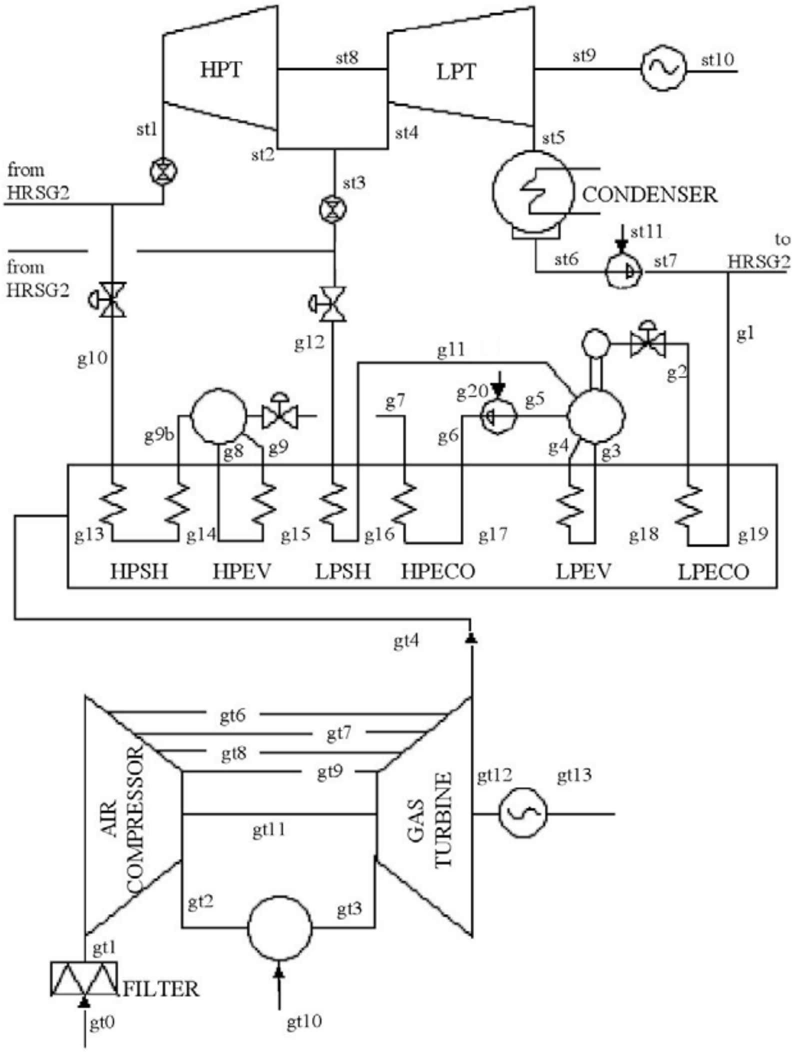
The components actually affected by functional decay and responsible for additional losses can be identified with a good confidence, at both block and control volume level.

This result can not be obtained on the basis of exergy analysis only, because of the well-known non-equivalence of losses.

Unit exergy consumptions (k_{ij}) result to be strongly dependent from the products (E_i), so that meaningful results could not be obtained without taking account of the dependence of MF_i^* on the product E_i through partial derivatives $\partial_P k_{ij}$.

In cases like this, the main effort has to be devoted to detect induced malfunction, while other strategies to improve the Productive Structure, like exergy splitting, or re-allocation of the malfunction cost related to the Junctions (Reini and Taccani, 2002), do not generally allow important improvements in the diagnosis. The situation may be different dealing with other kinds of power plants.

Nevertheless, in the case (C), Authors' expectation is that a revised definition of flows and control volumes, at the limits between



