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AN EVALUATION OF THERMOECONOMIC DIAGNOSIS THROUGH THE LOCALIZED DISAGGREGATION IN A REFRIGERATION SYSTEM

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Abstract. *Thermoeconomics can be defined as the energetic efficiency science that joins concepts of the Second Law of Thermodynamics with ones from economic analysis. With this new approach, issues related to local optimization, operational diagnosis, and rational cost assessment of the plant final products could now be addressed. The thermoeconomic diagnosis is applied to identify the source of extra fuel consumption in each system element due to the presence of anomalies. The physical exergy disaggregation (E^T&E^M, H&S and UFS Models) has been introduced as an alternative for treatment of dissipative components and improvement of the results accuracy. However, it increases the complexity of the model. In this work, a refrigeration system with different simulated anomalies is evaluated by combining four different methodologies (E, E^T&E^M, H&S, and UFS Models) in order to perform a localized physical disaggregation only in the dissipative components (condenser and valve). The results show that the diagnosis analysis using localized physical disaggregation is able to isolate the condenser and valve. Furthermore, the E Model with localized UFS Model, the E Model with localized H&S, and UFS Models and E Model with localized E^T&E^M Model, present similar and coherent results of malfunctions and dysfunctions.*

Keywords: *diagnosis, productive diagram, physical exergy disaggregation, localized disaggregation, thermoeconomics*

1. INTRODUCTION

Thermoeconomics can be defined as the energetic efficiency science that joins concepts of the Second Law of Thermodynamics with ones from economic analysis, being mainly applied to solve problems in complex systems where the exclusive use of the First Law of Thermodynamics (mass and energy balances) in conventional analysis methods would not be enough (Erlach *et al.* 1999). With this new approach, issues related to local optimization, operational diagnosis, and rational cost assessment of the plant final products could now be addressed.

Sometimes, under a thermoeconomic analysis, it is necessary to consider the components as a group of subsystems and/or the exergy flows consisting of several components, i.e., thermal and mechanical components, as the more disaggregated is the system the more accurate are the results (Torres et al. 1996). Depending on the type of analysis, different levels of accuracy of the results are required, i.e., each thermoeconomic analysis requires a specific disaggregation level of the components and flows (Valero et al. 2006). For local optimization and diagnosis, for instance, total disaggregation of the components of the system is generally required. In agreement with (Lozano & Valero 1993), the deeper and more detailed the disaggregation is, the clearer the interpretation of the obtained costs will be and the wider the catalog of applications to theoretical and practical problems.

In the last years, new kinds of physical exergy disaggregation have been introduced in thermoeconomics as consistent alternatives to disaggregate the dissipative components of the systems and allocate the cost of the residues to the final products. In the case of condensers, a solution was proposed by (Frangopoulos 1983, 1987) to define its product and input. It uses a fictitious flow called negentropy, which is considered the product of the condenser, and exergy, as its input. In this way, the condenser becomes the negentropy supplier for the system. Some researchers have found that this fictitious flow generates inconsistent results when used in conjunction with total exergy (Santos 2009; Santos *et al.* 2006). These inconsistent results were resolved by H&S Model that defines the productive structure by disaggregating the physical exergy into enthalpic and entropic components. This kind of physical exergy disaggregation was introduced by (Santos et al. 2006, 2009) and it was proposed as an alternative exergy disaggregation methodology to isolate condensers. The total physical exergy is defined as the difference between the enthalpic and entropic components.

Despite the H&S disaggregation defines condenser input and product, the same is not possible for valves, as identified by (Lourenço et al. 2011). One proposes of solution for the valve is the use of thermal and mechanical exergy disaggregation (E^T&E^M Model) with the calculation methodology presented by (Tsatsaronis 1993). However, the methodologies are arbitrary and the disaggregation does not define input and product for refrigeration cycle valves and depends on the state of the fluid at the valve inlet (de Faria 2014). Thus, (Lourenço et al. 2011) looking for an alternative for disaggregation of valves, presented the UFS Model that utilizes physical exergy disaggregation into internal energy (U), work flow (F), and entropic term (S) (UFS Model). It was the first methodology of exergy disaggregation capable of consistently isolating valves. This level disaggregates the enthalpic term in internal energy and work flow and maintains the entropic one. Nevertheless, when the thermoeconomist chooses one of these methodologies, the productive diagrams greatly increase the complexity. At this point, an approach to reduce this complexity in thermoeconomics is needed.

For plants with dissipative equipment, such as the condenser or valve, the productive diagram, based on total exergy (E Model), needs to join this dissipative equipment with other productive equipment. Bearing this in mind, it is possible to combine E Model with other models, in a localized physical exergy disaggregation, to adequately isolate the dissipative equipment with less complexity associated, as shown in (Santos *et al.* 2020b).

In this work, a refrigeration system with different simulated anomalies is evaluated by combining four different methodologies (E, E^T&E^M, H&S, and UFS Models). This paper aims to perform a localized physical disaggregation only in the dissipative components (condenser and valve) in the thermoeconomic diagnosis in a refrigeration system. It is worth mentioning that E, H&S, and E^T&E^M Models are unable to isolate and treat the condenser and/or valve, so this study combines at least two methodologies that are capable of doing it. The fuel impact formula is used as a thermoeconomic diagnosis methodology to quantify the effects of each malfunction and evaluate the complexity involved. The novelty of this work is related to the idea of applying localized physical exergy disaggregation in the thermoeconomic diagnosis in a refrigeration system, in other words, whether using localized disaggregation is possible to identify and quantify the anomalies in the diagnosis.

