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ON THE NEED FOR TOTAL AND LOCALIZED EXERGY DISAGGREGATION IN THERMOECONOMIC DIAGNOSIS BASED ON COMPREHENSIVE DIAGRAMS

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Abstract. *Thermoeconomics, the discipline that combines thermodynamic and economic concepts, can be divided into three main areas of application: cost allocation, diagnosis, and optimization. Thermoeconomic diagnosis has been widely applied to find the causes of additional irreversibility and to assess its impact on energy consumption. The dissipative components and residues can still be considered a challenge in thermoeconomics due to the difficulties that some approaches have to deal with. Most of the diagnosis works use the productive diagram and exergy disaggregation for dissipative component isolation. Recently, an alternative to deal with dissipative components, and to reduce the complexity of the modeling, was presented through the localized physical exergy disaggregation in the productive diagram. This paper aims to implement a thermoeconomic diagnosis analysis through the comprehensive diagram, which combines the characteristics of the conventional physical and productive diagrams. A Rankine cycle with different simulated anomalies is evaluated by two distinct thermoeconomic models (E and H&S) and also with the localized physical exergy disaggregation. The thermoeconomic diagnosis method called Fuel Impact Formula is used to quantify the effects of each malfunction. The methods used are also evaluated regarding the capability to isolate the dissipative equipment of the plant and the complexity of the modeling. Results show that all models applied in the diagnosis analysis using comprehensive diagram present coherent results of additional fuel consumption caused by the simulated anomalies. The exergy disaggregation is required to isolate dissipative components and allows an adequate diagnosis analysis. Nevertheless, a total exergy disaggregation increases the complexity and the localized disaggregation appears as an interesting solution for that.*

Keywords: *diagnosis, comprehensive diagram, localized disaggregation, physical exergy disaggregation, dissipative component, thermoeconomics*

1. INTRODUCTION

Thermoeconomics combines economic and thermodynamic analyses by applying the concept of cost (economic property) to exergy (energetic property) to provide the system designer/operator information not available in conventional energy and economic analyses, but crucial to the design and operation (Valero *et al.* 2006). Most analysts agree that exergy, instead of enthalpy only, is the most adequate thermodynamic property to associate with cost since it contains information from the Second Law of Thermodynamics and accounts for energy quality. An exergy analysis locates and quantifies the irreversibilities of the processes and systems (Valero *et al.* 2006).

Thermoeconomics can be divided into three main areas of application: cost allocation, diagnosis, and optimization. Thermoeconomic diagnosis has been widely applied to find the causes of additional irreversibility and assess its impact on energy consumption, and to optimize maintenance routines. An accurate diagnosis avoids prolonged and unnecessary downtime, reducing operational costs.

Most of the diagnosis works use the productive diagram, such as in (Lorenzoni *et al.* 2020; Mendes *et al.* 2020; Piacentino & Talamo 2013; Zhang *et al.* 2007). There are also studies using physical structure with a method based on advanced exergy analysis (Fu *et al.* 2016; Kelly *et al.* 2009; Wang *et al.* 2017; Yang *et al.* 2013) and also combining physical with productive diagram (Hernández 2005; Orozco *et al.* 2017; Pacheco Ibarra *et al.* 2010).

The dissipative components and residues can still be considered a challenge in thermoeconomics due to the difficulties that some approaches have to deal with. Most of the diagnosis works use the productive diagram and exergy disaggregation for dissipative component isolation. According to the isolation principle, a thermal system component is thermoeconomically isolated from other system components when its product and resource costs can be completely described (Evans 1980).

Although physical exergy disaggregation into thermal and mechanical components may improve the accuracy of the results in thermoeconomics, it increases the complexity of the model (Lazzaretto & Tsatsaronis 2006). Recently, an alternative to deal with dissipative components, and to reduce the complexity of the model, was presented through the localized physical exergy disaggregation in the productive diagram (Santos *et al.* 2020a, 2020b). It was applied in thermoeconomic diagnosis with productive diagram in (Santos *et al.* 2021).

This paper aims to implement a thermoeconomic diagnosis analysis through the comprehensive diagram (Avellar *et al.* 2018a, 2018b), which combines the characteristics of the conventional physical and productive diagrams. A Rankine cycle with different simulated anomalies is evaluated by two distinct thermoeconomic models, E and H&S, and also with the localized physical exergy disaggregation. The novelty of this paper is the combination of the localized physical exergy disaggregation with the comprehensive diagram for diagnosis application.

The thermoeconomic diagnosis method called "Fuel Impact Formula" (Valero 2004) is used to quantify the effects of each malfunction. The methods used are also evaluated regarding the capability to isolate the dissipative equipment (condenser) of the plant and the complexity of the modeling.

2. METHODOLOGY

The "Fuel Impact Formula" thermoeconomic diagnosis method (Valero 2004) is applied through the E and H&S Models and the Localized physical exergy disaggregation using the comprehensive diagram. This diagnosis method uses mathematical equations to determine the additional fuel consumption caused by system anomalies and, subsequently, comparing thermodynamic data from the operational and reference conditions.

2.1 Fuel Impact Formula

The operational and reference (or design) conditions compared in the Fuel Impact Formula are represented by (x) and (x^0), respectively. The main objective is to identify and quantify the additional fuel consumption (ΔF_T) due to anomalies, which is determined by Eq. (1). The (ΔF_T) is defined as the sum of the additional resource consumption of each component, where P_i^0 is the contribution of each equipment to the final system product.

