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ON THE IMPROVEMENT AND ACCURACY IN THERMOECONOMIC DIAGNOSIS: DISSIPATIVE COMPONENT AND EXERGY DISAGGREGATION

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Abstract. Thermoeconomics join concepts of Economics and Thermodynamics in order to describe the cost formation process of the overall thermal system. It has great applicability in product cost allocation, optimization and diagnosis aiming to reduce operating costs and to prove the system's economic feasibility. Thermoeconomic diagnosis is applied to identify the source of extra fuel consumption in each system element. In this study, a Rankine cycle with five simulated anomalies was evaluated by four different thermoeconomic models based on productive diagrams (E, E&S, H&S and UFS) together with the fuel impact formula, focusing in analyse its efficiency in quantifying the effects of each malfunction with the presence of a dissipative component. The results showed that the E and E&S models are not adequate to identify the main malfunction, whilst H&S and UFS models presented satisfactory behaviour. UFS did not improve accuracy for this system when compared to H&S.

Keywords: Diagnosis, thermoeconomics, Rankine cycle, dissipative components.

1. INTRODUCTION

Diagnosis is a general term that refers to a method to search and comprehend anomalies and to quantify its consequences through its symptoms (Lazzaretto, et al., 2006). In energy systems, especially power plants, it is extremely important to ensure its reliability and unstoppable operation, minimising the use of resources and, therefore, improving the plant's efficiency. In this context, the thermal diagnosis has a major role, as monitors the system conditions in order to find anomalies that can cause the efficiency drop or extra fuel consumption and to determine which component is being influenced by it. Studies show that over 20 billion dollars losses in the American petrochemical industry could be avoided with an improved abnormal conditions management program (Nimmo, 1995).

Thermoeconomics embraces Thermodynamics and Economics concepts, that joined, assist in solving complex systems to allocate costs rationally to its products, for instance. Several approaches have been developed for describing the diagnostics system: the reconciliation method (Zaleta, et al., 2004), the characteristic curves approach (Tofollo and Lazzaretto, 2004), the progressive elimination of induced effects (Zhang, et al., 2007), the fuel impact equation (Lozano, et al., 1994) and others. The latter was further improved (Valero, et al., 2004) and will be used for this work analysis.

To describe the system for diagnostic purposes, the productive objective of each system element is defined in terms of exergy-based equations of the input and output flows with the productive structure (Valero, et al., 1993). Although its functionality, some methods struggles to isolate dissipative components in the diagram, due to its lack of exergetic product. New methodologies have been developed to solve this issue, which disaggregates exergy into more parcels targeting to improve accuracy and to avoid individual assumptions to describe the system, which leads to obstacles in comparing different works and its results.

This study aims at identifying the effects of five simulated anomalies in a Rankine Cycle through four different thermoeconomic models for the productive structure. A special concern is given on dissipative components.

2. FUEL IMPACT FORMULA

The fuel impact formula (Valero, *et al.*, 2004) identify and quantify anomalies in each component of a thermal system comparing two different conditions, one considered as a reference or design (x^0), and the other one as an operational

condition (x) with the presence of anomalies or faults. The main indicator is the variation of the unitary exergetic consumption (κ_{ij}) in Eq. (1), where B_{ij} is the ith exergy resource of a j component and P_j is the exergetic product of the j component in the productive structure.

$$\kappa_{ij} = \frac{B_{ij}}{P_j} \tag{1}$$

The unitary exergetic cost (k*) is defined as the quotient between the flow cost and its exergetic value, as in Eq. (2):

$$k_{ij}^* = \frac{B_{ij}^*}{B_{ij}} \tag{2}$$

The additional fuel consumption (ΔF_T) due to the presence of anomalies is quantified by Eq. (3) 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.

$$\Delta F_T = \sum_{i=1}^{n} \left(\sum_{j=0}^{n} k_{P,j}^* \Delta \kappa_{ij} \right) P_i^0 \tag{3}$$

