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A comparative analysis of two thermoeconomic diagnosis methodologies in a building heating and DHW facility

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ABSTRACT

Concerning the building environment HVAC facilities, even if a great effort has been made in developing components and systems with high nominal efficiencies, less attention has been paid to the problem of system maintenance.

The main objective of the *thermoeconomic diagnosis* is to detect possible anomalies and their location inside a component of the energy system. The second objective, and indeed the one to be achieved in this paper, is indicated as *inverse problem*. It is associated with the quantification of the effects of anomalies in terms of thermoeconomic quantities. Its rigorous application in building thermal installations has some difficulties relating to the strong interrelation between the different components and the fact that energy supply facilities are continuously changing with time.

The way to deal with *dynamic* circumstances is thoroughly explored in this article. Likewise, this paper's main goal is to demonstrate an application of two thermoeconomic diagnosis methodologies in the building sector, one based on the *malfunction and dysfunction* analysis and the other one based on the *characteristic curves* of the components. The results obtained allow us to point out the advantages and limitations of both methodologies as well as to combine them and then develop a more reliable diagnosis.
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1. Introducction

In recent years, the construction sector has been in the spotlight of policies focusing on the reduction of primary energy consumption and also oriented in the downsizing of CO_2 emissions. It is estimated that heating, ventilation and air conditioning (HVAC) systems consume about 50% of the total energy used in buildings worldwide. Then by properly operating the HVAC systems, considerable energy savings can be achieved [1].

However, it is not only a matter of designing and sizing the higher performance thermal systems, optimizing its costs and trying to design them for the minimum environmental impact, since its *maintenance* should also be taken into consideration.

Systems are often poorly maintained and experience dramatic degradation of performance due to aging and the presence of malfunctions or faults [2]. Those anomalies do not cause the unit to stop functioning, but they do produce degradation in plant performance that could be the beginning of undesirable induced effects which can seriously damage the nominal operational condition of the facility.

Thermoeconomic diagnosis is focused on discovering reductions in system efficiency, the detection of possible anomalies, the identification of the components where these anomalies have occurred and their quantification [3]. This paper compares two thermoeconomic methodologies in the diagnosis of a heating and DHW supply system, one based on the malfunction and dysfunction method [4] and the other one based on the characteristic curves [5] of the components.

The paper is organized in 6 different sections as follows: after the introductory first section, Section 2 presents the main ideas and sums up the malfunction and dysfunction diagnosis formulas based on the productive structure of the system. In addition, drawbacks of this method are also exposed. Another diagnosis perspective, driven by characteristic curves, is introduced in Section 3 along with the generic formulas. The case study where both diagnosis methodologies are implemented is defined in Section 4. The application of both methods of diagnosis and the numerical results obtained are covered in Section 5. Finally, the main contributions of the paper and the discussions on the results are summarized in Section 6 (Fig. 1).

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MATRICIAL NOMENCLATURE

$\mathbf{X}$	(nx1) Generic vector of X variable
$\mathbf{X_D}$	(nxn) Diagonal matrix of X vector
$\mathbf{X^0}$	(nx1) Reference condition of generic X vector
$\Delta\mathbf{X}$	(nx1) Variation of generic X vector between two conditions
$^t\mathbf{X}$	(1xn) Transposed of generic X vector
$\mathbf{u}$	(nx1) Unitary vector
$X^{1^{st}}, X^{2^{nd}}$	(1x1) generic value of X for the 1st and 2nd diagnosis calculation

MF & DF ANALISYS

$\mathbf{P}$	(nx1) Component Product vector
$\mathbf{P_S}$	(nx1) Final product vector
$\mathbf{K}$	(nx1) Unit exergy consumption vector
$\boldsymbol{\kappa_0}$	(nx1) Vector of the marginal exergy consumptions related to the external resources
$\langle\mathbf{KP}\rangle$	(nxn) Matrix of the marginal exergy consumptions , κ_{ij}
$\mathbf{\|I\rangle}$	(nxn) Matrix irreversibility extended operator
F_T, F_T^0	(1x1) Resource consumption in real and reference operating conditions
$\mathbf{MF}$	(nx1) Malfunction vector
$\mathbf{DF}$	(nx1) Dysfunction vector
DF_{ij}	(−) Components of the Dysfunction matrix

CHARACTERISTIC CURVES

π	(1x1) Generic term for characteristic curves representation
ξ	(1x1) Subset of generic independent variables
κ	(1x1) Specific term for characteristic curves application
τ	(1x1) Subset of specific thermal independent variables
$\kappa^0_{i,ind}$	(1x1) Induced unit exergy consumption of the i^{th} component
$MF_{i,ind}$	(1x1) Induced malfunction of the i^{th} component
$MF_{i,int}$	(1x1) Intrinsic malfunction of the i^{th} component
ΔF_{save}	(1x1) Fuel impact saving between two diagnosis stages

Fig. 1. Nomenclature and brief description of symbols grouped according to their purpose.

2. Thermoeconomic diagnosis. MF & DF analysis

2.1. General characteristics

Thermoeconomics relates the thermodynamic parameters with the economic ones based on the idea that *exergy* is the unique parameter which rationally determines the cost of the fluxes; this is due to the fact that exergy takes into account the quality of energy and the irreversible nature of energy conversions [6].

Beyond that, thermoeconomic analysis is based on the *productive structure* [7] of the plant where the interactions between components are identified according to their functional relationships. The exergy flows related to the component resources are labelled as *Fuel*, F, whereas those associated with the desired output are known as *Product*, P, which meanwhile, can be fuel from other components and sometimes from wastes or residues. Components are described by their specific exergy consumptions which refer to the amount of resources needed to produce a unit of product, and this parameter being one of the key variables for diagnosis purposes.

Thermoeconomic diagnosis is difficult to apply in building HVAC systems, precisely because:

- It should be noted that exergy is always evaluated with respect to a reference environment, *dead state*. Exergy methods applied in buildings might seem cumbersome or complex to some people, since not only is a dead state difficult to define but it also changes dynamically over time, and the results might seem difficult to interpret and understand [8].
- The definition of *productive structure* may well lead to controversy [9] due to the dynamic behaviour of thermal installations in buildings. The same system can have more than one productive structure depending upon the switching on and switching off of the components. Likewise, the performance of any component, in fact, is heavily influenced by all other components because of the system balancing; then, the effects of any anomaly will propagate to the whole plant, due to the complex relationships.
- The most challenging enforcement of thermoeconomic diagnosis is to resolve the *direct problem,* which consists of detecting a possible anomaly and its location. It is a difficult task and the reliability of its results has not yet been proven [10]. For the moment, only the *inverse problem* of diagnosis has been solved, i.e., under the *knowledge* of specific anomalies in different components, the procedure involves quantifying the effects of those anomalies in terms of thermoeconomic quantities, such as fuel impact and malfunctions.

Nevertheless, several thermoeconomic diagnoses have been published during the last years, although most of them are applied to industry. Verda and his co-workers applied a zooming strategy in a combined cycle in order to first locate the macro-component where the anomaly occurs [9,11]. Besides that, this same author

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