Equation (2) enables one to rewrite the fuel consumption equation as a sum of the *i*th component malfunction (MF) and the *i*th component dysfunctions (DF) induced by the *j*th component of the system.

$$\Delta F_T = \sum_{i=1}^{n} (\sum_{j=0}^{n} k_{P,j}^{*} \Delta k_{ij}) P_i^0 \tag{1}$$

$$\Delta F_T = \sum_{i=1}^{n} (MF_i + \sum_{j=1}^{n} DF_{ij}) \tag{2}$$

The MF (or endogenous irreversibility) is caused by an increase in the unit consumption of the equipment itself; and the DF (or exogenous irreversibility) is induced by an MF in another component, which forces the unit to consume more resources to provide more of its product to the system, with the same exergy efficiency (Torres *et al.* 2002). Equations (3) and (4) are used to calculate the MF and DF, respectively.

$$MF_i = P_i^0 \Delta k_i = \sum_{j=0}^{n} P_i^0 \Delta k_{ji} \tag{3}$$

$$DF_i = (k_i - 1) \Delta P_i \tag{4}$$

The parameters (k_{ij}) and (k_{ij}^{*}) in Eqs. (1), (3) and (4) represents the unitary exergetic consumption and the unitary exergetic cost, respectively. The (k_{ij}), an important performance index of the Fuel Impact method, is determined by Eq. (5), where E_{ij} is the ith exergy fuel of a j component and P_j is the exergetic product of the j component in the productive structure. The (k^*_{ij}) is the amount of exergy required to obtain one exergy unit of this flow (Valero *et al.* 2006) and is defined as the ratio between the flow cost and its exergetic value, as shown in Eq. (6)

$$k_{ij} = \frac{E_{ij}}{P_j} \quad (5)$$

$$k^*_{ij} = \frac{E^*_{ij}}{E_{ij}} \quad (6)$$

2.2 Thermoeconomic Models

Two conventional thermoeconomic methodologies are applied in this work, E and H&S Model, and also a combination of these two in a localized physical exergy disaggregation. Modeling using exergy total flows (E Model), i.e., without exergy disaggregation in components, is widely applied. However, it is not able to isolate dissipative components in the diagrams, as is not possible to define its product based on exergy flows.

To overcome this limitation, the H&S Model (Santos *et al.* 2006, 2009) has been proposed already considering the residue cost allocation and the dissipative component isolation, which is carried out through its productive structure definition with its flows of enthalpic, entropic, and chemical exergy terms. This model approached the negentropy concept by (Frangopoulos 1987), with a different perspective, i.e., the entropic component is used alongside with enthalpy, both considered as components of exergy (Lourenço *et al.* 2014). In this method, the resources and products of each unit are systematically defined by taking into account all enthalpy, entropy, and also chemical exergy inputs and outputs for all the streams.

This model also introduces the chemical exergy flows ($E^{CH}_{i:j}$) explicitly in the diagram. Although, in the case study of this paper, there are no chemical exergy flows, as the working fluid does not have its chemical composition changed, it just changes its physical state. In the H&S Model the physical exergy of a mass flow can be divided into two alternative components/terms, enthalpic (H) and entropic (S), as shown in Eq. (7) and demonstrated by (Lourenço *et al.* 2014).

$$E_{i:j} = H_{i:j} - S_{i:j} + E^{CH}_{i:j} \quad (7)$$

The H&S Model was originally proposed to be used with productive diagram. Nevertheless, the model can be easily adapted to be used in any other thermoeconomic diagram, such as the comprehensive applied herein.

As the physical exergy disaggregation may increase the complexity of the model, a localized physical exergy disaggregation was proposed in order to be able to isolate dissipative components without excessive increase in the modeling complexity (Santos *et al.* 2020a, 2020b). In this kind of application, whereas the productive components have their fuels and products defined through total exergy flows, the dissipative ones use exergy flows disaggregated in components for these definitions. In the case of this work, the Model H&S is used to isolate the condenser and the E Model is used to deal with the pump, the steam generator and the steam turbine (Figure 2b).

3. CASE STUDY

A Rankine cycle is adopted as a case study in this paper. Besides presenting a dissipative component (condenser) in its structure, the same cycle was evaluated by (Lorenzoni *et al.* 2020; Santos *et al.* 2021) through a conventional productive diagram analysis. In this work, the capability of achieving coherent results of thermoeconomic diagnosis carried out with comprehensive diagram is assessed and compared with the results of the works mentioned above. The thermoeconomic models are analyzed concerning its ability to isolate the dissipative component of the plant and the complexity associated.

3.1 Physical Structure

Figure 1 represents the physical structure of the Rankine cycle, which is defined by the following units (or subsystems): pump (PMP), steam generator (SG), steam turbine (TRB), and condenser (CND). The thermodynamic data of the cycle in reference conditions are shown in Table 1.

The cycle provides a net power (W_N) of 20,000 kW and the power required by the pump (W_P) and by the cooling system (W_C) is 155 kW and 75 kW, respectively, in reference conditions. The methane is used as fuel, with exergetic consumption (Q_F) of 70,000 kW. All fluids' properties were obtained with the software EES®. The exergetic reference state is defined by T_0 = 25 °C and P_0 = 1 atm. More information is available in (Lorenzoni *et al.* 2020).

Table 1. Thermodynamic data for the Rankine cycle in reference conditions.