Accordingly to Torres, *et al.*, 2002, there are two types of anomalies: the endogenous irreversibility or malfunction (MF), which is caused by an increase in the unit consumption of the equipment itself; and the exogenous irreversibility or dysfunction (DF) which is induced by a malfunction in another component, which forces the unit to consume more resources to provide more of it product to the system, with the same exergy efficiency. Both mathematical definitions can be seen in Eq. (4) and (5):

$$MF_i = P_i^0 \Delta k_i = \sum_{j=0}^{n} P_i^0 \, \Delta \kappa_{ji} \tag{4}$$

$$DF_i = (k_i - 1) \Delta P_i \tag{5}$$

With the proper analogies, the fuel impaction equation can be rewritten as in Eq. (6) as a sum of the ith component malfunction and the ith component dysfunctions induced by the jth component of the system:

$$\Delta F_T = \sum_{i=1}^{n} \left(MF_i + \sum_{j=1}^{n} DF_{ij} \right) \tag{6}$$

3. THERMOECONOMIC MODELS

One of the first methods to be utilised for this purpose was the E model that considers the whole exergy value of a flow, including its chemical (B^{CH}) and physical parcels (B^{PH}), being more utilised for cost allocation analysis (Santos, 2009), as in Eq. (7). The components of the physical term can be seen in Eq. (8), as the difference of the enthalpy (h) and entropy (s) to its reference states (T_0, P_0). However, this model fails to describe correctly the condenser, as it has no product and only dissipates the system exergy.

$$B = (B^{PH} + B^{CH}) \tag{7}$$

$$B^{PH} = \dot{m}\{h(T, P) - h(T_0, P_0) - T_o[s(T, P) - s(T_0, P_0)]\} \tag{8}$$

With the introduction of the negentropy (Frangopoulos, 1983) as a fictitious flow, the condenser was finally able to be isolated in the productive structure. As in Eq. (9), the negentropy magnitude (S) has a negative contribution to the system exergy and it is considered a resource in the thermoeconomic diagrams, while the other magnitudes have a positive contribution to the system exergy and so, they increase are considered products. The exergy expression of each flux including all of it parcels using the E&S model is represented in Eq. (10), where the terms in parenthesis represent the exergy flow in the productive diagram.

$$S = -\dot{m}T_0[s(T,P) - s(T_0,P_0)] \tag{9}$$

$$B = (B^{PH} + B^{CH}) + S \tag{10}$$

However, there is a criticism of the method (Santos, *et al.*, 2008), because it counts the entropy twice in the analysis, inside (entropic parcel) and outside the exergy term (negentropy). This implies that an equipment could present an exergy efficiency higher than the unity, violating the irreversibility concept, as described in the Second Law of Thermodynamics, and which is also the cause of exergy cost generation. In order to avoid this, the H&S model was proposed (Santos, *et al.,* 2006), where the physical exergy term is now divided into its enthalpic and entropic parcels, as in Eq. (11-13). The terms in parenthesis in Eq. (11) are the parcels in which the physical exergy was disaggregated. Although the condenser could be not correctly described in the structure, valves, for instance, remained unable to be isolated, due to its isenthalpic behaviour.

$$B = (H + S) + B^{CH} \tag{11}$$

$$H = \dot{m}[h(T,P) - h(T_0,P_0)] \tag{12}$$

$$S = -\dot{m}T_0[s(T,P) - s(T_0,P_0)] \tag{13}$$

Aiming to solve this issue and to extend the previous methods to be applied in refrigeration systems, the UFS model was proposed (Lourenço, *et al.*, 2015), which further disaggregates the enthalpy into its internal energy (U) and flow work (F) parcels (Eq. 14-17), where the latter depends exclusively on the flow specific volume (v) and pressure (P). In Eq. (14), the terms between the brackets represent the parcels of the physical exergy and the ones between parentheses, the parcels of its enthalpy. The valve, modelled as an isenthalpic process, could now be isolated in the productive structure since they have as product the increase in flow work, which has the same magnitude as its internal energy reduction, treated as a resource as well as the entropy increase.