2. FUEL IMPACT FORMULA

The diagnosis method used is the “Fuel Impact Formula”(Valero 2004), which identifies and quantifies anomalies in each component of a thermal system comparing two different conditions: one considered as a reference or design (x°); and the other one as an operational condition (x) with the presence of anomalies or faults. The main index is the variation of the unitary exergetic consumption (k_{ij}) in Eq. (1), where R_{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.

$$K_{ij} = \frac{R_{ij}}{P_j} \tag{1}$$

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

$$K_{ij}^{*} = \frac{E_{ij}^{*}}{E_{ij}} \tag{2}$$

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.

$$\Delta F_T = \sum_{i=1}^{n}\left(\sum_{j=0}^{n} K_{pj}^{*}\Delta K_{ij}\right) \tag{3}$$

According 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. The latter, forces the unit to consume more resources to provide more of its product to the system, with the same exergy efficiency. Both mathematical definitions can be seen in Eqs. (4) and (5).

$$MF_i = P_i^0 \Delta K_i = \sum_{j=0}^{n} P_i^0 \Delta K_{ji} \quad (4)$$

$$DF_i = (K_i - 1) \cdot \Delta P_i \quad (5)$$

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

$$\Delta F_T = \sum_{i=1}^{n} \left(MF_i + \sum_{j=0}^{n} D_{ij} \right) \quad (6)$$

3. THERMOECONOMIC MODELS

The physical exergy of the flow (E_F) is given by Eq. (7), for productive diagram definition, i.e., exergy without disaggregation, called here E Model. Nevertheless, this model does not provide any additional advantage for dissipative equipment isolation because it cannot define a product to this kind of equipment (e.g., the condenser) and isolate it into the productive diagram.

$$E_F = \dot{m}\left[(h - h_0) - T \cdot (s - s_0) \right] \quad (7)$$

The physical exergy disaggregated into thermal and mechanical components could be used as a possible solution. In Eq. (8) the thermal exergy term is defined along the isobaric line at P, from state [T, P] to state [T_0, P]. On the other hand, in Eq. (9) the mechanical exergy term is defined along the isothermal line at T_0 (temperature at "0" state), from state [T_0, P]. to state [T_0, P_0]. Therefore, the auxiliary specific enthalpy, h_m ,and auxiliary specific entropic, s_m , are defined for state [T_0, P].

$$E^T = \dot{m}\left[(h - h_m) - T_0 \cdot (s - s_m) \right] \quad (8)$$

$$E^M = \dot{m}\left[(h_m - h_0) - T_0 \cdot (s_m - s_0) \right] \quad (9)$$

It increases the complexity of the model, although it improves the accuracy of the results in thermoeconomic analyses. Furthermore, this splitting might not be always meaningful, as it can contain arbitrariness involved in the distinct calculation of mechanical and thermal components, particularly when using working fluids that can change phases in the process under consideration, as the real fluids (Lazzaretto & Tsatsaronis 2006). Therefore, at the level of verification and comparison, in this work, in addition to using this methodology that fixes the temperature (T_0) and varies the pressure point to point, an approach will also be made setting the pressure (P_0) and varying the point-to-point temperature. This approach will be called E^{T*}&E^{M*}, this idea was used in (de Faria 2014).

Bearing this in mind and to overcome the arbitrariness mentioned above, the H&S Model (Santos et al. 2006, 2009), a thermoeconomic methodology of exergy disaggregation, has been proposed already considering the residue cost allocation and the dissipative component treatment/isolation. In its productive diagram, the fuels and the products of each productive unit are systematically defined by taking into account all enthalpy, entropy, and also chemical exergy variations, additions and removals from all the streams.

The productive flows in the H&S Model are defined using the variation of the enthalpic ($H_{i:j)}$ and entropic ($S_{i:j}$) components of the exergy between two physical states, i and j, respectively. In other words, the physical exergy of a mass flow can be divided into two alternative components/terms: enthalpic (H) and entropic (S), as shown (Lourenço *et al.* 2014). Therefore, it is able to define a product to the dissipative components based on the entropic component of the exergy. For instance the condenser has now its product defined by the variation of entropic term, whilst its resource is the reduction of the enthalpic term. Thus, the condenser is isolated automatically as an inherent feature of the model. This thermoeconomic model also introduces explicitly the chemical exergy flows in the productive diagram. However, in this case study there is no such component because the working fluid does not have its composition changed.

The UFS Model (Lourenço *et al.* 2011) maintains the entropic term from Eq. (7) and disaggregates the enthalpic term in terms of internal energy (U) and flow work (F), which be calculated with Eqs. (10) and (11), respectively.

$$U = \dot{m}\cdot\left(u - u_0\right) \tag{10}$$

$$F = \dot{m}\cdot\left(P\cdot\upsilon - P_0\cdot\upsilon_0\right) \tag{11}$$

4. CASE STUDY

In order to evaluate whether the diagnosis analysis through the model using localized physical disaggregation is able to treat the dissipative component and present coherent results of diagnosis point of view, a vapor compression refrigeration system is studied, whose dissipative component are condenser and valve.

4.1.1 Physical Structure

The system's working fluid is Refrigerant R134a with a flow rate of 0.0796 kg/s extracting 12.08 kW of heat from the cold region at 0 °C through the evaporator and rejecting heat into the hot region at 26 °C through the condenser. The useful exergy taken from the cold region (E_{Useful}) corresponds to -1.15 kW. The compressor consumes 2.83 kW to increase the fluid pressure from 201.1 kPa to 900.9 kPa and has an isentropic (η_{CMP}) efficiency of 90%. The exergetic reference conditions are the same as in the hot environment, corresponding to 26 °C (T_0) and 1 atm (P_0). Figure 1 shows the physical structure of the refrigeration system.