Flow	T [°C]	P [kPa]	E [kW]	H [kW]	S [kW]
1	39	7	24.19	1,140.97	1,116.78
2	39	6,300	148.82	1,289.78	1,140.96
3	500	6,300	26,821.18	64,690.61	37,869.43
4	39	7	1,920.83	43,405.32	41,484.49

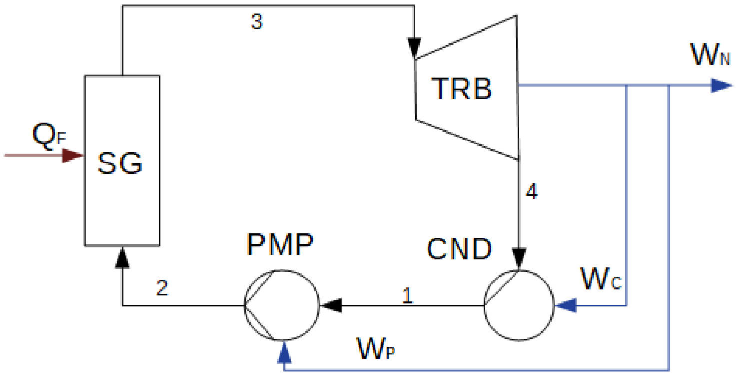


Figure 1. Physical structure – Rankine cycle.

Five different anomalies are simulated and their impact on resource consumption is analyzed with the Fuel Impact Formula (Valero 2004). In this kind of analysis, the final product (W_N) is not modified in any simulation, so that additional fuel consumption (ΔF_T) can be assessed due to anomalies, keeping the final product constant.

Anomalies 1-4 are individual for each unit of the cycle and anomaly 5 is the combination of all of them simultaneously. The reduction of 10% on the thermal efficiency of the steam generator (η_{SG}), on the isentropic efficiencies of the turbine (η_{TRB}) and of the pump (η_{PMP}) represent the Anomalies 1, 2 and 4 respectively. Anomaly 3 is a 10% reduction in the condenser vacuum (P_{CND}) and Anomaly 5 is a combination of the previous ones. Table 2 summarizes the anomalies and their respective control parameters in the cycle.

Table 2. Anomalies imposed in the power generation system. Available from (Lorenzoni *et al.* 2020).

	Reference	Anomaly				
		1	2	3	4	5
η_{TRB}	0.849	0.849	**0.749**	0.849	0.849	**0.749**
η_{PMP}	0.830	0.830	0.830	0.830	**0.730**	**0.730**
η_{SG}	0.906	**0.806**	0.906	0.906	0.906	**0.806**
P_{CND} [bar]	0.070	0.070	0.070	**0.160**	0.070	**0.160**

3.2 Comprehensive Diagrams

In the comprehensive diagrams (Avellar *et al.* 2018a, 2018b), the characteristics of the conventional physical and productive diagrams are combined in a single diagram. In addition, the subsystems are interconnected using the same physical exergy flows presented in the flow sheet, and in this way, there are no fictitious subsystems, such as junction and bifurcation used in the productive diagrams. It avoids the arbitrariness linked to the use of these fictitious units.

This kind of diagram, which combines physical and productive diagrams features, has been applied, with different nomenclatures, for cost allocation (Barone *et al.* 2021; de Faria *et al.* 2020, 2021; Lazzaretto & Macor 1995; Torres & Valero 2018a, 2018b, 2021) and diagnosis studies (Hernández 2005; Orozco *et al.* 2017; Pacheco Ibarra *et al.* 2010). However, none of them use localized physical exergy disaggregation.

In the E Model (Figure 2a) is not possible to define a product to the condenser based on exergy flows and therefore, it cannot be isolated. Thus, it should be allocated along with another productive equipment. In this case, the condenser is arbitrarily merged with the turbine (TRB/CND). In Figure 2 b) and c) all components are isolated and the condenser product is defined based on the entropic component of exergy. The H&S Model is used for total exergy disaggregation in Figure 2c), whereas in Figure 2 b), it is applied only in a localized disaggregation in the dissipative equipment.