$$B = [(U + F) + S] + B^{CH} \tag{14}$$

$$U = \dot{m}[u(T,P) - u(T_0,P_0)] \tag{15}$$

$$F = \dot{m}[Pv(T,P) - P_0v(T_0,P_0)] \tag{16}$$

$$S = -\dot{m}T_0[s(T,P) - s(T_0,P_0)] \tag{17}$$

All the thermodynamic magnitudes mentioned above are present in all thermoeconomic models; however, they can be gathered in the same flow in the productive diagram representation. In this work, as there is no chemical composition change of the flow, the parcel of chemical exergy is not going to be represented in the thermoeconomic diagrams.

4. METHODOLOGY

In order to prove the efficiency and accuracy of the thermoeconomic models for diagnosis, a simple Rankine cycle composed by a pump, a Steam Generator (SG), a turbine and a condenser is analysed, whose system representation and Figure 1 and Table 1, respectively. It provides a net power (W_L) of 20,000 kW, utilising methane as fuel, with exergetic consumption (Q_F) of 70,000 kW, the required power by the pump (W_P) is 155 kW and the required power by the cooling system (W_C) is 75 kW. All fluids properties were obtained with the software EES®.
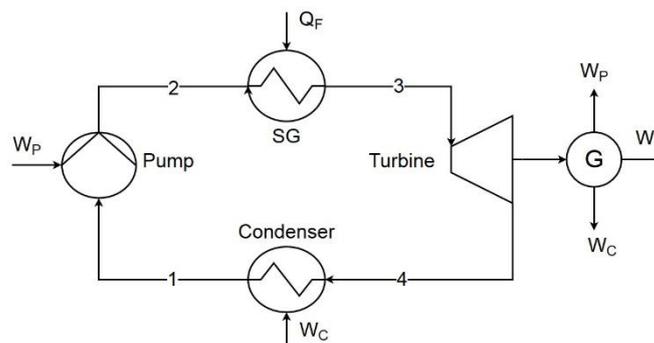

Figure 1. Physical representation of the proposed Rankine cycle.

Table 1. Physical states of the Rankine Cycle flows.

Flow	Description	T (°C)	P (bar)	$\dot{m}$ (kg/s)
Ref.	Environment	25.00	1.01	-
1	Water	39.04	0.07	19.5
2	Water	39.50	63.00	19.5
3	Steam	500.00	60.00	19.5
4	Mixture (x=0.9)	39.04	0.07	19.5

Even knowing that all the system components adapt their behaviour in the presence of one single fault, some conditions were maintained by the control system of the plant: The temperature in the turbine inlet will be 500 °C; the fluid will leave the condenser as saturated liquid; the efficiencies of the generator (G) and the pump motor will be held at 95 and 96 %, respectively; and the required power for the cooling pump (W_c) of the condenser will be 75 kW.

Afterwards, five different anomalies are simulated and its impact on resource consumption is analysed with the fuel impact formula. The final product is not modified in any simulation (W_L) for interpretation easiness. Anomalies 1, 2 and 4 are a 10% reduction in the thermal efficiency of the Steam Generator (η_{SG}), the isentropic efficiency of the turbine ($\eta_{turbine}$) and the pump (η_{pump}), respectively. Anomaly 3 is a 10% ofreduction in the vacuum of the condenser (P_{cond}) and Anomaly 5 is all the previous ones combined. The overview of the anomalies along its respective control parameters in the system can be seen in Table 2. Even though all anomalies are studied, the condenser issue is discussed here in more detail.

Table 2. Anomalies imposed in the system.