gt0 Ambient
gt1 Inlet compressor
gt2 Outlet compressor
gt3 Inlet turbine
gt4 Outlet turbine
gt5 Outlet HRSG
gt6 Refrigeration 4° stage turbine
gt7 Refrigeration 3° stage turbine
gt8 Refrigeration 2° stage turbine
gt9 Refrigeration of the rotor
gt10 Fuel
gt11 Mechanical power compressor
gt12 Mechanical power turbine
gt13 Electric power
st1 Inlet high pressure turbine
st2 Outlet high pressure turbine
st3 Low pressure steam
st4 Inlet low pressure turbine
st5 Outlet low pressure turbine
st6 Outlet condenser
st7 Outlet extraction pump
st8 Mechanical power HP turbine
st9 Total mechanical power turbine
st10 Electric power steam turbine
st11 Electric power extraction pump
g1 Inlet low pressure economizer
g2 Outlet low pressure economizer
g3 Inlet low pressure evaporator
g4 Outlet low pressure evaporator
g5 Inlet circulation pump
g6 Inlet high pressure economizer
g7 Outlet high pressure economizer
g8 Inlet high pressure evaporator
g9 Outlet high pressure evaporator
g9b Inlet high pressure super-heater
g10 Outlet high pressure super-heater
g11 Outlet low pressure super-heater
g12 Inlet low pressure super-heater
g13 Gas inlet h.p. super-heater
g14 Gas inlet h.p. evaporator
g15 Gas inlet l.p. super-heater
g16 Gas inlet h.p. economizer
g17 Gas inlet l.p. evaporator
g18 Gas inlet l.p. economizer
g19 Gas outlet HRSG
g20 Electric power circulation pump

Figure 5. A partial schematic of the tadeus test case power plant.

TABLE I. COST OF MALFUNCTION [KW] IN CASE (A) FILTER FOULING.

	$(MF_i^*)_P$	MF_i^*	Ex.losses	Comments[(0)]
TG 1				
Combustor	–354,24	-645,11		Induced (a + partially b)
Stack[(1)]	–281,88	855,03		INTRINSIC
Compressor	85,84	40,10		Induced (b)
J1[(2)]	20,16	62,77		Induced (partially b + c)
Gas Turbine	–122,75	–146,23		Induced (a + b)
Alternator	–0,73	–0,73		Induced (a + b)
		165,83	**135,86**	**INTRINSIC**
TG 2				
Combustor	–105,55	-105,55		Induced (a + b)
Stack[(1)]	123,25	113,58		Induced (b)
Compressor	102,32	102,32		Induced (b)
J1[(2)]	–0,27	–0,27		Induced (a + b + c)
Gas Turbine	–115,74	–115,74		Induced (a + b)
Alternator	–0,73	–0,73		Induced (a + b)
		–6,38	**54,4423**	**INDUCED**
HRSG 1				
HP circuit	169,54	170,48		Induced (b)
LP circuit	–159,92	–161,64		Induced (a + b)
		8,84	**–15,827**	**INDUCED**
HRSG 2				
HP circuit	171,46	171,04		Induced (b)
LP circuit	–160,94	–160,91		Induced (a + b)
		10,13	**–15,316**	**INDUCED**
STEAM				
J2[(3)]	–0,32	–0,32		Induced (a + b + c)
HP turbine	–31,84	–31,80		Induced (a + b)
LP turbine	–11,90	–12,29		Induced (a + b)
Condenser	31,34	31,11		Induced (b)
Extraction pump	–0,67	–0,67		Induced (a + b)
J4[(4)]	1,30	1,46		Induced (b + c)
Alternator	–1,53	–1,60		Induced (a + b)
		–14,09	**6,4917**	**INDUCED**
J3[(5)]	0,00	1,23		Induced (c)
Total		**165,56**	**165,65**	

(0) The letters a, b and c refer to the “rules” in the text.
(1) Including Heat and pressure losses across the stack and the Air filter.
(2) Including all terms related to fictitious junction inside the Block TG.
(3) Including all terms related to fictitious junction inside the Block STEAM.
(4) Steam turbine product junction.
(5) Including all terms related to junction outside the Blocks.

HRSGs and STEM blocks, would lead to an easier identification of the real malfunction. A complete detection of induced malfunction can be performed only by introducing for each component a number of local independent variables equal to the number of actual degrees of freedom and by evaluating their effects on each cost of malfunction MF_i^*. Some temperatures are especially recommended in cases (A) and (C), like the gas outlet temperature from HRSGs, to highlight induced malfunction inside the stack control volume.