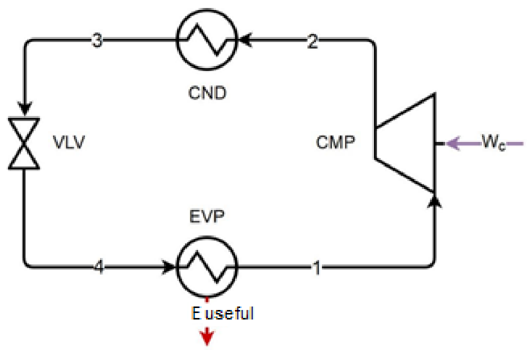

Figure 1. The physical structure of the refrigeration system. Available from (Lorenzoni 2017)

Table 1 shows the thermodynamic data for the refrigeration system in reference conditions. All fluids properties were obtained with the software EES®. The data related to the exergetic reference state (T_0 = 26 °C and P_0 = 1 atm). Others information are available from (Lorenzoni 2017).

Table 1. Thermodynamic data for the refrigeration system in reference conditions. Available from (Lorenzoni 2017).

Flows	T (°C)	P (kPa)	E (kW)	S (kW)	H (kW)	U (kW)	F (kW)	E^T (kW)	E^M (kW)	E^{T*} (kW)	E^{M*} (kW)
1	-4.80	201.10	1.408	-3.671	-2.263	-1.991	-0.271	0.117	1.291	0.113	1.295
2	49.80	900.90	3.976	-3.407	0.569	0.697	-0.128	0.493	3.483	0.062	3.914
3	32.50	900.90	3.491	-17.830	-14.340	-12.500	-1.840	0.008	3.483	0.005	3.486
4	-9.80	201.10	3.054	-17.400	-14.340	-12.900	-1.441	1.763	1.291	0.153	2.901

To compare thermoeconomic methodologies in the diagnosis analysis, five different anomalies are simulated in the system and their influences on the consumption of additional resources are analyzed by the Fuel Impact Formula. Anomaly 1 is the reduction of 5 percentage points in the isentropic efficiency of the compressor (η_{CMP}), anomaly 2 is the 5% decrease in the fluid pressure during the passage of the fluid through the condenser, anomaly 3 is the extra 5% reduction in the fluid pressure during the thermostatic valve, anomaly 4 is the 5% pressure loss during fluid flow through the evaporator and anomaly 5 is the combination of Anomalies 1 to 4. The overview of the anomalies along with their respective control parameters in the system can be seen in Table 2.

Table 2. Thermodynamic data for the refrigeration system in reference conditions. Available from (Lorenzoni 2017).

	Reference	**Anomaly 1**	**Anomaly 2**	**Anomaly 3**	**Anomaly 4**	**Anomaly 5**
η_{CMP}	0.900	0.850	0.900	0.900	0.900	0.850
P_3 (kPa)	900.9	900.9	855.9	900.9	900.9	855.9
P_4 (kPa)	201.1	201.1	156.1	166.1	201.1	121.1
P_1 (kPa)	201.1	201.1	156.1	166.1	191.1	115.0

4.1.2 Conventional Thermoeconomic Diagrams with Physical Exergy Disaggregation

Figures 2a-2c show the productive diagrams of the refrigeration system using the E Model, which uses total exergy flows (E) as the thermodynamic magnitude to define the productive structure, with localized physical exergy disaggregation. The only external resource of the system is the mechanical power (W_C). The rectangles are the real units (or subsystems) that represent the actual equipment of the system. The rhombus and the circles are fictitious units called junction (J) and bifurcations (B), respectively. Each productive unit of Figures 2a-2c has inlet and outlet arrows, that represent its fuel (or resource) and products, respectively.

The E Model cannot define a product for the condenser (CND) and the valve (VLV). Hence cannot isolate them in the productive structure. The H&S Model was the first exergy disaggregation methodology capable to isolate (without inconsistencies) condensers in the productive diagrams, although it cannot define a product for the valve. The E^T&E^M Model is the opposite, it cannot isolate the condenser, however, it is capable to isolate the valve (the same idea for the E^{T*}&E^{M*}). The UFS Model was the first methodology of exergy disaggregation capable consistently to isolate valves. It disaggregates the enthalpic term in internal energy and work flow and maintains the entropic one.

