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Application of Quantitative Causality Analysis to the Quantification of Intrinsic and Induced Effects in the Thermoeconomic Diagnosis of a Coal-fired Power Plant*

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Abstract

The aim of thermoeconomic diagnosis is to detect malfunctioning components in thermal systems and to quantify the additional fuel consumption caused by each these components. Thermoeconomics provides tools for this task such as malfunctions, malfunction costs and fuel impact formula, whose applicability to real examples may be difficult due to induced effects. On the other hand, the quantitative causality analysis is a diagnosis method based on a thermodynamic description of the system. In this paper, both approaches are integrated by applying the quantitative causality analysis to perform a systematic quantification of intrinsic and induced effects. The formulation is successfully applied to a coal-fired power plant.

Keywords: thermoeconomic diagnosis, malfunctions, quantitative causality analysis.

1. Introduction

Thermoeconomics is based on the combination of thermodynamics and economics with the aim of improving energy intensive systems. Besides the development of efficient devices and thermal systems, there is a large potential of savings in the proper maintenance and operation of existing plants. In this framework, the aim of thermoeconomic diagnosis is to analyse the operation of thermal systems in order to detect malfunctioning components and to quantify the additional fuel consumption caused by each of these components (Valero et al., 2004a, b). A different type of diagnosis is mechanical condition diagnosis, aimed at the detection of failures that can cause component breaking and, perhaps, plant shut-off.

A basic tool for thermoeconomic diagnosis is the fuel impact formula, which relates the variation of fuel consumption of a system with the variation of unit exergy consumption (characterizing the efficiency of the components) and the variation of final product. It was suggested by Valero et al. (1990, 1999) and developed by Reini (1994), Lozano et al. (1994) and Torres et al. (1999).

An increment of irreversibility in a component (malfunction) causes an increment in the exergy consumption of that component. Each malfunction implies an additional amount of fuel which is called malfunction cost. The advantage of unit exergy consumptions as indicators of components behaviour is that they are homogeneous for all types of components. Their disadvantage appears because they are not always able to represent the physical behaviour. Due to this fact, when a component is damaged, besides an intrinsic malfunction in it, induced malfunctions may appear in other components.

The presence of induced malfunctions is the main drawback in the application of Thermoeconomic analysis in the diagnosis problem. Due to the importance of this task, the TADEUS initiative was launched as a common test-bench for several diagnosis methodologies. In the first paper (Valero et al., 2004a), the diagnosis problem is stated and a practical example is proposed. In the second paper (Valero et al., 2004b), the main tools and concepts provided by Thermoeconomics are summarized.

Verda (2004) has developed a methodology based on the filtration of effects induced by the control system. Reini and Taccani (2004) proposed to calculate the cost of malfunction induced by fuel variation.

After making a critical review of thermoeconomic diagnosis methodologies, Lazzaretto and Toffolo (2006) concluded that thermoeconomic variables were not enough to distinguish intrinsic and induced effects, and thermodynamic variables were also needed. These authors have also analysed the use of several indicators to identify the component where anomalies occur, and propose to use the irreversibility of the component corrected by using the variation of local thermodynamic variables (Toffolo and Lazzaretto, 2004).

Valero et al. (1999) have proposed to use a simulator in order to calculate the effect of the variation of an operating parameter x_r on a unit exergy consumption. This allows to decompose malfunctions into two terms, intrinsic and induced, depending on whether the operating parameters are associated with the analysed component or not.

Other authors avoid the use of thermoeconomic models and calculate directly the influence of the independent thermodynamic variables of the system on a global indicator. To diagnose the TADEUS problem, Zaleta and Muñoz (2004) proposed the use of a simulator and Correas (2004) used a diagnosis algorithm which does not need a fine tuned simulator. This algorithm has been also applied

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to a combined cycle (García Peña et al., 2001) and a coal fired power plant (Usón et al., 2006). It is the origin of the quantitative causality analysis (Usón et al., 2007).