	Reference	Anomaly 1	Anomaly 2	Anomaly 3	Anomaly 4	Anomaly 5
$\eta_{turbine}$	0.849	0.849	0.749	0.849	0.849	0.749
η_{pump}	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_{cond} (bar)	0.070	0.070	0.070	0.160	0.070	0.160

Four different productive diagrams are used for the analysis and the respective productive structure for each of them are in Figure 2. Each flow is shown as X_{ij}, which represents the thermodynamic magnitude variation from the ith to the jth state. Each magnitude that increases its value exiting a component is considered as a product and the opposite behaviour as a resource. Only the negentropy and entropic parcels have the opposite behaviour, as they are considered negative contributions for the system's exergy. The condenser, for instance, consumes exergy and produces negentropy in the E&S Model.
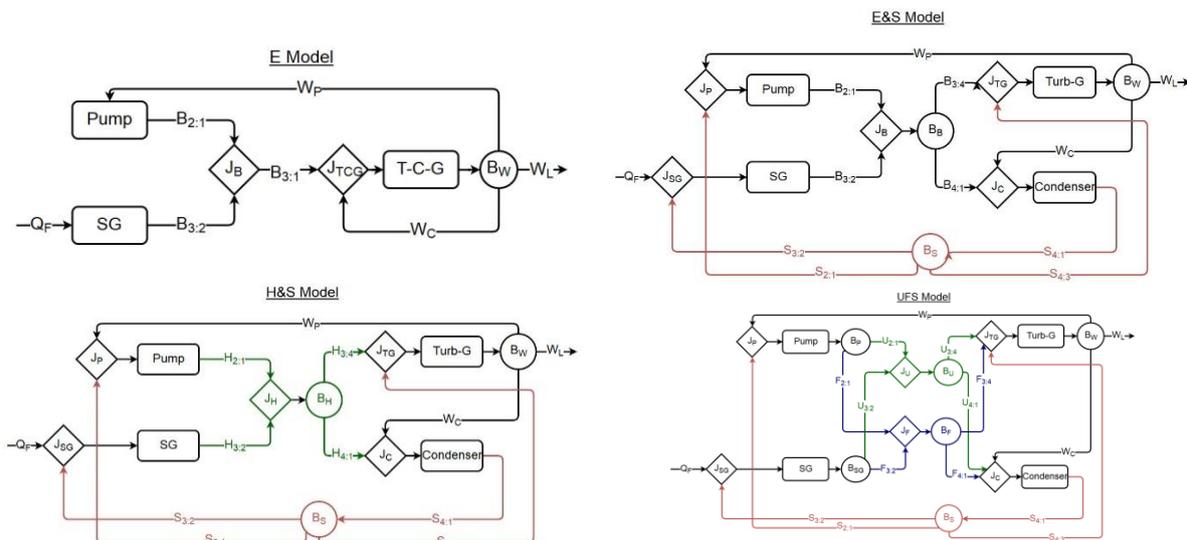

Figure 2. Productive structures of the thermoeconomic models.

As can be seen in Figure 2, it is impossible to isolate the condenser in the E model, due to its lack of exergetic product. For this reason, the condenser and the turbine, along with the generator, are considered as a single unit. For the other models, each component can be isolated in the productive structure, changing its respective products and resources accordingly to the disaggregation method utilised.

5. RESULTS AND DISCUSSION

The values of the system relevant variables for the reference condition and the faults can be seen in Table 3: The power required by the pump (W_P), the fuel consumption (Q_F), the system exergetic efficiency (ε_{system}), the mass flow rate ($\dot{m}$), the heat removed by the condenser (Q_{cond}) and the fluid quality at the turbine outlet (x_4). It can be observed that the exergetic efficiency of the system drop significantly for the all faults scenario while remaining almost the same for the anomaly in the pump, which can be inferred that an anomaly in this component does not cause a great exergetic impact in the whole system. In contrast, the same efficiency reduction in the turbine and in the SG causes around 13% increase in the fuel consumption. The significant rise in the Q_{cond} in anomalies 2 and 3 are a huge contributor to the exergy efficiency reduction.