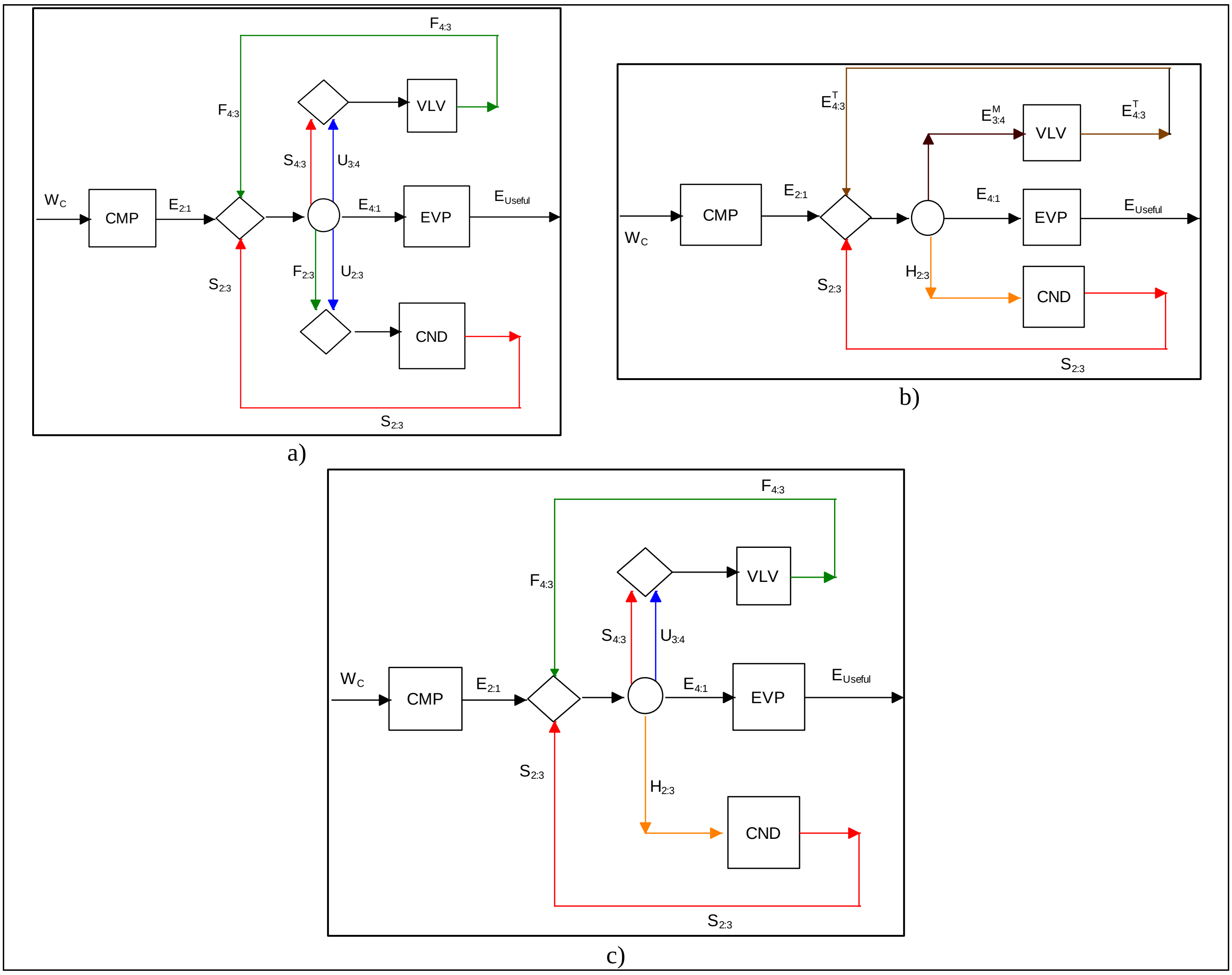

Figure 2. Productive Structure for the Refrigeration System using: a) E Model and Localized UFS Model; b) E Model and Localized H&S and E^T&E^M Models; c) E Model and Localized UFS and H&S Models.

As already mentioned, the E and $E^T\&E^M$ Models are not able to define a product to the condenser and the H&S Model is not able to define a product to the valve. On the other hand, the UFS Model can define a product and consequently isolate this equipment. Nonetheless, it considerably increases the complexity of the productive structure. At this point, the idea of localized physical exergy disaggregation arises proposing to combine these methodologies in the productive structure. In Figure 2a, the E Model is being used in all components, except in the condenser and valve where the UFS Model must be used (E-UFS). Hence, the complexity is reduced. Furthermore, it is worth mentioning that the exergetic balance at the junction/bifurcation remains consistent. In Figure 2b, the E Model is being used in all components, except in the condenser where H&S Model should be used, and valve where the $E^T\&E^M$ or $E^{T*}\&E^{M*}$ Model can be used (E-H&S- $E^T\&E^M$). It is worth mentioning, that the productive diagram using $E^T\&E^M$ or $E^{T*}\&E^{M*}$ is the same. The difference between Figures 2b and 2c (E-H&S-UFS) is the kind of disaggregation used in the valve, in this case, it uses the UFS Model. These combinations (E-UFS, E-H&S-UFS, E-H&S-$E^T\&E^{M,}$ E-H&S-$E^{T*}\&E^{M*}$) are called "Localized physical exergy disaggregation" which was proposed by (Santos et al. 2020a, 2020b).

It is noteworthy that, as the level of disaggregation increases, the number of flows, the complexity of the productive structure, the computational efforts, and the complexities involved in modeling also increases. The productive structure of E-UFS is the highest complexity of this study, whereas the E-H&S-$E^T\&E^M$ is the lowest.

5. RESULTS AND DISCUSSION

The models, in some cases, have presented different values of MF and DF for each component, as can be seen in Figures 3-7. The same figures show the malfunctions and dysfunctions induced by each component of the system for each model. All methodologies proposed are capable to identify the faulty component in Anomaly 1. Figure 3 clearly shows the highest value associated with the compressor. It is worth mentioning, that Anomaly 1 restricts the inefficiencies only to CMP, mostly because it is the input of the system resource, not affecting the other equipment. It is also observed small values of dysfunctions in all methodologies due to the difference in the thermodynamic state of the fluid downstream of the compressor.