Quantitative causality analysis and thermoeconomic analysis have been connected in a formulation based on the application of the first method to decompose the variation of unit exergy cost and final product (Usón and Valero, 2007). In this paper, the formulation is extended in order to be able to deal with productive structures including wastes (Torres et al., 2006, Rangel, 2005) and to provide exact results. Furthermore, the method is applied to a real example of diagnosis.

2. Connection of Quantitative Causality Analysis and Thermoeconomic Analysis

2.1. Quantitative Causality Analysis

A thermal system can be described by a set of n_t thermodynamic variables ($\boldsymbol{x}$): pressures, temperatures, flow rates, compositions and indicators of components' behaviour. n_d of these variables are considered as "free diagnosis variables": ambient conditions, set-points, indicators of fuel quality and indicators of components' behaviour. Finally, a global efficiency indicator e (heat rate or plant efficiency) is considered. The objective of the method is to compare two situations, actual and reference, characterized by $\boldsymbol{x^1}$ and $\boldsymbol{x^0}$ and to decompose the variation of e into a summation of terms each one corresponding to a free diagnosis variable.The first step is to introduce a set of n_r independent restrictions ($n_r=n_t - n_d$). If these relations are linearized, it is possible to write:

$$\mathbf{JD}\cdot\Delta\mathbf{x}\cong\begin{bmatrix}\mathbf{0}\\ \Delta\mathbf{x_d}\end{bmatrix} \tag{1}$$

where $\boldsymbol{JD}$ is a matrix containing the linearized restrictions and the definitions of the free diagnosis variables. If it is inverted, the variation of all variables is related to the variation of the free diagnosis variables:

$$\Delta\mathbf{x}\cong\mathbf{JD}^{-1}\cdot\begin{bmatrix}\mathbf{0}\\ \mathbf{U}\end{bmatrix}\cdot\Delta\mathbf{x}_d \tag{2}$$

Besides, e is a function of $\boldsymbol{x}$, so that it is possible to write:

$$\Delta e\cong\sum_{m=1}^{n_t}\frac{\partial e}{\partial x_m}\cdot\Delta x_m=\mathbf{ex}^t\cdot\Delta\mathbf{x} \tag{3}$$

Finally, Eqs. (2) and (3) can be combined to obtain the desired decomposition of Δe:

$$\Delta e=\mathbf{ex}^t\cdot\mathbf{JD}^{-1}\cdot\begin{bmatrix}\mathbf{0}\\ \mathbf{U}\end{bmatrix}\cdot\Delta\mathbf{x}_d+e^{res}=\mathbf{ed}^t\cdot\Delta\mathbf{x}_d+e^{res} \tag{4}$$

where the term e^{res} has been introduced in order to keep the relation exact. In a previous paper (Usón et al., 2007), the method is presented in detail and the error caused by linearization is studied for a large amount of actual operation points. It is proved that when $\boldsymbol{JD}$ and $\boldsymbol{ex}$ matrices are calculated by averaging their values in $\boldsymbol{x^0}$ and $\boldsymbol{x^1}$, the residual term is very low.

2.2. Malfunctions and Fuel Impact in Productive Structures Including Waste Flows

The same thermal system considered in the previous section can be described by a thermoeconomic model comprising n components connected by exergy flows. When one unit exergy consumption associated with a component i (the relation between fuel coming from j and the product) increases, there is an increment of the irreversibility of that component, which is called malfunction:

$$MF_{ji}=\Delta\kappa_{ji}\cdot P_i\left(\mathbf{x}^0\right) \tag{5}$$

The total malfunction of the component is calculated by summation:

$$MF_i=\Delta k_i\cdot P_i\left(\mathbf{x}^0\right)=\sum_{j=1}^{n}MF_{ji} \tag{6}$$