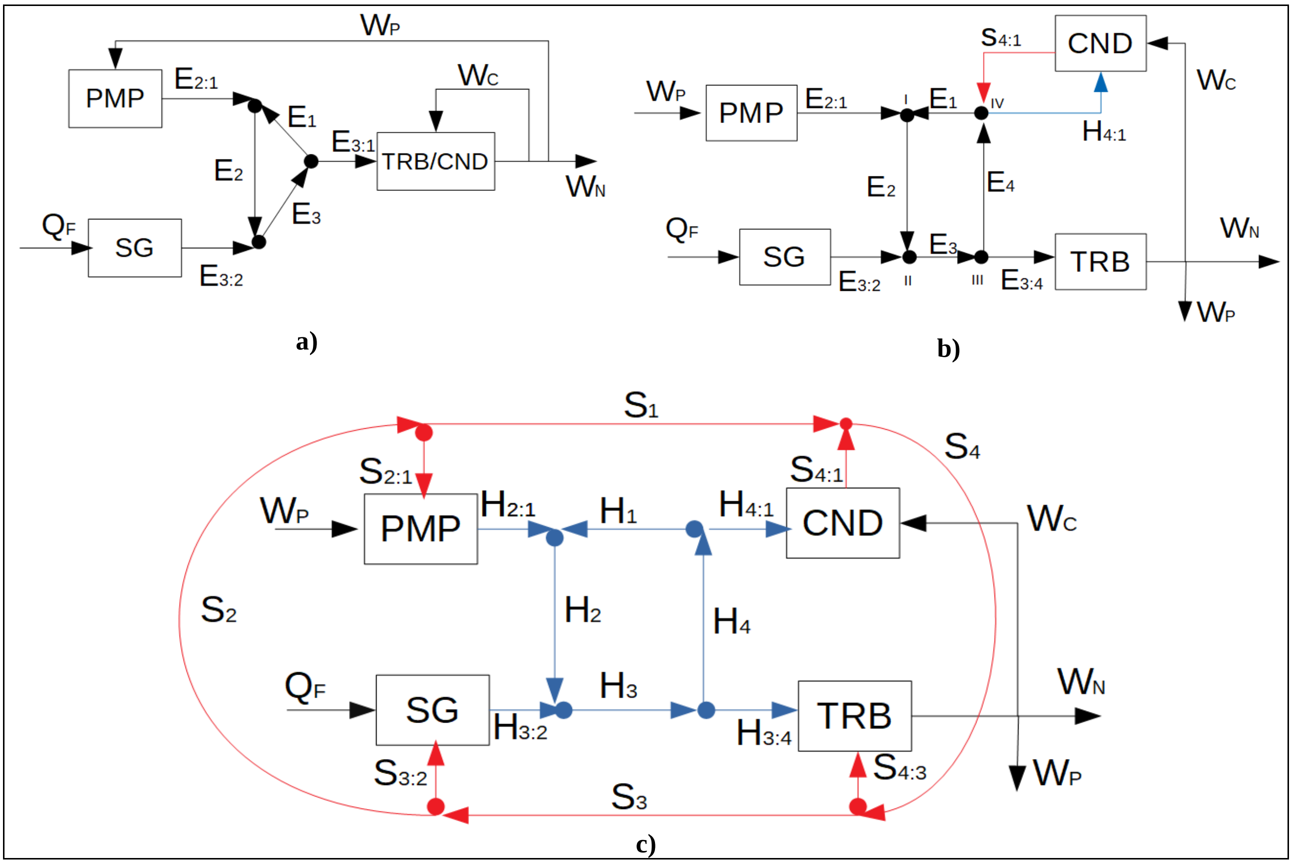


Figure 2. Comprehensive diagrams: a) E Model, b) Localized physical exergy disaggregation, and c) H&S Model.

4. RESULTS AND DISCUSSIONS

Table 3 shows the additional fuel consumption (ΔF_T) for each simulated anomaly. The lowest extra consumption is due to anomaly 4 (reduction in the isentropic efficiency of the pump) and the highest due to anomaly 5 (anomalies 1-4 simultaneously). The choice of the thermoeconomic model does not affect the total impact on the fuel consumption using the Fuel Impact Formula. Nevertheless, each model presents different values/behavior of MF and DF for each component, as can be seen in Figures 3-7.

Table 3. Total fuel impact due to anomalies.

	Anomaly (AN)				
	1	2	3	4	5
Additional fuel consumption [kW]	8,695	9,434	4,570	55	25,074

Results of Table 3 confirm that comprehensive diagrams are able to determine the additional fuel consumption due to each anomaly of the plant since these results are the same as the ones obtained with the conventional productive diagrams for the same cycle and simulated anomalies in (Lorenzoni *et al.* 2020; Santos *et al.* 2021).

Figures 3-7 show the malfunctions (MF) and dysfunctions (DF) induced by each component of the system for each thermoeconomic method. The analyses of MF and DF were carried out in all subsystems (SG, TRB, CND, and PMP), and also in the internal loops of physical flows, which were handled as a single unit/entity. In the case of E Model and localized disaggregation there is only one internal loop. In the H&S Model there is a loop of physical flows for each component of the exergy: loop H and loop S. In Figures 3-7 a) and b), in addition to the system equipment, there is a "loop" in the results. In Figures 3-7c) there are "loop H" and "loop S" additionally to the equipment.

In Figures 3-7 a), E Model, the results of the turbine and the condenser are together (TRB/CND) because, as explained previously, this model is not able to isolate the condenser.

Figure 3 analyze the anomaly 1 (AN1), a 10% reduction in the thermal efficiency of the steam generator. In this case, the inefficiencies are restricted only to SG, because it is the system's fuel input. Thus, any MF present in it reflects directly on its own input and not on the quantity required by other components. All methods were able to identify the SG as the component with MF.

Figures 4 and 5 show the results for anomalies 2 and 3, respectively, and presents similar aspects. As AN2 and AN3 are in the turbine and the condenser, the E Model cannot identify the component with MF because it cannot isolate the condenser, which is combined precisely with the turbine (TRB/CND). On the other hand, the localized disaggregation (Figures 4b and 5b) and the H&S Model (Figures 4c and 5c) can identify the component with MF. This same behavior was obtained with productive diagram in (Lorenzoni *et al.* 2020; Santos *et al.* 2021).

Negative values of DF were found in different components in anomalies 3-5. It happens due to a component product reduction when compared to the reference state.

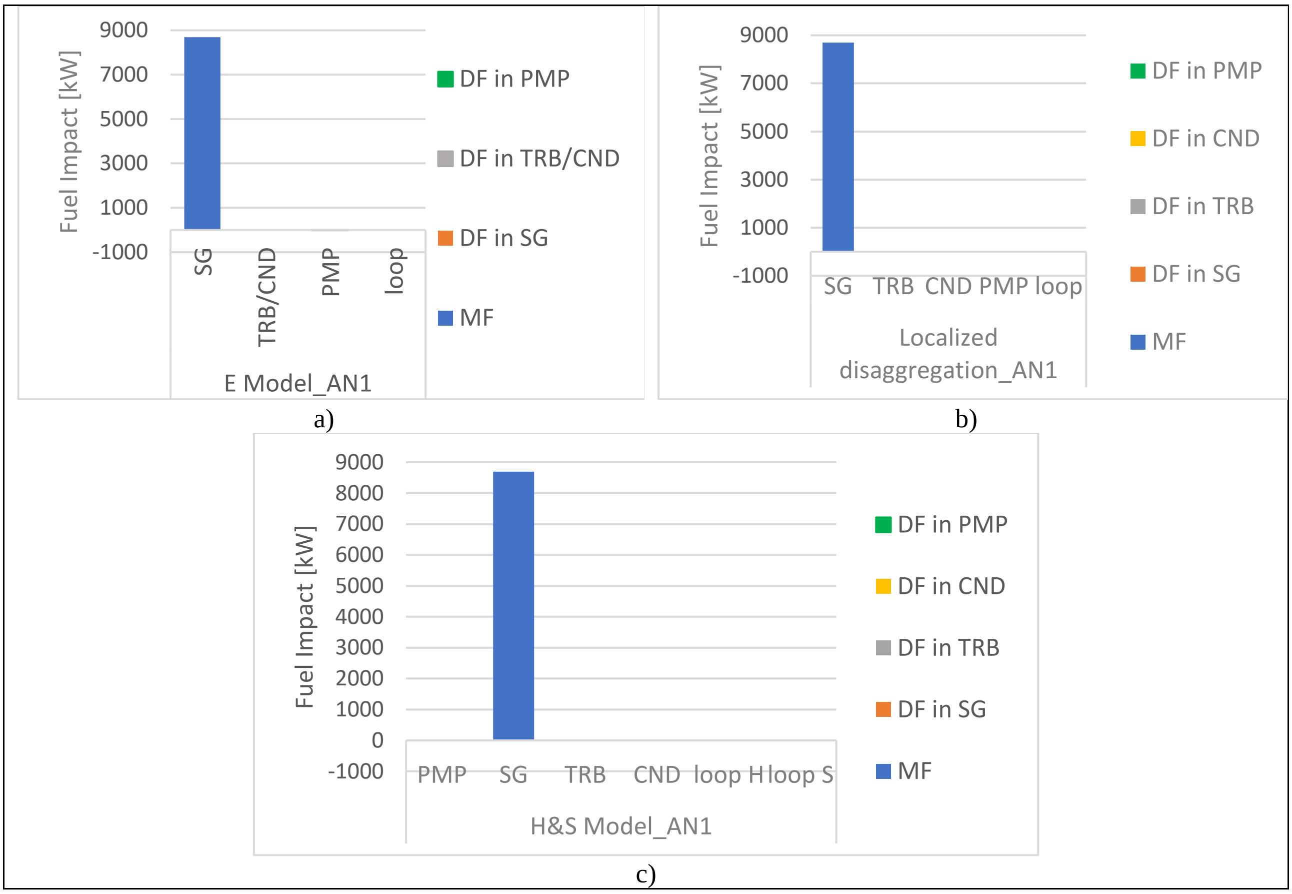
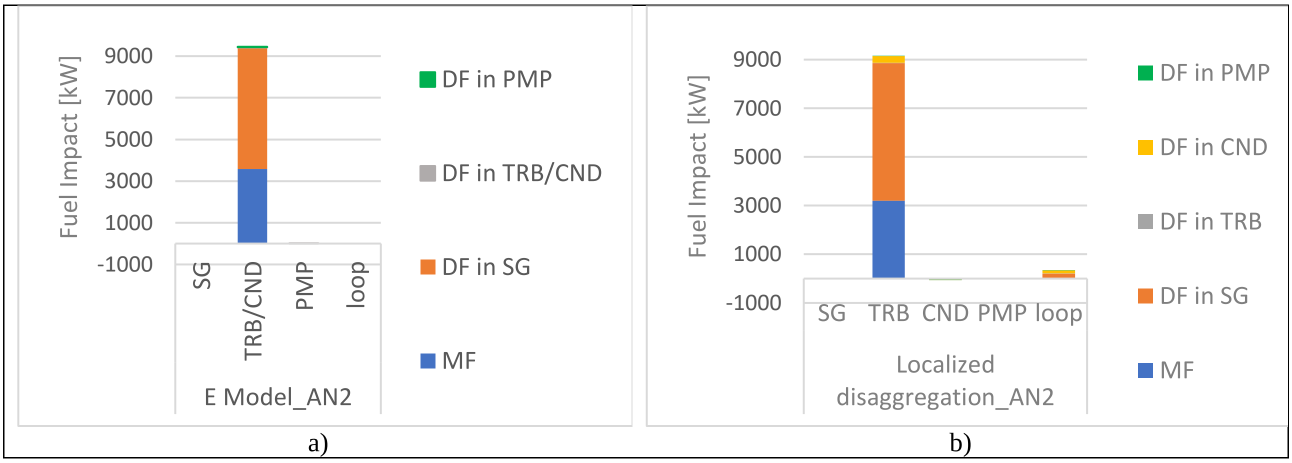
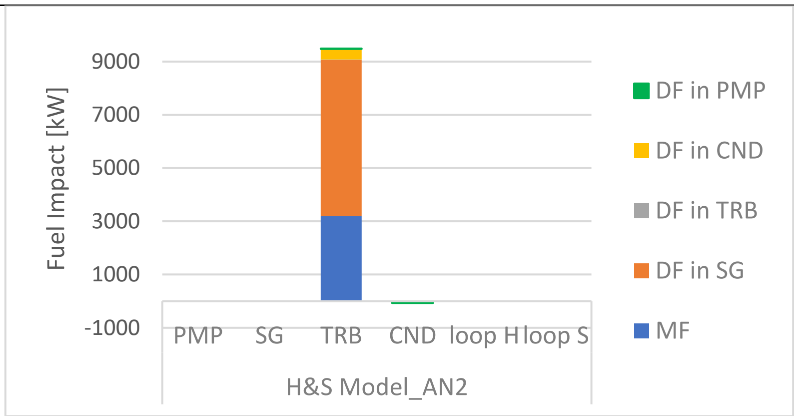


Figure 3. Faults origin due to Anomaly 1 for each component and thermoeconomic model.





c)

Figure 4. Faults origin due to Anomaly 2 for each component and thermoeconomic model.

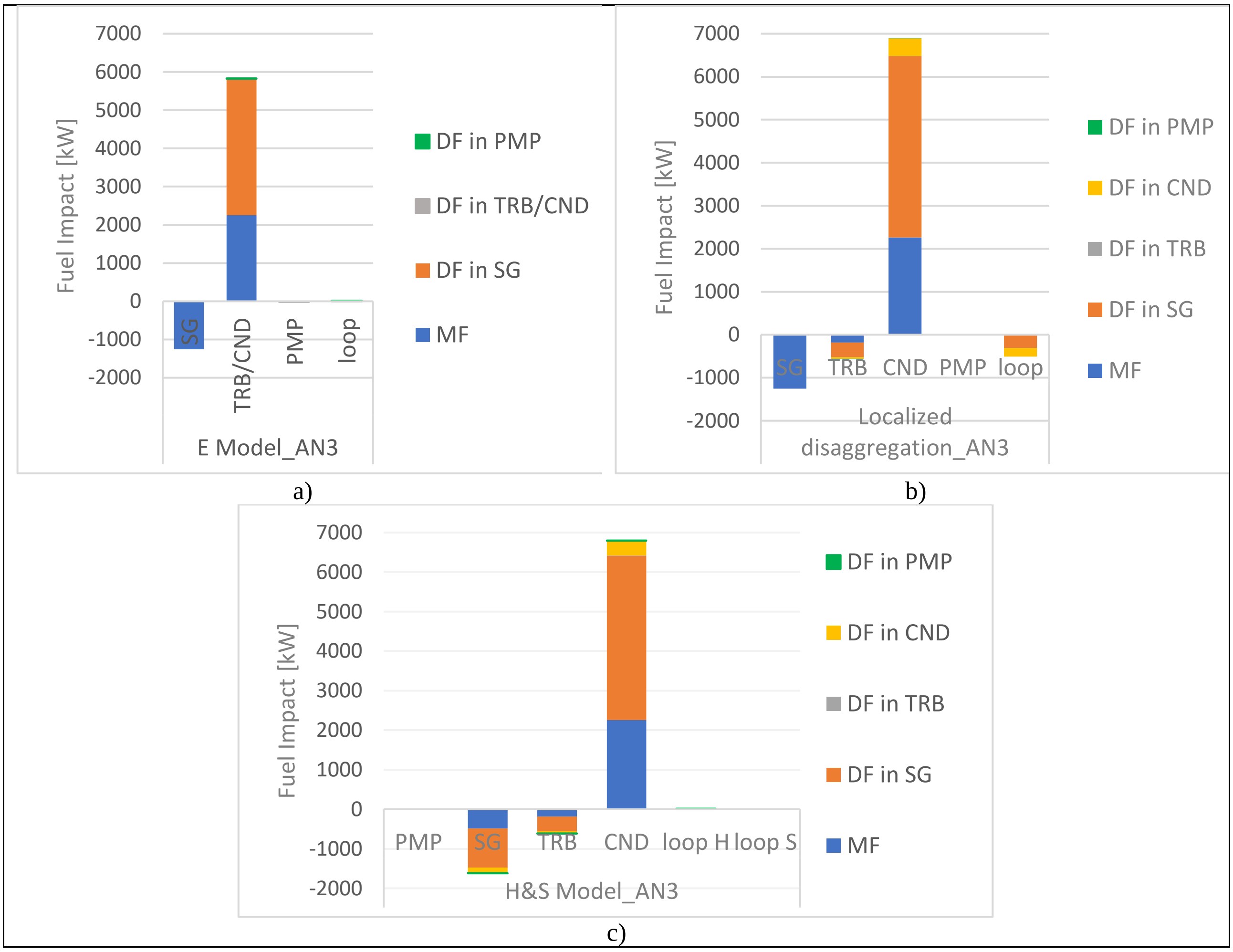


Figure 5. Faults origin due to Anomaly 3 for each component and thermoeconomic model.

Figure 6 shows that all methods used are able to identify the pump as the component with MF due to anomaly 4. It was also observed that the MF of the PMP induces an MF in the SG, as shown by the negative value of malfunction in the steam generator in Figure 6 a), b) and c). One may note in Figure 6 c) that the “loop H” presents DF values of the same order of magnitude as other DF and MF in the analysis which influence and disturb the diagnostic evaluation. It is possible to notice that in some other results (Figures 4 b), 5 b) and 6 b), for instance) the internal loops are also inducing anomalies in real components, however, the values are much lower compared to the others in each analysis.

In studies with productive diagrams were already observed cases with fictitious unities inducing anomalies in real components, even not having any anomaly on their own in (Lorenzoni *et al.* 2020; Piacentino & Talamo 2013; Santos *et* *al.* 2021). Besides, (Pacheco Ibarra *et al.* 2010) and (Orozco *et al.* 2017) noted similar behavior in what they called "fictitious" and "junction-branch", respectively, and which can be interpreted as the interface between physical and productive flows at the component boundary identified with roman numbers (I-IV) in Figure 2 b), for instance. This same interface is called "productive group" by (Torres & Valero 2021).

Comparing with the productive diagram analysis (Santos *et al.* 2021), the H&S Model Figure 6 c) and Localized disaggregation Figure 6 b) present similar behavior for MF and DF for each component and while the productive found DF linked with the junctions-bifurcations, the comprehensive found it in the internal loop. According to (Lazzaretto & Toffolo 2006) the mathematical formulation is probably the weak point for finding the sources of anomalies in the Fuel Impact Formula method and this could be one of the possible reasons for these uncommon results in the loop.

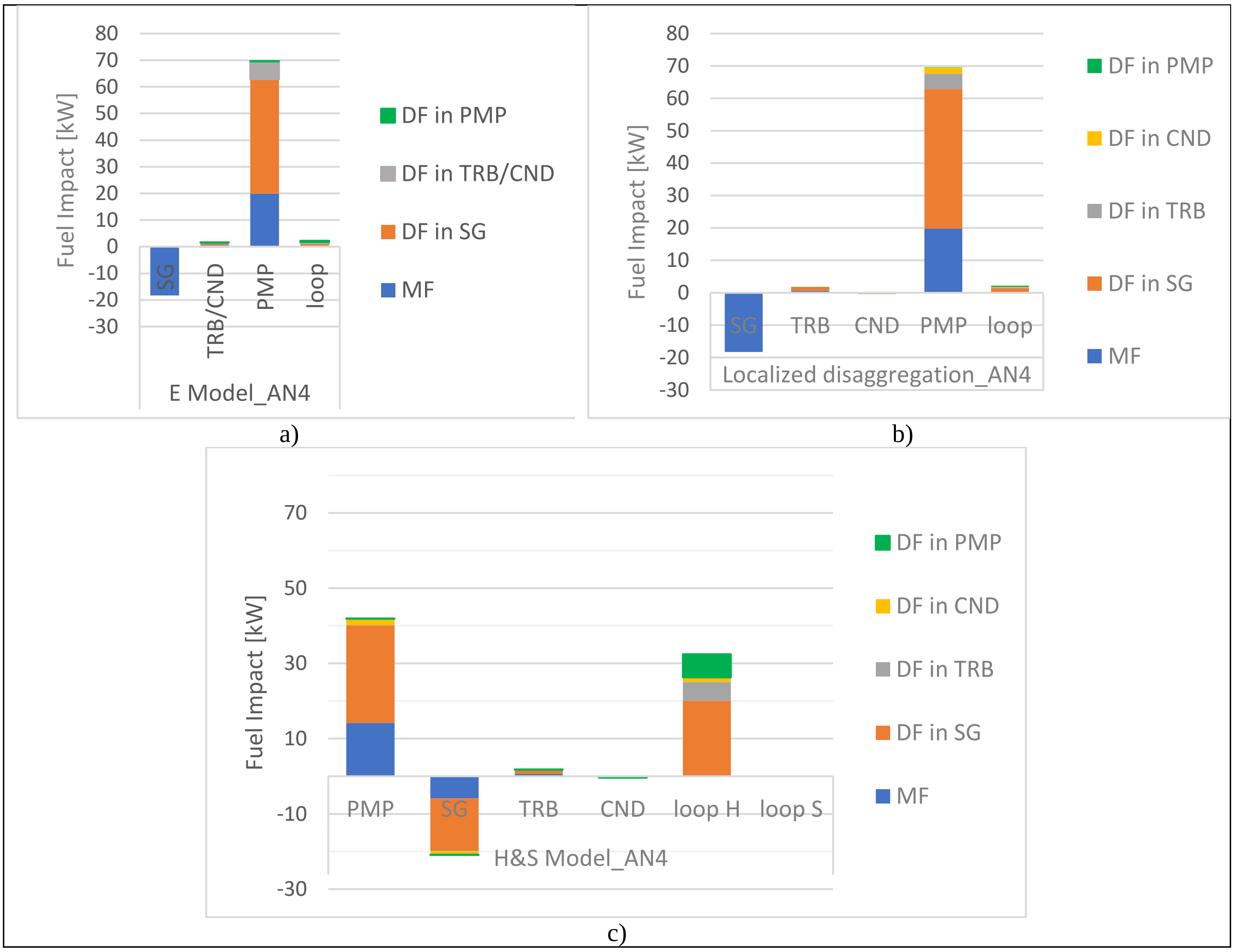


Figure 6. Faults origin due to Anomaly 4 for each component and thermoeconomic model.

Figure 7 shows the MF and DF obtained by the different thermoeconomic models for each component due to the combination of anomalies 1-4 simultaneously. The H&S Model (Figure 7 c) and the localized disaggregation (Figure 7 b), which isolate the condenser, can identify the MF and DF for each component and the results are similar to those obtained with the conventional productive diagram in (Lorenzoni *et al.* 2020; Santos *et al.* 2021). The E Model (Figure 7 a), which cannot isolate the condenser, achieves coherent MF values, however, the values obtained for the TRB and CND are merged, which does not allow an isolated analysis of each equipment

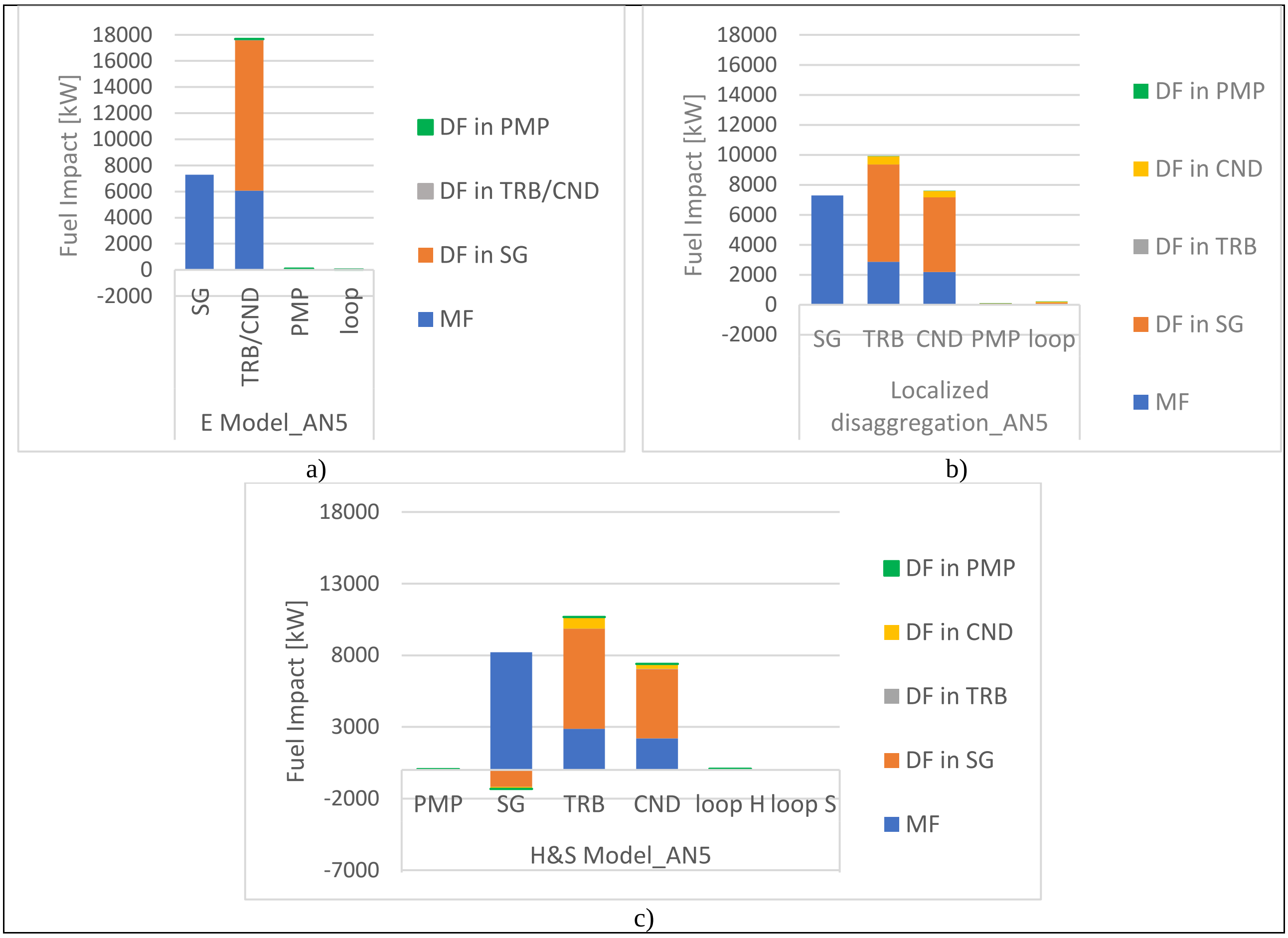


Figure 7. Faults origin due to Anomaly 5 for each component and thermoeconomic model.

5. CONCLUSIONS AND CLOSURE

This work verified the ability to use the comprehensive diagram in analyzes of thermoeconomic diagnosis using different thermoeconomic methodologies with the Fuel Impact Formula diagnosis method. The analysis was carried out through a case study in a Rankine cycle. The methodologies were analyzed for the ability to determine additional fuel consumption due to anomalies and to determine the behavior of MF and DF in the plant components. In addition, it was verified the influence of the isolation of the dissipative equipment (condenser) of the cycle on the results obtained and the complexity associated.

Regardless of the thermoeconomic method used, the total additional fuel consumption for each simulated anomaly is the same and coinciding with the results obtained by the conventional productive diagrams. These results are interesting for the correct decision in the maintenance priorities. Nevertheless, the results need to be analyzed in more detail through the behavior of the malfunctions (MF) and dysfunctions (DF).

The E Model cannot isolate the condenser and it is arbitrarily merged with the turbine. Thus, this model is not advisable since it cannot identify which of these two devices has MF.

The exergy disaggregation is required in order to isolate the dissipative component of the plant and allows an adequate diagnosis analysis identifying the component with malfunctions. Both the H&S Model and the localized physical exergy disaggregation are able to isolate all components of the system. Whereas the H&S Model carries out an exergy disaggregation in the entire system, the localized disaggregation performs it only in the condenser. The total disaggregation (H&S Model) is more complex than the localized as shown in the diagram by the greater number of flows (physical and productive) which implies more equations to be solved. Therefore, the localized disaggregation seems to be an interesting alternative to reduce the modeling complexity and achieve satisfactory diagnosis results.

The H&S Model can define a product for the condenser (and isolate it) based on the entropic component of the exergy and obtains coherent results of MF and DF in most cases. Only anomaly 4 obtains DF values in the internal loop of the enthalpic physical flows that are of relevant magnitude to the case. It may imply an incorrect diagnostic assessment.

For anomaly 5, which is the most likely scenario to occur in a real diagnosis analysis with faults present randomly in every component of the system, the H&S Model and the localized disaggregation obtain satisfactory results for MF and DF for all components. Nonetheless, modeling with localized disaggregation is less complex.

Perhaps this kind of analysis requires further studies and discussions to generate more consistent results and give credibility to the method with comprehensive diagram. Since the comprehensive diagram used combines the physical and productive ones, a better adaptation of the analysis via physical diagram must be done prior to be adopted in conjunction with the productive diagram to be used in the comprehensive one.

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