In case of simultaneous functional decay of more than one component, it would be difficult to quantify energy- recovery, related to design conditions restoration in a particular component, even if induced malfunction were completely discovered. This is because induced malfunction does not explicitly contain the information about the component responsible for, as intrinsic malfunction does. This fact highlights the importance of a proper Productive Structure definition, reducing at the minimum level the interdependence among unit exergy consumptions, and therefore the induced malfunction effects. The highlighted dependence of unit exergy consumptions (k_{ij}) from the products (E_i) suggests the idea of re-formulating the *Characteristic Equation* of the plant Thermo-economic Model, by introducing a linear (instead of proportional) relation among the product (E_i) and the fuels (E_j, E_y) of each component. In this case the unit exergy consumptions would be replaced by the derivatives

$$\lambda_{ij} \equiv \frac{\partial f^{+}_{ij}(E_i, \tau_{T-1})}{\partial E_i}; \quad \lambda_{iy} \equiv \frac{\partial f^{+}_{iy}(E_i, \tau_{T-1})}{\partial E_i} \qquad (18)$$

These linear approximations are only slightly affected by small modifications of the production level of the component (in the proximity of the reference condition), whatever the mathematical form of the relations f_{ij} and f_{iy} is. In this way, a more stable (less interdependent) set of values is expected to be obtained.

On the other hand, the fuel impact relation would become more complicated, because of the effect of the constant terms introduced to describe the linear relations among products and the fuels. This new approach is object of present investigation.

TABLE II. COST OF MALFUNCTION [KW] IN CASE (B)
GAS TURBINE EFFICIENCY DEGRADATION.

	$(MF_i^*)_P$	**MF_i^***	**Ex.losses**	**Comments**
TG 1				
Combustor	–779,90	–1376,99		Induced (a + partially b)
Stack(1)	509,18	1628,99		Partially induced (b)
Compressor	77,78	85,16		Induced (b)
J1(2)	43,27	13,04		Induced (c)
Gas Turbine	–125,81	74,80		INTRINSIC
Alternator	–0,73	–0,74		Induced (b)
		424,26	**316,14**	**INTRINSIC**
TG 2				
Combustor	–243,89	–243,93		Induced (a + b)
Stack(1)	287,26	264,13		Induced (b)
Compressor	95,94	95,94		Induced (b)
J1(2)	9,16	9,16		Induced (b + c)
Gas Turbine	–121,60	–121,61		Induced (a + b)
Alternator	–0,73	–0,73		Induced (a + b)
		2,96	**123,66**	**INDUCED**
HRSG 1				
HP circuit	124,82	164,08		Induced (b)
LP circuit	–157,72	–161,29		Induced (a + b)
		2,79	**–14,92**	**INDUCED**
HRSG 2				
HP circuit	169,59	166,76		Induced (b)
LP circuit	–160,09	–159,83		Induced (a + b)
		6,93	**–16,74**	**INDUCED**
STEAM				
J2(3)	–0,44	–0,35		Induced (a + b + c)
HP turbine	–31,37	–29,50		Induced (a + b)
LP turbine	–17,40	–16,84		Induced (a + b)
Condenser	50,30	49,33		Induced (b)
Extraction pump	–0,67	–0,67		Induced (a + b)
J4(4)	5,78	3,20		Induced (c)
Alternator	–1,59	–1,59		Induced (a + b)
		3,58	**37,59**	**INDUCED**
J3(5)		4,74		Induced (c)

TABLE III. COST OF MALFUNCTION [KW] IN CASE (C)
HIGH PRESSURE SUPER HEATER FOULING.

	$(MF_i^*)_P$	MF_i^*	Ex.losses	Comments
TG 1				
Combustor	–71,23	–71,22		Induced (a + b)
Stack(1)	–94,65	69,97		INTRINSIC (?)
Compressor	103,89	103,88		Induced (b)
J1(2)	–2,60	–2,60		Induced (a + b + c)
Gas Turbine	–114,28	–114,27		Induced (a + b)
Alternator	–0,73	–0,73		Induced (a + b)
		–14,98	**28,11**	**INTRINSIC** (?)
TG 2				
Combustor	–71,23	–71,24		Induced (a + b)
Stack(1)	123,25	77,72		Induced (b)
Compressor	103,89	103,90		Induced (b)
J1(2)	–2,60	–2,60		Induced (a + b + c)
Gas Turbine	–114,28	–114,28		Induced (a + b)
Alternator	–0,73	–0,73		Induced (a + b)
		–7,23	**39,45**	**INDUCED**
HRSG 1				
HP circuit	175,41	234,86		INTRINSIC / Part. Ind. (b)
LP circuit	–163,52	–169,81		Induced (a + b)
		65,05	**19,89**	**INTRINSIC**
HRSG 2				
HP circuit	173,39	169,01		Induced (b)
LP circuit	–161,06	–160,79		Induced (a + b)
		8,22	**–17,16**	**INDUCED**
STEAM				
J2(3)	–0,31	–0,43		Induced (a + b + c)
HP turbine	–22,84	–7,26		Induced (a)
LP turbine	–6,49	14,48		INTRINSIC
Condenser	35,07	59,30		Induced (b)
Extraction pump	–0,67	–0,67		Induced (a + b)
J4(4)	–14,00	1,45		Induced (c)
Alternator	–1,65	–1,61		Induced (a + b)
		65,27	**27,30**	**INTRINSIC** (?)
J3(5)	0,00	–18,52		Induced (c)
Total		**97,80**	**97,58**	

Nomenclature

E	vector of exergy flows [kW];
E_{ij}	flow of the productive structure [kW];
F	fuel;
f	generic function;
h	specific enthalpy;
$\mathbf{k}^*$	exergy cost vector;
k_{ij}	unit exergy consumption;
K	matrix of unit exergy consumption;
m	mass flow rate;
MF*	malfunction cost [kW];
P_i	product of the i^{th} component [kW];
$\mathbf{U}_D$	unit matrix;
λ	linear approximation coefficient;
τ	vector of independent variables;
ω	vector of system output exergy flows;

Subscripts

e	coming from outside the plant;
ref	reference condition;
T	total

References

Lozano M. A., Bartolome J. L., Valero A. and Reini M., 1994, “Thermoeconomic Diagnosis of Energy Systems”, *Proceedings of the third Florence World Energy Research Symposium*, Florence, July.

Reini M., 1994, “Analisi e Sviluppo dei Metodi Termoeconomici per lo studio degli Impianti di Conversione dell'Energia”, Ph.D. Thesis, University of Padova, Italy

Reini M., Giadrossi A., 1994, “On the costs of products in multi-task systems: theoretical development and application to a cogeneration engine”, *Proceedings of the third Florence World Energy Research Symposium*, Florence, July.

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.

Reini M., Tacani R., 2002. “On Energy Diagnosis of Steam Power Plants: A Comparison among three Global Losses Formulation”, *Int. J. of Applied Thermodynamics*, Vol.5 No.4 pp. 177-188.

Reini M., Tacani R., 2002. “Improving the Energy Diagnosis of Steam Power Plants Using the Lost Work Impact Formula”, *Int. J. of Applied Thermodynamics* Vol.5, No4 pp. 189-202.

Reini M., Valero A., 2002. “Towards a Unified Formulation of Exergy Cost Theory and Emergy Algebra for Ecological and Technological Energy System Evaluation”, *Proceedings of the third Int. Workshop on Advances in Energy Studies*, Porto Venere.

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

Valero A., Correas L., Lazzaretto A., Rangel V., Reini M., Taccani R., Toffolo A., Verda V., Zaleta A., 2004, “Thermoeconomic Philosophy Applied to the Operating Analysis and Diagnosis of Energy Utility Systems”, Int. J. of Thermodynamics, Vol.7, No.2, pp. 33-39.

Valero A., Correas L., Rangel V., Zaleta A., Lazzaretto A., Verda V. Reini M. (2002) “On the Thermoeconomic Approach to the Diagnosis of Energy Systems Malfunction Part-2 Malfunction Definitions and Assessment; proceedings of Efficiency, Costs, Optimization and Simulation of Energy Systems”, *Proceedings of* ECOS 2002, Berlin, Germany.

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, Part III: Energy Savings and Thermoeconomics”, *Computer-Aided Engineering of Energy System*, A.S.M.E. W.A.M., AES- Vol. 2-3, pp.1-21.

Valero A., Torres C. and Lozano M. A., 1990, “On Causality in Organized Energy Systems: - Part II: Symbolic Exergoeconomics; Part III: Theory of Perturbations”, Proceedings of FLOWERS 90, Florence,.

Valero A., Serra L. and Lozano M. A., 1993, “Structural Theory of Thermoeconomics”1, Thermodynamics and the Design, Analysis and Improvement of Energy System, ASME, AES-Vol.30/HTD-Vol.266, Richter H. J. Ed., N.Y.

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 92, Zaragoza.

von Spakovsky, M R, 1986, “A Practical Generalized Analysis Approach to the Optimal Thermoeconomic Design and Improvement of Real World Thermal Systems”, PhD Thesis, Georgia Intitute of Technology