Each malfunction has an increment of the fuel needed by the thermal system to keep production constant, which is called malfunction cost:

$$MF_{ji}^*=k_{P,j}^*\left(\mathbf{x}^1\right)\cdot MF_{ji} \tag{7}$$

$$MF_i^*=\sum_{j=0}^{n}MF_{ji}^* \tag{8}$$

The previous equations correspond to productive flows. However, there are other flows (such as gases leaving the stack or heat dissipated in a condenser) which are necessary for the operation of the thermal system but do not have a productive purpose. These flows are called wastes or residues (Torres et al., 2006, Rangel, 2005), and have to be charged to the component where they have been produced. For example, the cost of flue gases leaving the stack should be charged to the combustion process, and the cost of heat dissipated in a condenser is usually shared according to the entropy produced in the different components of the steam cycle.Consequently, the productive structure has to be enlarged in order to include these issues. A waste flow produced in a component i and charged to the component j is represented as R_{ij}. So that, it is possible to define unit exergy consumptions associated with the wastes:

$$\theta_{ij}=\frac{R_{ij}}{P_j} \tag{9}$$

Costs associated with residues are calculated as:

$$k_{Rij}^*=\frac{R_{ij}^*}{R_{ij}} \tag{10}$$

The variation of these unit exergy consumptions entails malfunctions associated with the wastes:

$$MR_{ji}=\Delta\theta_{ji}\cdot P_i\left(\mathbf{x}^0\right) \tag{11}$$

$$MR_i=\Delta\theta_i\cdot P_i\left(\mathbf{x}^0\right)=\sum_{j=0}^{n}MR_{ji} \tag{12}$$

These malfunctions have their corresponding malfunction costs:

$$MR_{ji}^*=k_{PR,j}^*\left(\mathbf{x}^1\right)\cdot MR_{ji} \tag{13}$$

$$MR_i^* = \sum_{j=0}^{n} MR_{ji}^* \tag{14}$$

In a productive structure where both productive flows and wastes have been defined, the fuel impact can be calculated by a summation of all malfunction costs:

$$\Delta F_T = \sum_{i=0}^{n} MF_i^* + \sum_{i=1}^{n} MR_i^* \tag{15}$$

where the term MF_0^* correspond to the increment of plant products ($\Delta\omega_i$):

$$MF_0^* = \sum_{i=1}^{n} k_{P,i}^* \left(\mathbf{x}^1\right) \cdot \Delta\omega_i \tag{16}$$

2.3. Application of Quantitative Causality Analysis to the Determination of Intrinsic and Induced Malfunctions

The formulation presented in the previous section has the advantage of being homogeneous and provides directly the relation between variation in components behaviour and fuel impact. However, as said in the introduction, unit exergy consumptions are not always suitable indicators for describing components' behaviour, so that problems of induced effects appear. For this reason, methods based on the thermodynamic representation of the system, such as that one presented in section 2.1, usually provide better results in practical applications. In this section, both approaches are connected. The goal is to take advantage of the ability of quantitative causality analysis to reproduce the physical behaviour and apply it to determine the intrinsic and induced malfunctions.

Quantitative causality analysis is used to decompose a global efficiency indicator (*e*) only for convenience; it may be possible to use it for decomposing any variable which depends on the set of thermodynamic variables $\boldsymbol{x}$. Thus, the idea is to apply quantitative causality analysis to decompose the independent variables of thermoeconomic analysis: κ_{ij}, θ_{ij} and ω_i. Since they are exergies or quotients between them, they depend on $\boldsymbol{x}$, so that it is possible to write:

$$\Delta\kappa_{ij} \cong \sum_{m=1}^{n_t} \frac{\partial\kappa_{ij}}{\partial x_m} \cdot \Delta x_m = \mathbf{kx^{ij,t}} \cdot \Delta\mathbf{x} \tag{17}$$

$$\Delta\theta_{ij} \cong \sum_{m=1}^{n_t} \frac{\partial\theta_{ij}}{\partial x_m} \cdot \Delta x_m = \mathbf{tx^{ij,t}} \cdot \Delta\mathbf{x} \tag{18}$$

$$\Delta\omega_i \cong \sum_{m=1}^{n_t} \frac{\partial\omega_i}{\partial x_m} \cdot \Delta x_m = \mathbf{wx^{i,t}} \cdot \Delta\mathbf{x} \tag{19}$$