Table 3. Relevant variables for all analysed conditions.

Variable	Reference State	Anomaly 1 SG	Anomaly 2 Turbine	Anomaly 3 Condenser	Anomaly 4 Pump	Anomaly 5 All faults
W_p (kW)	155.0	155.0	175.9	169.4	176.5	218.8
Q_F (kW)	70,000	78,695	79,434	74,457	70,058	95,074
ε_{system}	0.2857	0.2541	0.2518	0.2686	0.2855	0.2104
$\dot{m}$ (kg/s)	19.5	19.5	22.13	21.19	19.52	24.07
Q_{cond} (kW)	42,267	42,267	50,805	46,298	42,312	55,458
x_4	0.90	0.90	0.95	0.92	0.90	0.97

The fuel impact, dysfunctions and malfunctions for each component in all anomalies and models studied can be seen in Table 4. Firstly, it is clearly observed that the thermoeconomic model utilized does not affect the total fuel impact for each anomaly, however, the value of DF and MF differs in each model. This occurs due to the different parcels of exergy that are considered as resource and product, which change the κ_{ij}, MF and DF values accordingly Eq. (4) and (5). The E&S disaggregation presents a higher difference, owing to its implicit double consideration of negentropy in the productive structure, making its values more expressive than the other models.

For all cases, negative DF values are observed for the condenser only in the E&S. Conceptually, dysfunction represents how much irreversibility is generated in the component, considering that it has the same efficiency as the reference condition, as in Eq. (5). Negative values imply a reduction in the product of the condenser, however, the other system components are requiring more entropy on account of faults, making this term a positive value. Therefore, DF can be negative only if it has an exergetic unit consumption smaller than the unity and, which is impossible, and represents an inconsistency in the application of thermoeconomic diagnosis.

Additionally, with the E model, it is not possible to treat dissipative components, as the condenser, separately, which is a drawback for diagnosis interpretation, since it is not possible to identify the faulty component, only reducing the available options. The H&S and UFS models presented around the same MF and DF values in all cases studied. When the fault occurs in a more advanced process of production the dysfunctions can be greater than the malfunctions, which is clearly described when comparing the anomalies in the SG and in the condenser, where the first presented, basically, only the malfunction. Torres, *et al.*, 2002, observed the same behaviour in his studies in a gas turbine cycle.

Table 4. Fuel impact due to each anomaly in E, E&S, H&S and UFS thermoeconomic models.

A) Anomaly 1 - SG 10% isentropic reduction

Fuel impact (kW)	E DF	E MF	E&S DF	E&S MF	H&S DF	H&S MF	UFS DF	UFS MF
SG	4	8,689	7	8,689	2	8,693	3	8,691
Pump	0	0	0	0	0	0	0	0
Turbine	0	2	0	3	0	2	0	1
Condenser			-3	0	0	0	0	0
Total	4	8,692	4	8,692	3	8,694	3	8,692
Total	8,695		8,696		8,697		8,695	

B) Anomaly 2 - Turbine 10% isentropic reduction

Fuel impact (kW)	E DF	E MF	E&S DF	E&S MF	H&S DF	H&S MF	UFS DF	UFS MF
SG	5,839	1	10,788	1	5,838	2	5,838	2
Pump	4	0	7	0	4	0	4	0
Turbine	11	3,579	15	6,397	8	3,199	8	3,198
Condenser			-7,761	-13	396	-12	396	-13
Total	5,854	3,581	3,049	6,385	6,246	3,189	6,246	3,187
Total	9,434		9,434		9,435		9,433	

C) Anomaly 3 - Condenser 10% vacuum reduction

Fuel impact (kW)	E DF	E MF	E&S DF	E&S MF	H&S DF	H&S MF	UFS DF	UFS MF
SG	3,565	-1,255	6,581	-2,393	2,796	-485	2,796	-485
Pump	3	-1	5	-3	3	-1	3	-1
Turbine	6	2,252	6	-364	3	-182	3	-182
Condenser			-1,520	2,259	178	2,260	178	2,260
Total	3,574	996	5,072	-501	2,980	1,592	2,980	1,592
Total	4,570		4,571		4,572		4,572	