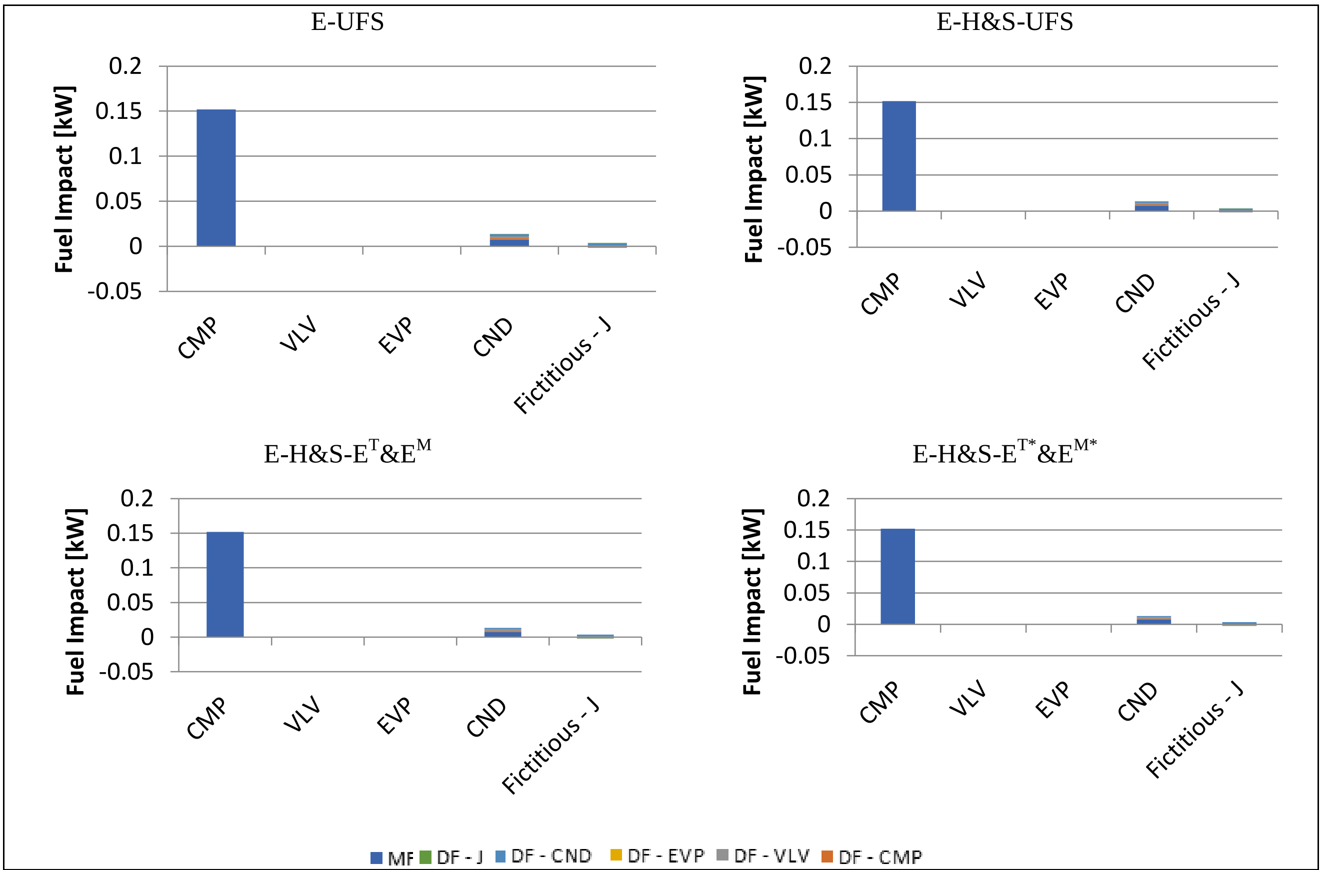

Figure 3. Faults origin in refrigeration system Anomaly 1 for each component and thermoeconomic model.

Figure 4 shows the results due to anomaly 2. It is not possible to identify the subsystem with MF. Although in this anomaly the condenser has a reduced pressure value, the highest MF value is associated with the EVP. Only for this analysis, the evaporator is wrongly identified as a defective component due to the presence of faults in large quantities.

All models have similar trends. It is important to highlight that, the fictitious units induce anomalies in other real components, although they do not have any dysfunctions or malfunctions in them This behavior was also observed by (Lorenzoni *et al.* 2020; Piacentino & Talamo 2013). Negative values of DF were found in the valve in the E- H&S-E^{T*}&E^{M*} Model. It happens due to a component product reduction when compared to the reference state.

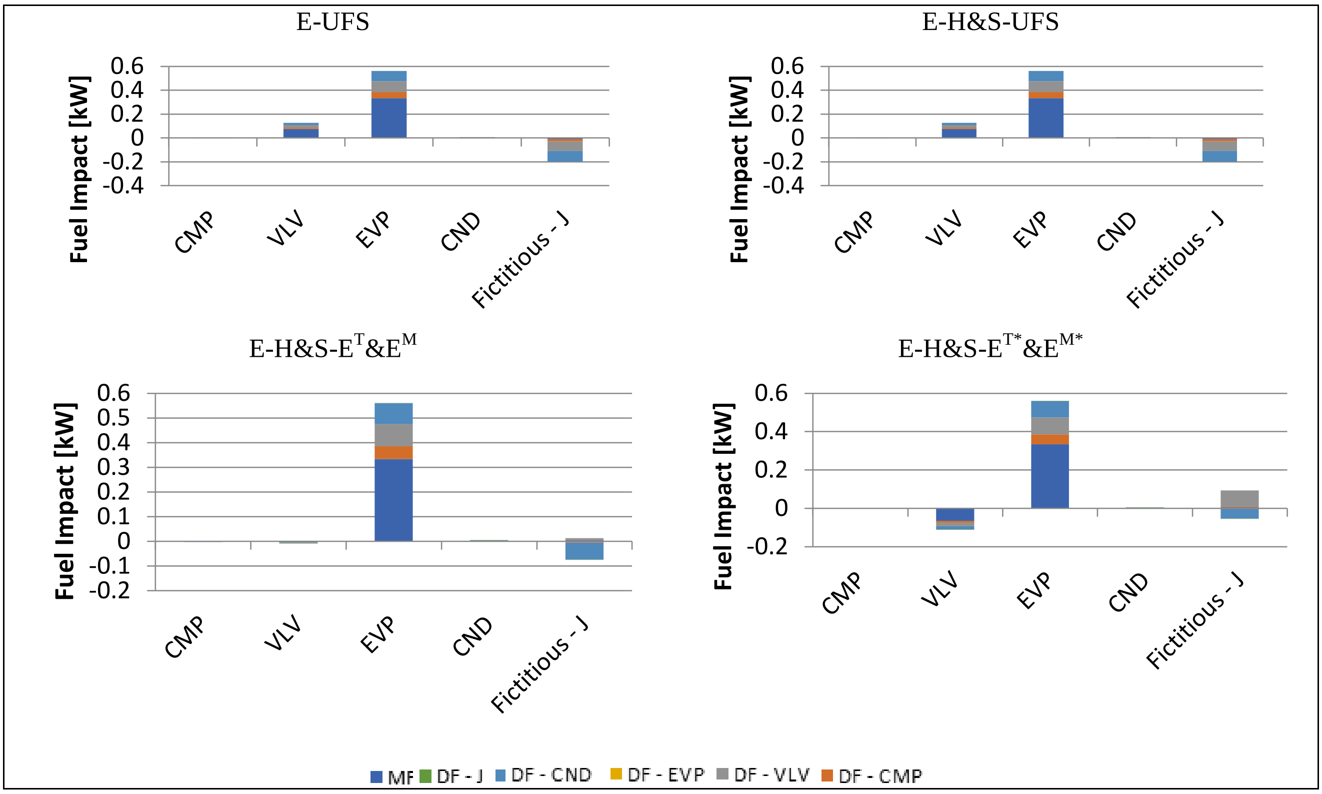

Figure 4. Faults origin in refrigeration system Anomaly 2 for each component and thermoeconomic model.

Although the results of Figure 5 shows a value of MF associate with the valve, the highest value of MF can be observed with the EVP. One more time, it is not to possible identifying correctly the subsystem with the MF and the fictitious units also induce anomalies in other real components. In this case, for all models, the CMP does not have any DF or MF and the evaporator cause dysfunctions in all others subsystem.

Figure 6 shows the origin of the failures in anomaly 4. For this anomaly the research presents coherent results, since all methodologies proposed are capable to identify Anomaly 4 and the evaporator shows the highest value of malfunctions. In the other components the models present the same trend, including the fictitious units, which also induce anomalies in other real components, except the evaporator.

Figure 7 shows the faults origin in the refrigeration system for anomaly 5 for each component and thermoeconomic model. 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. It is observed that the evaporator has the highest MF value and also induces a large number of dysfunctions in the other components, causing a greater additional fuel impact. Although the compressor shows a malfunction, there is no dysfunction associate with them. Negative values of DF were found in the valve in the E- H&S-E^{T*}&E^{M*} Model. It happens due to a component product reduction when compared to the reference state.

In this research, the extra consumption of fuel is associated with the increase of consumption of the compressor, which is the subsystem that receives the stream external consumption. Table 3 shows the impacts of the total fuel value for each anomaly. There is no difference between the localized physical exergy disaggregation in the additional fuel consumption, as this does not depend on the thermoeconomics methodology used, but on the thermodynamic conditions of the system. The lowest extra consumption is associated with anomaly 4 and the highest with anomaly 5, which is the combination of anomalies 1 to 4.

Table 3. Total fuel impact due to anomaly.

	Anomaly 1	Anomaly 2	Anomaly 3	Anomaly 4	Anomaly 5
Total Fuel Impact (kW)	0,167	0,492	0,438	0,115	1,426

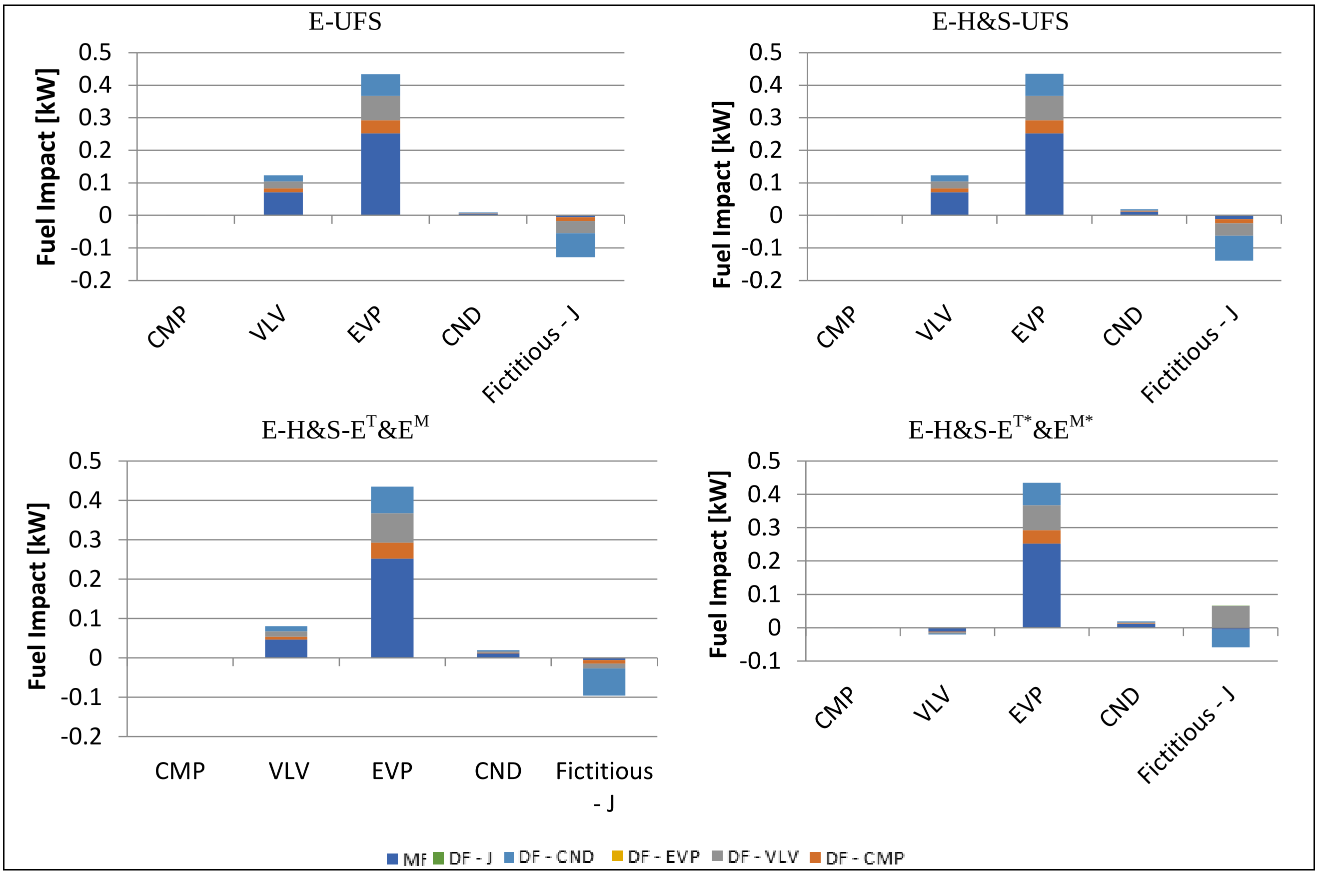

Figure 5. Faults origin in refrigeration system Anomaly 3 for each component and thermoeconomic model.

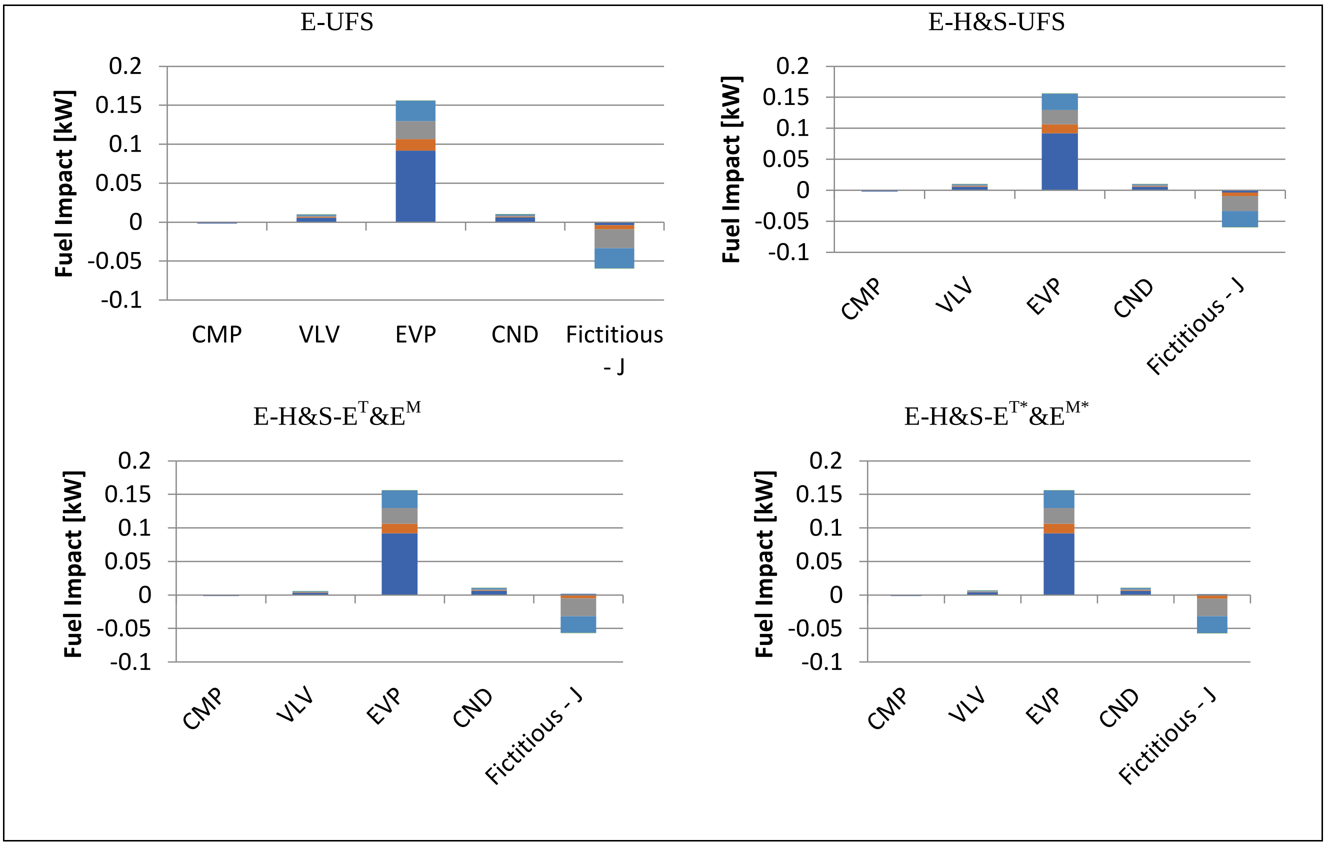

Figure 6. Faults origin in refrigeration system Anomaly 4 for each component and thermoeconomic model.

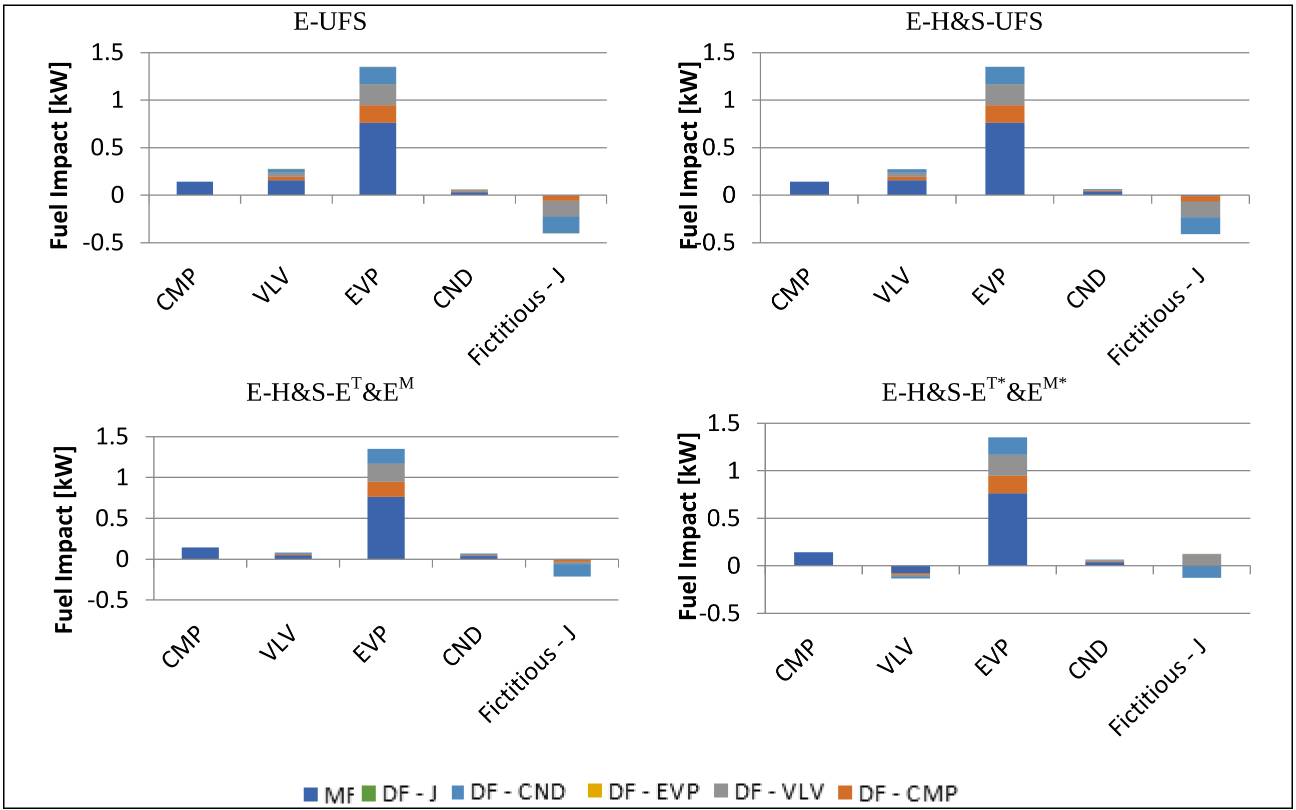

Figure 7. Faults origin in refrigeration system Anomaly 5 for each component and thermoeconomic model.

6. CONCLUSIONS AND CLOSURE

In this study, a refrigeration system with different simulated anomalies was evaluated by combining four different methodologies (E, E^T&E^M, H&S and UFS Models) to perform a localized physical exergy disaggregation only in the dissipative components (condenser and valve). It is worth mentioning that E, H&S and E^T&E^M Models are unable to isolate and treat the condenser and/or valve. Thus, this study combines at least two methodologies that are capable of doing it. The Fuel Impact Formula was used as a thermoeconomic diagnosis methodology to quantify the effects of each malfunction and evaluate the complexity involved.

For anomalies 1 and 4 all methodologies proposed are capable to identify the malfunctions of compressor and evaporator, respectively, and also in a qualitative, way all the other results gave the same answers. It is worth mentioning, that Anomaly 1 restricts the inefficiencies only to CMP, mostly because it is the input of the system resource, not affecting the other equipment.

The results due to anomalies 2 and 3 show that it is not possible to identify the subsystem with MF. For both analyses, the evaporator is wrongly identified as a defective component due to the presence of faults in large quantities.

It is important to highlight that the fictitious units induce anomalies in other real components, although they do not have any dysfunctions or malfunctions in them. Negative values of DF were found in the valve in the E- H&S-E^{T*}&E^{M*} Model. It happens due to a component product reduction when compared to the reference state.

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. It is difficult to identify which subsystem has a malfunction in this situation.

It is worth mentioning that the E-UFS and E-H&S-UFS Models present the same results for all anomalies, and similar to other models.

Finally, the results show that any models that use a correct localized physical disaggregation are able to isolate and treat the condenser and the valve and can be used for the diagnosis analysis. Furthermore, they present some consistent results of malfunctions and dysfunctions, reaching results with less complexity involved. Thus, thermoeconomic diagnosis with localized physical exergy disaggregation allied to a productive structure that does not present fictitious elements could be promising.

7. ACKNOWLEDGEMENTS

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