If Eq. (2) is substituted in the previous equations, the decomposition is achieved:

$$\Delta\kappa_{ij} = \mathbf{kx^{ij,t}} \cdot \mathbf{JD}^{-1} \begin{bmatrix} 0 \\ \cdot \\ U \end{bmatrix} \cdot \Delta\mathbf{x}_d + \kappa_{ij}^r = \sum_{q=1}^{n_d} \kappa_{ij}^q + \kappa_{ij}^r \tag{20}$$

$$\Delta\theta_{ij} = \mathbf{tx^{ij,t}} \cdot \mathbf{JD}^{-1} \begin{bmatrix} 0 \\ \cdot \\ U \end{bmatrix} \cdot \Delta\mathbf{x}_d + \theta_{ij}^r = \sum_{q=1}^{n_d} \theta_{ij}^q + \theta_{ij}^r \tag{21}$$

$$\Delta\omega_i = \mathbf{wx^{i,t}} \cdot \mathbf{JD}^{-1} \begin{bmatrix} 0 \\ \cdot \\ U \end{bmatrix} \cdot \Delta\mathbf{x}_d + \omega_{ij}^r = \sum_{q=1}^{n_d} \omega_{ij}^q + \omega_{ij}^r \tag{22}$$

where κ_{ij}^r, θ_{ij}^r and ω_{ij}^r have been introduced to keep the relation exact.

Once unit exergy consumptions and plant products have been decomposed into a summation of terms induced by all free diagnosis variables and a residual term, it is possible to decompose also malfunctions only by substituting Eqs. (20) and (21) into Eqs. (5) and (11):

$$MF_{ji} = \left(\sum_{q=1}^{n_d} \Delta\kappa_{ji}^q + \kappa_{ji}^r \right) \cdot P_i\left(\mathbf{x}^0\right) = \sum_{q=1}^{n_d} MF_{ji}^q + MF_{ji}^r \tag{23}$$

$$MR_{ji} = \left(\sum_{q=1}^{n_d} \Delta\theta_{ji}^q + \theta_{ji}^r \right) \cdot P_i\left(\mathbf{x}^0\right) = \sum_{q=1}^{n_d} MR_{ji}^q + MR_{ji}^r \tag{24}$$

If the previous equations are substituted in Eqs. (6) and (12) it yields:

$$MF_i = \sum_{q=1}^{n_d} MF_i^q + MF_i^r \tag{25}$$

$$MR_i = \sum_{q=1}^{n_d} MR_i^q + MF_i^r \tag{26}$$

The decomposition can also be extended to malfunction costs:

$$MF_{ji}^* = \sum_{q=1}^{n_d} MF_{ji}^{*,q} + MF_{ji}^{*,r} \tag{27}$$

$$MF_i^* = \sum_{q=1}^{n_d} MF_i^{*,q} + MF_i^{*,r} \tag{28}$$

$$MR_{ji}^* = \sum_{q=1}^{n_d} MR_{ji}^{*,q} + MR_{ji}^{*,r} \tag{29}$$

$$MR_i^* = \sum_{q=1}^{n_d} MR_i^{*,q} + MR_i^{*,r} \tag{30}$$

Besides, the malfunction cost caused by the variation of the product can be decomposed by using Eq. (22):

$$MF_0^* = \sum_{i=1}^{n} \left(\sum_{q=1}^{n_d} k_{P,i}^*\left(\mathbf{x}^1\right) \cdot \Delta\omega_i^q + k_{P,i}^*\left(\mathbf{x}^1\right) \cdot \omega_i^r \right) = \sum_{q=1}^{n_d} MF_0^{*,q} + MF_0^{*,r} \tag{31}$$