D) Anomaly 4 - Pump 10% isentropic reduction

Fuel impact (kW)	E DF	E MF	E&S DF	E&S MF	H&S DF	H&S MF	UFS DF	UFS MF
SG	45	-18	84	-36	33	-5	33	-5
Pump	0	20	1	39	6	14	6	14
Turbine	7	0	9	1	5	1	5	0
Condenser			-41	0	2	-2	2	-2
Total	53	2	53	4	46	8	46	7
Total	55		56		54		53	

Fuel impact (kW)	E		E&S		H&S		UFS	
	DF	MF	DF	MF	DF	MF	DF	MF
SG	11,648	7,288	19,840	6,159	10,729	8,208	10,729	8,208
Pump	13	17	24	33	18	12	18	12
Turbine	40	6,068	44	5,720	24	2,860	24	2,859
Condenser			-8,941	2,194	1,029	2,195	1,029	2,195
	11,701	13,373	10,967	14,106	11,800	13,275	11,800	13,274
Total	25,074		25,073		25,075		25,074	

<p style="text-align:center">E) Anomaly 5 - Anomalies 1, 2, 3 e 4 combined</p>

Furthermore, Anomaly 1 restricts the inefficiencies only to SG, mostly because it is the input of the system resource, not affecting the other equipment. Although, the same behaviour is not observed in the other simulations, which anomalies were induced in other system elements. For this reason, the highest dysfunction values are found in the SG for all faults. For anomalies 1-4, the component with the intrinsic malfunction is easily identified for being the only one with positive MF values, while the others have negative values, representing an induced malfunction. Whereas, this behaviour is not seen in Anomaly 5, which handicap the identification of the faulty components. A deeper analysis to separate the intrinsic from the induced malfunction can be achieved using the performance curves from each component as, e.g., described by the reconciliation method (Zaleta, *et al.*, 2004) or by the transition structure (Orozco, *et al.*, 2017).

The anomaly 5 malfunctions for each component are roughly the sum of each individual anomaly, where a linear relationship among them can be inferred (Valero, *et al.*, 2002). Yet, the same behaviour is not observed for the dysfunctions. In all anomalies, there is no DF in the turbine because it was an assumption of this work, not to change the final net power provided by the system, the smaller changes are due to the increase in the power required by the pump.