Finally, if Eqs. (28), (30) and (31) are substituted in Eq. (15), it can be seen that the fuel impact is the result of a double summation: malfunctions caused by each one of the free diagnosis variables (and the residual term) and malfunctions appearing in the components of the thermoeconomic model (associated with both productive and dissipative flows):

$$\Delta F_T = \sum_{i=0}^{n} \left(\sum_{q=1}^{n_d} \left(MF_i^{*,q} \right) + MF_i^{*,r} \right) + \sum_{i=1}^{n} \left(\sum_{q=1}^{n_d} \left(MR_i^{*,q} \right) + MR_i^{*,r} \right) \tag{32}$$

The previous result can be represented in a table, where each column corresponds to a free diagnosis variable plus a column for the residual term, and the rows are associated with the components of the thermoeconomic model. Each component has one row for productive flows and another one if wastes are charged to it. The previous results are very important because they include the influence of each one of the n_d free diagnosis variables on each one of the n plant components and, finally, on the variation of fuel consumption. However, in a real example, the number of free diagnosis variables can be quite high, so it may be interesting not to include all results separately but to simplify the results by grouping free diagnosis variables in five groups:

1) Intrinsic (*int*): free diagnosis variables corresponding to the component with the same number as the row,
2) Induced by other components (*oc*): free diagnosis, variables describing the behaviour of other components,
3) Induced by ambient conditions (*ac*),
4) Induced by fuel quality (*fq*),
5) Induced by set-points (*sp*).

These results can be summarized in a table of intrinsic and induced malfunctions (MFI) as given in Table 3.

Table 1: Table of Malfunctions Induced by Free Diagnosis Variables (MFD).

$MF_0^{*,1}$	$\cdots$	MF_0^{*,n_d}	$MF_0^{*,r}$	MF_0^*
$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$
$MF_n^{*,1}$	$\cdots$	MF_n^{*,n_d}	$MF_n^{*,r}$	MF_n^*
$MR_1^{*,1}$	$\cdots$	MR_1^{*,n_d}	$MR_1^{*,r}$	MR_1^*
$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$
$MR_n^{*,1}$	$\cdots$	MR_n^{*,n_d}	$MR_n^{*,r}$	MR_n^*
$MF^{*,1}+$ $+MR^{*,1}$	$\cdots$	$MF^{*,n_d}+$ $+MR^{*,n_d}$	$MF^{*,r}+$ $+MR^{*,r}$	ΔF_T

3. Application to a Coal-Fired Power Plant.

In this section, the theory presented is applied. First, the power plant and its physical structure are briefly described. Afterwards, the productive structure is presented. Finally, an example of diagnosis is developed.

3.1 Description and Thermodynamic Model

The Teruel power plant is composed of three pulverised-coal fired units of 350 MWe each. It is owned by Endesa Generación and located in Andorra, in the Spanish region of Aragón. The anamnesis or the repeated diagnosis of this plant during six years can be seen in Usón et al. (2006) and the comparison of quantitative causality analysis with other diagnosis methods such as linear regression and neural networks is developed in Usón et al. (2007).

The thermodynamic model has 47 free diagnosis variables, including ambient conditions (temperature, relative humidity and wind speed), fuel quality (composition and high heating value), set-points (main-steam temperature and pressure, power, and many others) and indicators of the efficiency of components (such as isoentropic efficiency and flow coefficient for turbines, or effectiveness for heat exchangers).

The thermoeconomic model is composed of 14 elements plus the environment (Table 2). The furnace and all heat exchangers of the boiler (except air pre-heaters and coil heaters) have been grouped in only one component. Besides, low pressure water heaters, deaerator and turbo-pump form one single unit. These components are connected according to the productive structure represented in Figure 1. All plant fuel enters to the boiler (6) but there are four plant products, produced by the four turbine sections. There are two waste flows: flue gases (produced in 6 and charged to 5) and heat dissipated in the condenser (11) which is shared according to the fraction of entropy produced in each component.

Table 2. Components of the Thermoeconomic Model.

Comp.	Description
0	Ambient
1	Primary air coil heaters
2	Secondary air coil heaters
3	Primary air pre-heaters
4	Secondary air air pre-heaters
5	Boiler
6	Mixer of flue gases
7	High pressure steam turbine
8	1st intermediate pressure steam turbine
9	2nd intermediate pressure steam turbine
10	Low pressure steam turbine
11	Condenser
12	Low pressure feeding water heaters, deaerator and turbo-pump
13	5th feeding water heater
14	6th feeding water heater

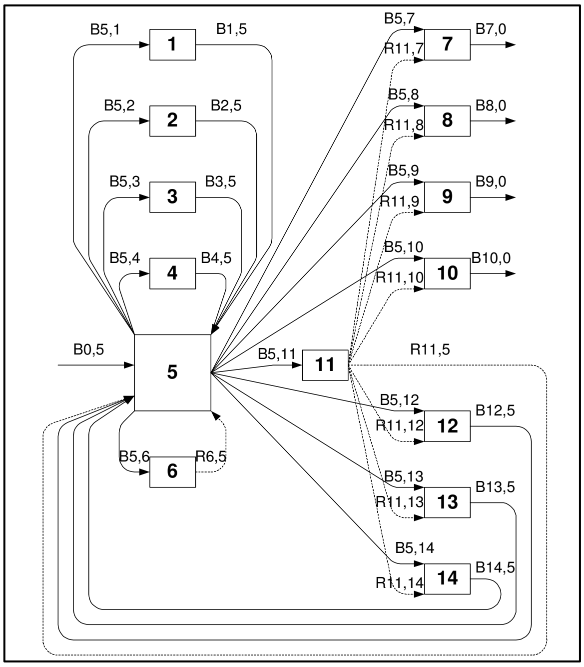

Figure 1. Productive Structure.

3.3. Example of Diagnosis

Operation of unit 1 on April 26th of 2004 at full load (above 320 MW) has been selected as actual case, which is compared with unit 3 on September 17th 2003 at full load (reference case). This comparison is quite representative because most free diagnosis variables vary.

The complete procedure explained in section 2 has been applied according to the productive structure previously presented. The decomposition of unit exergy consumptions of the boiler is shown in Figure 2 where the

Table 3. Table of Intrinsic and Induced Malfunctions, MFI (kW).

	Ambient	Fuel	Set-points	Intrinsic	Induced	Error	Total
MF_0^*	**1223.14**	**-22.659**	**49533.3**	**9650.78**	**-11836.4**	**-2.5492**	48545.6
MF_1^*	**222.653**	**-96.836**	**-35.981**	**0**	**120.975**	**-2.188**	208.623
MF_2^*	**1035.71**	**67.2392**	**166.959**	**0**	**-116.14**	**8.51615**	1162.28
MF_3^*	**-3.6009**	**-1015.8**	**-1265.4**	**1814.81**	**120.651**	**9.79102**	-339.605
MF_4^*	**19.1812**	**2918.05**	**6252.61**	**-6613**	**407.857**	**135.862**	3120.58
MF_5^*	**2952.33**	**254.984**	**-6893**	**3276.61**	**8641.55**	**950.207**	9182.66
MF_6^*	**-0.8266**	**91.0295**	**244.101**	**0**	**-130.852**	**98.2792**	301.731
MF_7^*	**48.5634**	**-0.3782**	**-163.21**	**65.3341**	**-171.924**	**9.59065**	-212.019
MF_8^*	**-0.3597**	**0.87055**	**25.0896**	**-970.14**	**-55.5988**	**-34.133**	-1034.27
MF_9^*	**-6.3476**	**0.59917**	**29.3314**	**3432.97**	**84.1649**	**113.402**	3654.12
MF_{10}^*	**82.5177**	**9.03462**	**-108.73**	**8768.67**	**96.2304**	**-157.01**	8690.71
MF_{11}^*	**7387.96**	**2.63096**	**41.8375**	**-7606.6**	**-343.452**	**-359.85**	-877.461
MF_{12}^*	**379.023**	**-5.3794**	**239.811**	**-660.8**	**601.261**	**-24.316**	529.596
MF_{13}^*	**2.05732**	**10.6732**	**-67.333**	**42.307**	**-204.739**	**-2.0657**	-219.1
MF_{14}^*	**-7.8586**	**2.26523**	**23.019**	**1.88763**	**253.555**	**-2.1588**	270.709
MR_5^*	**-11997.3**	**620.007**	**-1394.76**	**1714.93**	**2677.62**	**-921.647**	-9301.17
MR_7^*	**-375.99**	**-2.8782**	**23.9363**	**6.61792**	**246.967**	**7.53239**	-93.8177
MR_8^*	**-152.38**	**-0.643**	**27.752**	**-126.26**	**128.89**	**9.76867**	-112.874
MR_9^*	**-222.81**	**-0.4341**	**43.3401**	**425.302**	**190.28**	**6.88719**	442.566
MR_{10}^*	**-1416.2**	**-1.8208**	**916.273**	**467.459**	**1437.15**	**-95.897**	1306.93
MR_{12}^*	**-5114.4**	**23.3432**	**752.908**	**-55.497**	**3346.96**	**184.464**	-862.268
MR_{13}^*	**-1141**	**-38.768**	**3.03088**	**47.1471**	**723.605**	**26.3784**	-379.557
MR_{14}^*	**-1045.4**	**-35.944**	**2.33185**	**-15.851**	**675.817**	**24.1149**	-394.96
Total	-8131.4	2779.15	48397.2	13666.7	6894.39	-17.024	63589

influence of effects induced by ambient, fuel set points and other components can be seen. The term associated with the residual element of the decomposition (error) is negligible.

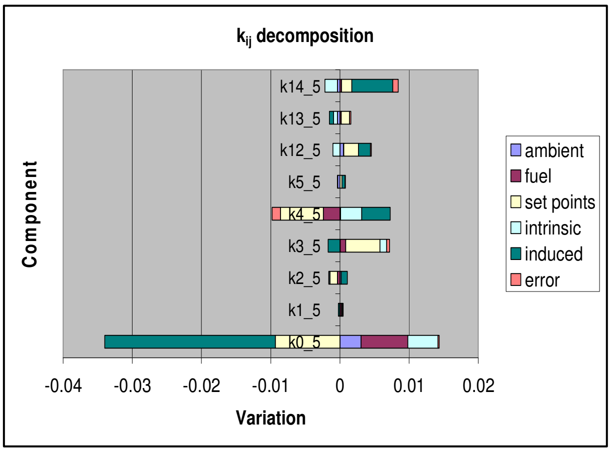

Figure 2. Decomposition of Unit Exergy Consumptions of the Boiler.

The decomposition of unit exergy consumptions and final products is used to decompose malfunctions and finally, malfunction costs. Figure 3 shows the decomposition of malfunction cost associated with productive flows. The highest fuel impact is due to the variation of plant product (MF_0^*), which is mainly caused by set points. Malfunction costs associated with turbines are practically intrinsic, so that this productive structure is suitable for the diagnosis of these components. On the other hand, effects induced by other components in the boiler are high. This may be due to the simplified structure adopted for this component. Besides, ambient has high influence on the condenser. Last but not the least, residual effects are negligible.

All malfunction costs (intrinsic and induced and associated with productive flows and with wastes) are summarized in the table of intrinsic and induced malfunctions (Table 3). Due to the use of malfunction cost associated with the residual term in the decomposition of unit exergy consumptions, the fuel impact calculated in this table (63589 kW) is exact. It should be noted that some negative values appear, even in the intrinsic malfunctions, because there are some components whose performance is better than that in the reference condition.