Anomaly 5 is the most likely scenario to occur in a real diagnosis analysis, where faults could be present randomly in every component of the system. To optimise maintenance planning, the equipment which higher potential of fuel saving should be prioritised, which could be done evaluating the combination of its malfunction and its Induced Dysfunctions (ID) in other components, as in Figure 3. Even though the turbine has a smaller MF than the Steam Generator, it induces great values of dysfunctions in other components, representing a total fuel impact of 10,679 kW, having a higher value than the SG, with 6,890 kW. Albeit the models present different values of MF and ID for each component, the total value of its fuel impact does not change, therefore, the thermoeconomic model does not interfere with the correct choice of maintenance priorities. Valero, *et al.*, 2002, observed that the total fuel impact is not affected by the exergy disaggregation scheme, however, as shown in this study, further thermoeconomic methods can change the values of MF and DF, even if the total fuel impact per component is the same. The only issue would be the E Model, because it is impossible to identify which equipment has the highest Fuel Impact, turbine or condenser, due to the impossibility of disaggregation.
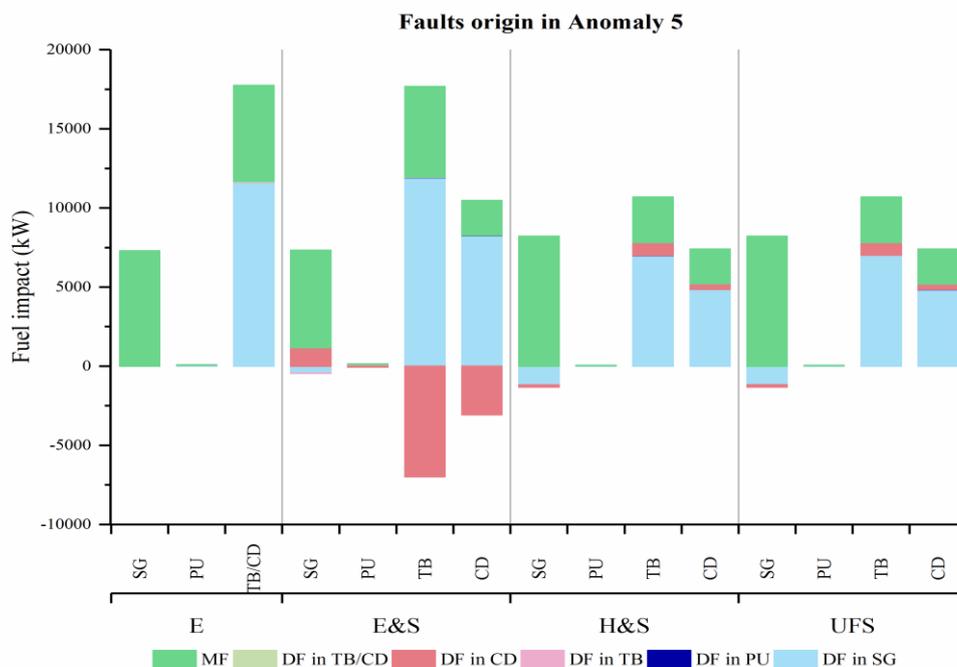

Figure 3. Faults origin in Anomaly 5 for each component and thermoeconomic model.

Although the fuel impact caused by each component does not change with the thermoeconomic model, the Dysfunction and Malfunctions distribution can be modified, especially for the E&S model, which presented more expressive variations, accordingly to Table 4.

Analysing the unitary exergy consumption for anomaly 3 in Table 5, it is possible to notice that each component that presents a negative malfunction (induced malfunction), have also a reduction of its exergetic consumption, which can be seen as an exergetic efficiency improvement. The opposite behaviour is observed for the condenser, which has a positive malfunction, as expected. The H&S and UFS models have not presented difference in the κ values because the extra level of disaggregation does not affect these specific components, but this is a not a general rule, especially for more complex systems with components as valves, when the flow work and internal energy variations are considered product and resource, respectively (Lourenço, *et al.*, 2015).

Table 5. Unitary exergetic consumptions for anomaly 3.

κ (kW/kW)	Reference				Anomaly 3 - Condenser			
	E	E&S	H&S	UFS	E	E&S	H&S	UFS
SG	2.624	4.001	1.683	1.683	2.577	3.912	1.676	1.676
Pump	1.240	1.438	1.204	1.204	1.231	1.414	1.195	1.196
Turbine	1.328	1.410	1.231	1.231	1.440	1.392	1.222	1.222
Condenser		0.049	1.049	1.049		0.105	1.105	1.105
Cycle	**3.50**				**3.73**			

Owing to the limitation of the E&S model for using the negentropy twice (in and out the exergy parcel), the unitary exergetic consumption of the condenser is smaller than the unity, indicating that it produces more entropy than consumes exergy, which is thermodynamically impossible by the Second Law of Thermodynamics (Santos, *et al.*, 2008).