4. Conclusion

The concepts of malfunction and malfunction cost and the fuel impact formula are valuable tools provided by Thermoeconomics to solve the diagnosis problem

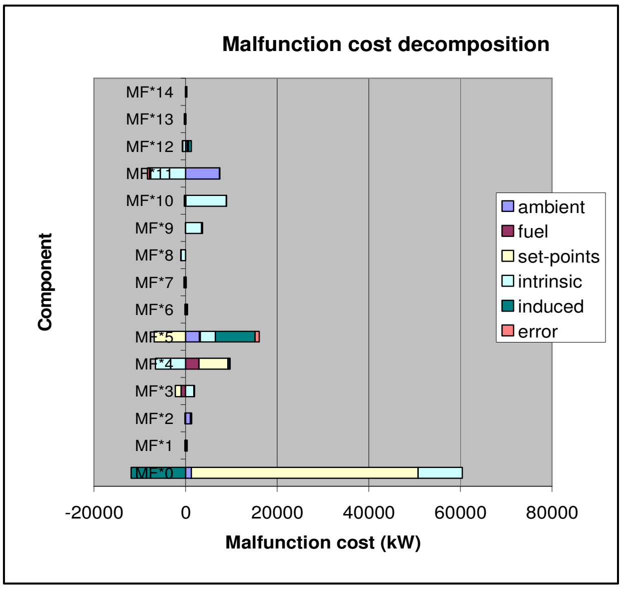

Figure 3. Decomposition of Malfunction Costs.

(detection of malfunctioning components and quantification of impacts on fuel consumption). They are homogeneous and allow a direct and elegant formulation. However, problems appear in their practical application due to the presence of induced malfunctions.

Different diagnosis methodologies have been developed in order to solve this problem. Some of them directly avoid the use of Thermoeconomics and rely on a pure thermodynamic description of the thermal system. Among them, the quantitative causality analysis provides good results with quite low implementation cost.

In this paper, a formulation is developed which combines both approaches. Quantitative causality analysis is used to decompose the variation of the independent variables of the thermoeconomic model. Although the approach has been previously proposed, it is substantially improved here by including residual terms (which allows exact calculation) and waste flows (which allow the development of a more precise productive structure).

The capability of the approach is demonstrated by an application to a real example. A systematic decomposition of effects, both intrinsic and induced by ambient conditions, fuel quality, set-points and other components is achieved. Results also serve as a valuable indicator of the strengths and limitations of the proposed productive structure.

Nomenclature

e	Global efficiency indicator
F_T	Fuel entering the plant [kW]
k^*	Unit exergy cost
MF	Malfunction [kW]
*MF**	Malfunction cost [kW]
MFD	Table of malfunctions induced by free diagnosis variables
MFI	Table of intrinsic and induced malfunctions
MR	Malfunction associated with wastes [kW]
*MR**	Malfunction cost associated with wastes [kW]
n	Number of components
n_t	Number of thermodynamic variables
n_d	Number of free diagnosis variables
P	Product [kW]

Greek

Δ	Increment
κ	Unit exergy consumption
θ	Unit exergy consumption associated with wastes.
ω	Product of the plant [kW]

Matrices and vectors

ed	Sensitivity vector of e related to xd
ex	Sensitivity vector of e related to x
JD	General restrictions matrix for the diagnosis problem
kd	Sensitivity vector of κ related to xd
kx	Sensitivity vector of κ related to x
td	Sensitivity vector of θ related to xd
tx	Sensitivity vector of θ related to x
U	Unit matrix
wd	Sensitivity vector of ω related to xd
wx	Sensitivity vector of ω related to x
x	Vector of thermodynamic variables
$\mathbf{x}_d$	Vector of free diagnosis variables

Subscripts

P	Product

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