The DF induced by each component for each model in anomaly 3 is represented in Figure 4. In the E model, the turbine-condenser induces a dysfunction in itself and a negative malfunction in the SG. For the H&S and UFS models, the induced malfunctions in the turbine and SG are the reason for the dysfunctions induced by them in other equipment. In the E&S model, the negative dysfunction that the condenser induces in itself, represented by the red bar, is the increase in the negentropy production to meet the requirements of the other components production, leading to an efficiency increase. For all models, the dysfunctions induced by the system elements with no faults are negative due to its efficiency improvement, as can be seen in Table 5, i.e., they require fewer resources.
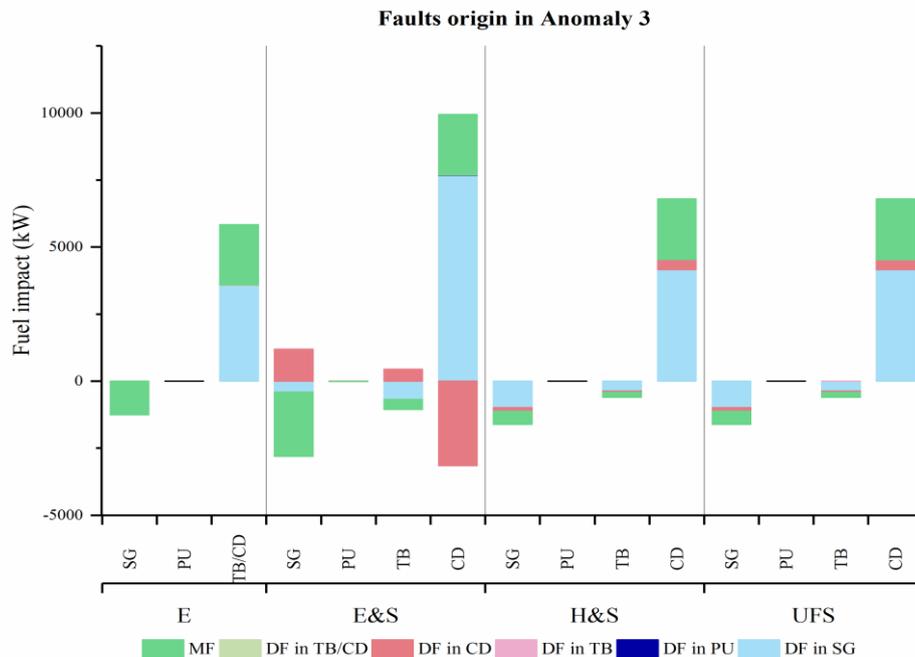

Figure 4. Faults origin in Anomaly 3 for each component and thermoeconomic model.

6. CONCLUSIONS

The thermoeconomic diagnosis for a simple Rankine Cycle was performed with E, E&S, H&S and UFS productive structures for five different fault conditions.

Firstly, the E model is not adequate for thermal diagnosis since it is not possible to separate the condenser from the other components due to the method limitation to isolate dissipative components, which can be even worse for complex thermal systems. Secondly, E&S model presented thermodynamic inaccuracies for the condenser, since its efficiency was higher than the unity, overestimating the impact of each anomaly per component. Finally, the condenser could only be isolated, in a coherent thermodynamic manner, with the H&S and UFS models. Although the UFS provides more accuracy, its increase for this system does not compensate the model complexity enhancement, as the results were very similar to the H&S. A larger difference would be seen in the presence of valves or other expansion devices.

Moreover, the total fuel impact does not change for an anomaly, independent of the disaggregation method adopted, however, the values of MF and DF for the whole system and per component varies with the adopted model. The total fuel impact in each component it is not dependent on the thermoeconomic methodology, still, the same behaviour is not observed in E&S, presenting greater absolute values of MF and DF, since negentropy is applied twice.

Furthermore, the thermoeconomic models do not affect the identification of the component that it is causing the highest impact in the system, though it can change quantitatively how it distributes its impact to the other system elements. The malfunction occurring in simultaneous faults is roughly the sum of the malfunction of the faults individually, which can lead to further improvements in predictions of malfunctions locations in reverse problems. To further analysis, the intrinsic malfunctions could be identified through the performance curves of each component applying, for instance, the reconciliation method.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE