EVALUATION OF THERMOECONOMIC DIAGRAMS AND METHODOLOGIES FOR COST ALLOCATION IN A SIMULTANEOUS HEATING AND COOLING HEAT PUMP SYSTEM.

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ABSTRACT

Thermoeconomics, an interdisciplinary field merging concepts from thermodynamics and economics, addresses complex challenges beyond the individual capacity of these sciences. Its primary applications include cost allocation, optimization, and malfunction diagnosis of energy systems. In thermoeconomic modeling, defining the productive structure is critical, and exergy is a highly appropriate thermodynamic quantity for correlating with costs. Building upon the prior investigation presented at ECOS 2023, which explored thermoeconomic cost allocation in a simultaneous heating and cooling heat pump system with an emphasis on dissipative components such as valves, this study introduces the recent A&F Model. The novelty of this work lies in applying the A&F Model, which splits physical exergy into Helmholtz energy and flow work components, within a physical-productive thermoeconomic diagram. This approach integrates physical and productive internal flows, utilizing the same physical flows presented in the flow sheet and enabling the assessment of costs for both physical and productive flows. It is crucial to note that conventional use of productive diagrams may introduce arbitrariness due to the interconnection of subsystems through productive flows and fictitious components. This study's objectives align with those of the previous research. Firstly, it presents various methods for treating and isolating the valve in thermoeconomic modeling within the context of the physical-productive diagram. Secondly, it undertakes a comparative analysis between traditional thermoeconomic methodologies using conventional physical and productive diagrams and those employing the physical-productive diagram, emphasizing the integration of the A&F Model. Finally, the study discusses the advantages and drawbacks of each methodology, offering insights for future decision-making in thermoeconomic modeling, especially concerning the choice of diagrams and the integration of the A&F Model. In summary, this research contributes to the progression of thermoeconomic modeling by introducing the A&F Model within the context of a physical-productive diagram. This integration accurately represents physical and productive flows, mitigating the arbitrariness associated with conventional productive diagrams. The study aims to stimulate further discussions and developments, refining efficient energy system analysis tools and enhancing the applicability of the A&F Model in thermoeconomic assessments. The analysis of various thermoeconomic models applied to the heat pump system shows notable consistency, with a maximum variation of 17.5%, indicating that despite some cost formation discrepancies, all methodologies yield comparable results. This study underscores the significance of precise modeling in thermoeconomic analysis, offering valuable insights into the cost formation process in thermal systems. While acknowledging the applicability of all methodologies, it emphasizes the importance of selecting an appropriate methodology based on the specific characteristics of the system under study.

Keywords: Thermoeconomics; Cost allocation; Physical-Productive Diagram; A&F Model

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1 INTRODUCTION

Despite its applicability, thermoeconomic modeling based on physical structure proves insufficient to analyze residues' cost formation process and define dissipative equipment's productive purpose. Therefore, most models used to address residues have been proposed based on productive flows, such as functional methodologies, AFE (VON SPAKOVSKY, 1994) and AFT (FRANGOPOULOS, 1994) and the H&S Model (SANTOS et al., 2009). As highlighted by Lozano and Valero (1993a), defining the productive diagram is crucial in Thermoeconomics, as it contributes to identifying the residue cost formation process and improves cost allocation procedures (AGUDELO; VALERO; TORRES, 2012). Furthermore, the greater the disaggregation of the system into subsystems and flows in defining input and output, the better the results of thermoeconomic applications (LOZANO; VALERO, 1993a). Although each energy conversion system is defined by a single physical structure, different productive structures can be delineated depending on the analyst's interpretation. This variation is related to the definitions of input and output of components, as well as how they are interconnected, which can result in different cost values. However, the productive structure requires a physical basis to align with the plant's behavior and achieve rational exergetic costs (VALERO; SERRA; UCHE, 2006).

The best productive structure is the one that details with greater precision and simplicity the productive purpose of the subsystems and flows present in the physical structure of the analyzed plant. In order to achieve this, it is essential to evaluate all flows of the productive structure unequivocally in relation to the plant's state defined by the physical structure (LOZANO; VALERO, 1993a). The judicious choice of the productive structure, depending on input and output definitions, is essential to achieve rational exergetic costs (VALERO; SERRA; UCHE, 2006). Several studies (AVELLAR et al., 2018a; BARONE et al., 2022; FARIA et al., 2023) highlight that the arbitrariness in the interconnection of components, especially in junctions and bifurcations, can lead to different arrangements for the same thermal system. Thus, how the thermoeconomist develops the productive diagram can influence the scenarios in estimating thermoeconomic costs.

The combination of physical and productive diagrams emerges as a promising solution to overcome the arbitrariness of arrangements resulting from the use of fictitious components. The "comprehensive diagram," as named by Avellar et al. (2018b), interconnects subsystems using the same physical flows presented in the plant's flowchart. This type of diagram, which combines characteristics of physical and productive diagrams, has been applied, with different nomenclatures, for cost allocation (BARONE et al., 2021; FARIA et al., 2020, 2021; TORRES; VALERO, 2021) and in diagnostic studies (HERNÁNDEZ, 2005; OROZCO et al., 2017; PACHECO IBARRA et al., 2010). In this study, it will be referred to as the physical-productive diagram. This approach enables the simultaneous evaluation of unit costs and/or the specific emissions of internal physical and productive flows, as well as final products of a thermal system (AVELLAR et al., 2018b).

The main objective of this research is to present various methods for treating and isolating the valve in thermoeconomic modeling within the context of the physical-productive diagram. Additionally, the A&F Model is presented in the physical-productive diagram for the first time in the literature. Furthermore, a comparative analysis is conducted between traditional thermoeconomic methodologies employing conventional physical and productive diagrams and those utilizing the physical-productive one. Finally, the advantages and disadvantages of each methodology are discussed, providing valuable insights for future decision-making in thermoeconomic modeling. This study aims to contribute to the advancement of thermoeconomic modeling by introducing the A&F Model within the context of a physical-productive diagram, thereby enhancing the accuracy and applicability of cost allocation methods in energy systems analysis.

2 PHYSICAL EXERGY DISAGGREGATION

Thermoeconomics employed the concept of physical exergy disaggregation, which was initially proposed by Kotas (1985). According to Lazzaretto and Tsatsaronis (2006), disaggregate exergy components enhance the precision of results in thermoeconomics. The expression for physical exergy, excluding kinetic, potential, and other energy forms, follows Equation (1), aligning with the methodology used in the H&S Model (SANTOS et al., 2009). It's important to note that all exergy

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components discussed in this study are contingent solely upon the thermodynamic properties of the flows, which are known beforehand.

$$\dot{E}_i^{PH} = \dot{E}_i^{H} - \dot{E}_i^{S} = \dot{m}_i \cdot \left[\left(h_i - h_0 \right) - T_0 \cdot \left(s_i - s_0 \right) \right] \tag{1}$$

Applying the definition of specific enthalpy in Equation (1), h = u + Pv, Equation (2) is written. Rearranging Equation (2), the three terms of the UFS Model (LOURENÇO; SANTOS; DONATELLI, 2011) are obtained and given by Equation (3).

$$\dot{E}_i^{PH} = \dot{m}_i \cdot \left\{ \left[\left(u_i + P_i \cdot v_i \right) - \left(u_0 + P_0 \cdot v_0 \right) \right] - T_0 \cdot \left(s_i - s_0 \right) \right\} \tag{2}$$

$$\dot{E}_i^{PH} = \dot{E}_i^{U} + \dot{E}_i^{F} - \dot{E}_i^{S} = \dot{m}_i \cdot \left[\left(u_i - u_0 \right) + \left(P_i \cdot v_i - P_0 \cdot v_0 \right) - T_0 \cdot \left(s_i - s_0 \right) \right] \tag{3}$$

Furthermore, Equation (4) can be obtained by rearranging Equation (2) in a different way, specifically by combining the first and third terms of Equation (3).

$$\dot{E}_i^{PH} = \dot{m}_i \cdot \left\{ \left[\left(u_i - T_0 \cdot s_i \right) - \left(u_0 - T_0 \cdot s_0 \right) \right] + \left(P_i \cdot v_i - P_0 \cdot v_0 \right) \right\} \tag{4}$$

The specific Helmholtz energy of a closed system under a heat bath (reservoir at T_0) is given by $a = u - T_0 s$. This can be applied for both *i*-th and dead states. Equations (5) and (6) show the Helmholtz energy term and flow work term, respectively. Thus, the physical exergy could be written as in Equation (7), according to the A&F Model (SANTOS et al., 2022). It is important to highlight that the principle used in applying the A&F Model to disaggregate physical exergy into its Helmholtz energy terms (Equation (5)) and flow work term (Equation (6)) is similar to that used in the H&S and UFS Models.

$$\dot{E}_i^{A} = \dot{m}_i \cdot \left(a_i - a_0 \right) = \dot{m}_i \cdot \left[\left(u_i - T_0 \cdot s_i \right) - \left(u_0 - T_0 \cdot s_0 \right) \right] \tag{5}$$

$$\dot{E}_i^{F} = \dot{m}_i \cdot \left(P_i \cdot v_i - P_0 \cdot v_0 \right) \tag{6}$$

$$\dot{E}_i^{PH} = \dot{E}_i^{A} + \dot{E}_i^{F} = \dot{m}_i \cdot \left\{ \left[\left(u_i - T_0 \cdot s_i \right) - \left(u_0 - T_0 \cdot s_0 \right) \right] + \left(P_i \cdot v_i - P_0 \cdot v_0 \right) \right\} \tag{7}$$

The physical exergy disaggregated into thermal and mechanical components, E^T&E^M Model, is also assessed in this study. Based on Morosuk and Tsatsaronis (2019) and Tsatsaronis (1993), the Equation (8) of 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 Equation (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].

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

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

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3 THERMOECONOMIC MODELLING

The productive structure is a representation that elucidates the purpose of subsystems by explicitly revealing their input (fuels) and output (products) components in terms of productive flows. In thermoeconomic methodologies, physical and/or productive flows are conventionally utilized to illustrate the productive interconnections among subsystems graphically. This study employs productive and physical flows to construct a physical-productive thermoeconomic diagram. After defining the productive structure, each subsystem is represented by a cost equation balance relating to the thermodynamic magnitude and the unit cost of external resources and internal flows. The mathematical model lists a set of cost equation balances in each subsystem to calculate the unit costs. A thermoeconomic model should be performed by using Equation (10).

$$\sum\left(k_{out} \cdot Y_{out}\right) - \sum\left(k_{in} \cdot Y_{in}\right) = k_F \cdot E_F \tag{10}$$

In Equation (10), E_F is the external fuel exergy consumption (in kW), and Y_{out} and Y_{in} mean the generic thermodynamic magnitude of the internal flows at the outlet and intlet (including final products) of each subsystem. The solution of the set of equations results in the unit exergy costs of each internal flow and each final product. In this paper, Y assumes the thermodynamic magnitudes, such as power (W), total exergy (E), Helmholtz energy term (E^A), flow work term (E^F), internal energy term (E^U), entropic term (E^S), mechanical term (E^M), thermal term (E^T), and enthalpic term (E^H). The unknown k_{out} and k_{in} are the unit exergy costs of the internal flows at the outlet and the inlet of each subsystem. The unit exergy cost of a flow is the amount of external exergy units required to obtain one unit of this flow, meaning that the unit exergy cost of a flow is a measure of the thermodynamic efficiency of the production process when producing this flow (VALERO; SERRA; UCHE, 2006). Each subsystem provides a single cost balance equation. Thus, auxiliary equations are necessary when several products are obtained in a component. Thermoeconomic models which use physical exergy disaggregation based on the productive diagrams, consider the equality criteria (FRANGOPOULOS, 1994; LAZZARETTO; TSATSARONIS, 2006). Analyzes based on physical diagrams consider input and output principles to define auxiliary equations (LAZZARETTO; TSATSARONIS, 2006). Note that for all the methodologies studied in this research, in the absence of external assessment, the exergy cost of the mass and energy streams entering the plant equals their exergy ($k_w = 1$ [kJ/kJ]).

4 CASE STUDY

The investigation presented in this paper utilizes a simultaneous heating and cooling heat pump system, which is the same system examined by Nguyen et al. (2014). The system's flowsheet is illustrated in Figure 1, depicting four main components: evaporator, motor-compressor, condenser, and valve. For a comprehensive overview of the heat pump system parameters, refer to Table 1.

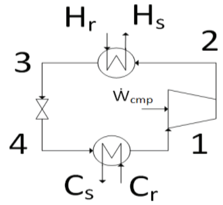

Figure 1: The physical structure of the heat pump system

Table 1: System parameters

Parameter	Symbol	Value	Unit
Condensation temperature	T_{cnd}	70	°C
Evaporation temperature	T_{evp}	7	°C
Evaporator heat transfer rate	$\dot{Q}_{evp}$	250	kW
Compressor isentropic efficiency	η_{cmp}	75	%
Electric motor efficiency	η_{em}	90	%
Water streams pressure	P_{H2O}	300	kPa

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Ammonia serves as the working fluid for this system. Specifically, the evaporator and condenser are designed as two water-coupled systems tailored for district heating and cooling, respectively. In Figure 1, the labels 'H', 'C', 'r', and 's' correspond to hot, cold, return, and supply, respectively. Several assumptions were considered in this analysis, with the primary assumption being that the processes are in a steady state. Furthermore, ammonia is presumed to exist as a saturated vapor at state 1 and a saturated liquid at state 3. Other assumptions include the absence of heat exchange with the environment, no alterations in kinetic and potential energy, no pressure drop for flow through heat exchangers, and the exclusion of chemical exergy considerations. Conventional mass, energy, and exergy balance equations were employed for each control volume based on the available data. The simulation was conducted using Engineering Equation Solver (F-CHART SOFTWARE, 2017) and can be found with more details in Santos et al. (2023). Table 2 shows the thermodynamic properties of ammonia.

Table 2: Thermodynamic properties of the main physical flows of the heat pump system

Flow	P [kPa]	T [°C]	E [kW]	E^A [kW]	E^F [kW]	E^S [kW]	E^H [kW]	E^T [kW]	E^M [kW]	E^U [kW]
1	554	7.00	64.50	68.76	-4.27	-82.50	-18.04	118.00	-53.46	-13.74
2	3312	179.80	147	129.95	17.04	-65.84	81.12	182.50	-35.45	64.11
3	3312	70.00	86.17	122.73	-36.57	-354.08	-267.98	182.50	-96.29	-231.39
4	554	7.00	76.09	105.58	-29.51	-344.08	-267.98	118.00	-41.87	-238.47

5 THERMOECONOMIC METHODOLOGIES

5.1 Thermoeconomic Methodologies

In the context of this study, a concise overview of the exergy cost allocation methodologies discussed in ECOS23 is presented in Santos et al. (2023). The TEC method employs exergy balance equations for control volumes, defining final products as the exergy flow increase of both hot and cold-water streams. However, interpreting these flows as fuels or products poses challenges (LOZANO; VALERO, 1993a). A limitation of the original formulation lies in defining the productive structure based on the same flows and components present in the physical structure (LOZANO; VALERO, 1993b). The E Model utilizes total exergy to define fuels and products, presenting challenges in assigning a productive purpose to a dissipative valve. Three options are proposed to treat the valve using total exergy, combining it with the condenser (E Model – CV), evaporator (E Model – VE), or separating it until ambient temperature T_0 (E Model – CVE). This decision complexity arises from the system's dual products and the nature of the valve's irreversibility. The UFS Model, justified by the presence of a valve, introduces increased computational effort but allows isolation of the valve. Using physical exergy disaggregation into internal energy, flow work, and entropic term, the UFS Model reduces the need for merging components (LOURENÇO; SANTOS; DONATELLI, 2011). The A&F Model isolates valves using Helmholtz energy and flow work terms. Its simplicity and universality, attributed to two terms instead of three, offer advantages over the E Model and reduced complexity and computational requirements compared to the UFS Model. The Localized Physical Exergy Disaggregation (E Model – LD) method disaggregates physical exergy in dissipative equipment, like valves, using Helmholtz energy and flow work terms. This model stands out for isolating the valve with fewer flows, presenting advantages in specific scenarios.

5.2 Physical-Productive Thermoeconomic Diagram

Figures 2 to 6 illustrate Physical-Productive Thermoeconomic Diagrams representing the heat pump system, combining the principles of both physical and productive diagrams. These diagrams visually presents the products and fuels of subsystems and their interconnections by integrating physical and productive internal flows into a cohesive graphical depiction. Notably, the Physical-Productive Thermoeconomic Diagram excludes fictitious subsystems, namely junctions (J) and bifurcations (B), interconnecting subsystems using the same physical exergy flows presented in the flow sheet.

Preserving essential characteristics of physical and productive diagrams, the Physical-Productive Thermoeconomic Diagram portrays each subsystem as a productive unit (depicted by a continuous line)

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and a component (indicated by a dotted line), effectively combining attributes from both diagram types. (LAZZARETTO; TSATSARONIS, 2006) explored the differentiation between productive units and components, although they did not employ the concept of productive units for cost calculations. In contrast to conventional diagrams, subsystems are viewed strictly as components (dotted lines) in physical diagrams or solely as productive units (continuous lines) in productive diagrams. The Physical-Productive Thermoeconomic Diagram presents all subsystems as productive units and components. This inclusive approach facilitates the evaluation of unit costs for both productive and physical flows within each subsystem. The mathematical model for exergetic cost allocation is derived by formulating cost equations for each subsystem within the Physical-Productive Thermoeconomic Diagram, as outlined in Equation (10). Notably, each subsystem allows for formulating two cost equations: one as a productive unit (continuous line) and the other as a component (dotted line). Auxiliary equations are also formulated at the component boundaries, aligning with the methodology employed in the physical diagram. It is essential to highlight that this diagram is versatile and applicable across various thermoeconomic methodologies. This adaptability stems from the consistent derivation of each productive flow ($E^{Y}_{j:k}$) as the difference between two physical flows (E^{Y}_{j} and E^{Y}_{k}). In contrast to traditional productive or functional diagrams, the Physical-Productive Thermoeconomic Diagram offers the distinct advantage of enabling the calculation of costs for each internal physical flow within the system rather than restricting it to the costs of internal productive flows alone. Additionally, this diagram connects subsystems using the same physical flows as presented in the flowsheet, eliminating the potential for arbitrariness associated with the criticized use of fictitious subsystems (junctions and bifurcations). Unlike conventional physical diagrams, the Physical-Productive Thermoeconomic Diagram allows calculating costs for each internal productive flow, not solely the costs of internal physical flows. Following the detailed explanation of physical-productive diagrams, this study will showcase six applications of thermoeconomic methodologies in physical-productive diagrams, focusing on addressing the dissipative equipment, namely the valve, in each methodology. Additionally, it is worth mentioning that this work will introduce the application of the thermoeconomic A&F methodology within a physical-productive diagram for the first time in the literature. The Physical-Productive Diagram is identified herein by "PP".

5.3 Physical-Productive Thermoeconomic Diagram – E Model (PP – E)

Figure 2 illustrates the Physical-Productive Diagram of the heat pump system using the E Model. It is important to note that the valve (VLV), a dissipative component, cannot be isolated by the E Model, meaning it is not possible to define its function (input and output) through this model, even when using the mentioned diagram. However, it can be considered that the valve was treated, which means it was separated from the other components through the physical input and output flows. However, these flows are not considered as input and output, respectively.

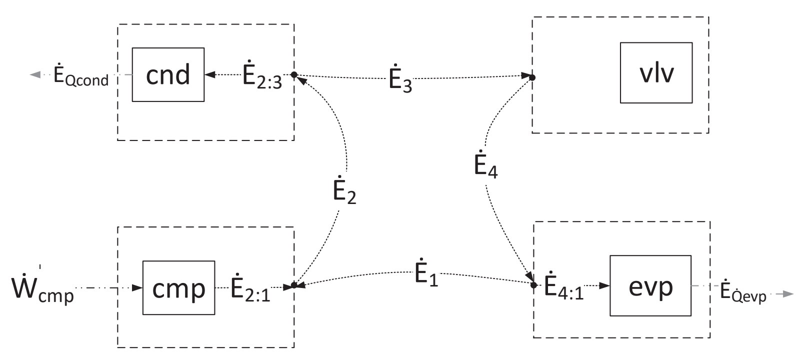

Figure 2: Physical-Productive Diagram of the heat pump system using the E Model

5.4 Physical-Productive Thermoeconomic Diagram – E Model with Localized A&F Model (PP – E/A&F)

Figure 3 a) illustrates the Physical-Productive Diagram of the heat pump system using the E Model with the A&F Model localized. To isolate the valve, this model adopts the concept of localized

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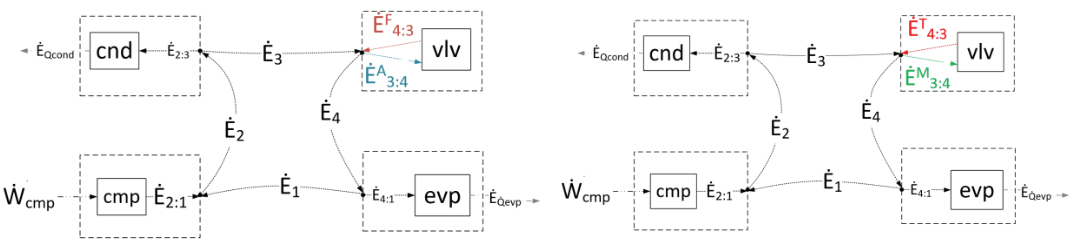
disaggregation, which involves selecting a methodology capable of assigning product and fuel to the equipment in question and applying this methodology exclusively to this productive unit. The exergetic balance at the valve boundary is observed to be consistent. It is important to note that the A&F Model breaks down physical exergy into its Helmholtz energy and flow work terms. Consequently, at the valve, inputs and outputs defined by the A&F thermoeconomic methodology can be identified.

5.5 Physical-Productive Thermoeconomic Diagram – E Model with Localized E^T&E^M Model (PP – E/E^T&E^M)

The diagram depicted in Figure 3a) resembles the diagram in Figure 3 b). However, the distinction lies in the selected thermoeconomic methodology used to isolate the valve, which is the E^T&E^M Model. In other words, this methodology conducts localized disaggregation.



a) E Model with Localized A&F Model   b) E Model with Localized E^T&E^M Model

Figure 3: Physical-Productive Diagram of the heat pump system

5.6 Physical-Productive Thermoeconomic Diagram – E^T&E^M Model (PP – E^T&E^M)

Figure 4 depicts the Physical-Productive Diagram of the heat pump system utilizing the E^T&E^M Model. This model disaggregates physical exergy into its thermal and mechanical components, thereby resulting in two loops in the diagram, traversing the diagram clockwise (both components contribute positively to exergy). One loop is associated with the thermal component, and the other with the mechanical component. However, it is unnecessary in this case because the plant in question is a heat pump system where the condenser is responsible for one of the plant's products, so it is isolated in the productive structure. In Figure 4 there are no productive flows of the mechanical terms associated with the condenser and evaporator as there is no pressure drop across this equipment. It is important to point out that one of the authors of this approach acknowledged possible arbitrariness in the separate calculation of the thermal and mechanical components, especially when the working fluid undergoes phase changes, as is the case with real fluids (LAZZARETTO; TSATSARONIS, 2006).

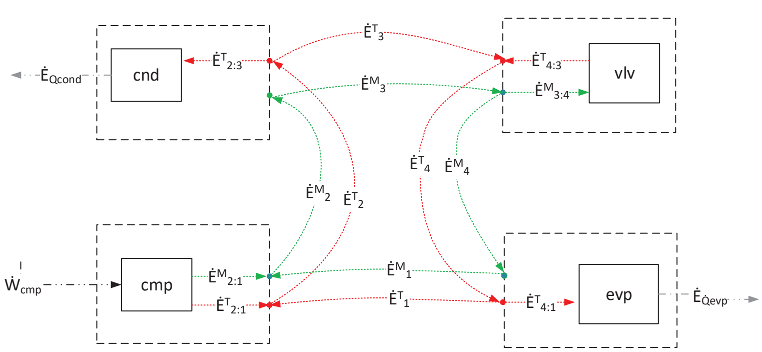


Figure 4: Physical-Productive Diagram of the heat pump system using the E^T&E^M Model

5.7 Physical-Productive Thermoeconomic Diagram – A&F Model (PP – A&F)

The Physical-Productive diagram depicted in Figure 5 represents the A&F Model. This marks the first instance in the literature where this model is showcased in a Physical-Productive Diagram.

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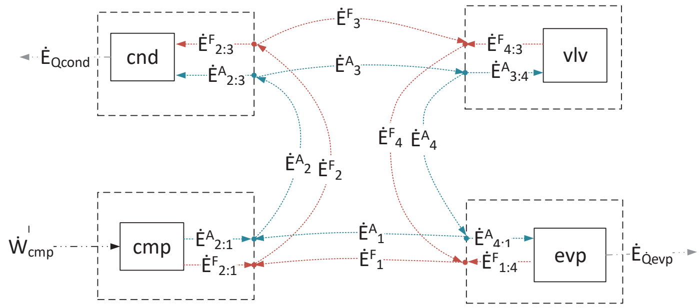

Figure 5: Physical-Productive Diagram of the heat pump system using the A&F Model

5.8 Physical-Productive Thermoeconomic Diagram – H&S Model with Localized UFS Model (PP -H&S/UFS)

Figure 6 depicts the Physical-Productive Diagram of the heat pump system using the H&S Model with localized UFS Model. The H&S Model is known for disaggregating physical exergy into its enthalpic and entropic terms. However, this model is limited when the system includes a valve because expansion valve is isoenthalpic. Therefore, this model also requires localized disaggregation at the valve. Since the UFS Model is considered an extension of the H&S Model and can isolate the valve, it is utilized here. It is observed that the loop associated with the entropic term is counterclockwise, as its contribution is negative in the exergy definition, Equation (1). Additionally, it is noteworthy that the exergetic balances at the valve are consistent. This localized disaggregation increases the number of flows and consequently of balance and auxiliary equations when compared with PP – E^T&E^M and PP – A&F Models, for instance.

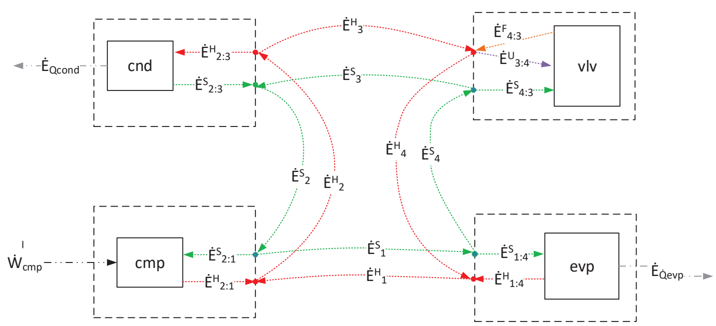

Figure 6: Physical-Productive Diagram of the heat pump system using the H&S Model with Localized UFS Model

6 RESULTS AND DISCUSSIONS

In this study, the cost allocation models faced the challenge of determining the unit exergetic cost for both heating and cooling. Regardless of the cost allocation method, the result consists of a pair of unit exergetic costs for both final products, forming a linear pattern mathematically.

For each model, an increase in the unit exergetic cost of heating (k_{EQcond}) corresponds to a decrease in the unit exergetic cost of cooling (k_{EQevp}). The results for each thermoeconomic methodology are represented by 15 points in Figure 7, showing pairs of unit exergetic costs for heating and cooling derived from the various methods analyzed in this study and the study conducted for the same plant presented in ECOS 2023 (SANTOS et al., 2023). These points, positioned along the same linear solution, exhibit consistency from a thermoeconomic standpoint. It is important to note that, upon examining Figure 7 a), it becomes evident that assigning the entire system input cost to a single final product result in unit exergetic costs of (0;2.98) and (17.99;0) for separately produced heating and cooling, respectively. The detailed analysis results reveal that, when excluding the ordered pairs associated with the system's input cost for a single final product, all methodologies exhibit a maximum

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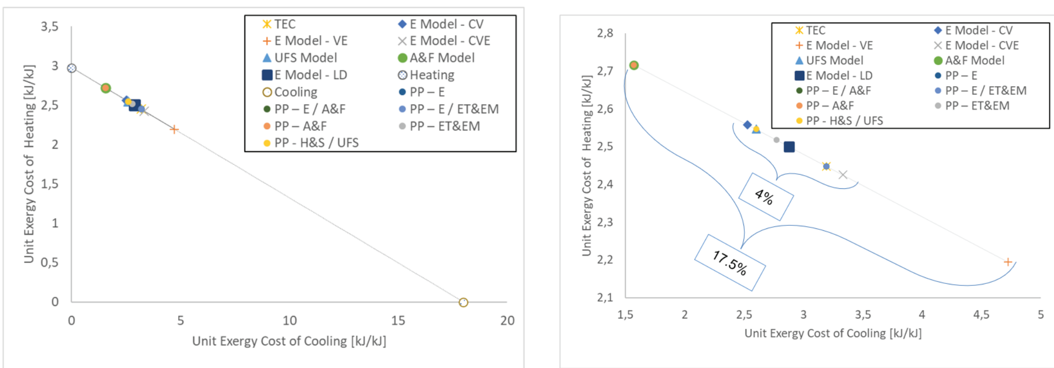
difference of 17.5%, as shown in Figure 7 b). This observation implies that, in assessing the unit exergetic heating and cooling costs, the applied methodologies generate comparable results clustered within a specific range of variation. Nevertheless, determining the optimal or correct cost among the methodologies through cost allocation is not viable, as all the methodologies outlined in this study produce consistent results. Nonetheless, specific comparative analyses can be undertaken. When comparing the ordered pairs with the highest cost associated with heating, it is evident that the values attributed to the A&F Models, whether linked to the productive diagram (ECOS23) or the physical-productive diagram, were equivalent. This equivalence can be expected to some extent since both can define the productive purpose of the valve. Notably, all models employing the physical-productive diagram can assess costs associated with both physical and productive flows. Additionally, there is a coincidence of values between the UFS Model and PP-H&S/UFS, which is coherent, considering that the UFS Model is viewed as an extension of the H&S Model. Subsequently, the PP-E^T&E^M Model presents intermediate values, indicating that, despite previous questions about this model, it demonstrated intermediate costs for this situation.



a) b)

Figure 7: Results of final unit exergy costs of products

Another exciting feature is that all models related to the E Model in the Physical-Productive Diagram (PP-E, PP-E/A&F, PP-E/E^T&E^M) exhibit the same value for unit exergetic costs. This suggests that, specifically for this case study, defining inputs and outputs for the valve does not influence the final costs of the plant's products. According to the Thermoeconomic Isolation Principle (EVANS, 1980), a component is considered fully isolated within the productive structure if the methodology used can define its productive purpose, namely its fuels and products. Local optimization and thermoeconomic diagnosis, for instance, require isolating all components of the plant in defining the productive structure. The information presented in Table 3 displays the values of fuel (Fu), product (Pr), and irreversibility (Ir) for methodologies that can isolate the valve, thus associating fuels and products with the valve as a productive unit.

Table 3. Exergy balances of valve of the heat pump system

Valve		Model					
		PP – E	PP – E/A&F	PP – E/ET&EM	PP – ET&EM	PP – A&F	PP - H&S/UFS
Productive Unit	Fu [kW]	-	17.2	64.5	64.5	17.2	17.2
	Pr [kW]	-	7.1	54.4	54.4	7.1	7.1
	Ir [kW]	-	**10.1**	**10.1**	**10.1**	**10.1**	**10.1**
Component	In [kW]	86.2	86.2	86.2	86.2	86.2	86.2
	Out [kW]	76.1	76.1	76.1	76.1	76.1	76.1
	Ir [kW]	**10.1**	**10.1**	**10.1**	**10.1**	**10.1**	**10.1**

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Additionally, Table 3 presents the irreversibility values for the valve when the subsystem is considered a component. It is worth noting that from the component's perspective, the input flow (In) and the output flow (Out) are not necessarily considered fuels and products but can be used to estimate irreversibility. This observation holds true for all models used in this study, where the calculated irreversibility remains consistent across all situations. Lastly, it is important to highlight that the costs generated by each productive unit depend on the product-fuel ratio (efficiency), resulting in different cost values.

7 CONCLUSIONS

After a thorough analysis of the results obtained through various thermoeconomic models applied to the heat pump system, several significant scientific conclusions emerge. Firstly, the results reveal a notable consistency among the different models, suggesting that the employed thermoeconomic methodologies are robust and capable of producing coherent results from a thermoeconomic perspective. The maximum variation of 17.5% in the results among the methods indicates that, despite some discrepancies in the cost formation processes, all analyzed methodologies, both those related to ECOS23 and those presented in this study, yield comparable and consistent results.

Furthermore, a detailed analysis of the cost formation process in the valve, considering the principle of thermoeconomic isolation, proved useful in identifying and evaluating the models' ability to isolate this dissipative component within the productive structure. Models that successfully isolated the valve as a productive unit demonstrated compliance with this principle, providing a solid foundation for local optimization analyses and thermoeconomic diagnosis. Notably, only the PP - E Model does not fit this possibility. The equivalence of results among different models, such as the A&F Model in its Physical-Productive Diagram and productive diagram contexts, highlights these models' ability to define the productive purpose of specific system components, such as the valve, across various scenarios, demonstrating coherence in the results when analyzed from a cost allocation perspective. This underscores the importance of precise and comprehensive modeling in thermoeconomic analysis and the significance of the PP - A&F Model, which is introduced for the first time in the literature.

Similarly, when observing PP models utilizing the E Model, whether with localized disaggregation or not, it is evident that the results are equal, suggesting that, in this scenario, whether the valve is isolated does not directly influence the exergetic costs of the final products. Nonetheless, subsystem isolation is important for thermoeconomic diagnosis and optimization purposes. Regarding models using the E^T&E^M Model, coherent results were also observed, despite some observations related to this model when dealing with real fluids. The PP - H&S / UFS Model also presents coherent values, although its localized disaggregation may introduce greater complexity due to the increased quantity of flows associated with the definition of valve input and output.

In summary, this study aims to provide valuable insights for a better understanding of the cost formation process in thermal systems and the possibilities of using different methodologies, depending on their specific application. However, it is important to note that, in thermoeconomics, it is not possible to determine which methodology presents the correct cost through cost allocation. Nevertheless, a suggestion from among the various methodologies presented can be required. In that case, this study tends to indicate the PP - E/A&F methodology for cost allocation analyses due to its ability to gather a large volume of information related to the costs of physical and productive flows, describe a productive purpose for the valve, demonstrate coherence from a thermoeconomic perspective, and estimate its components in an unlimited manner from a thermodynamic perspective, besides having low complexity in its thermoeconomic modeling due to the reduced quantity of flows associated with the model. The importance and applicability of all methodologies are acknowledged, and it is up to the thermoeconomist to arbitrate which methodology and model to use based on the specific characteristics of the system under study.

NOMENCLATURE

A	Helmholtz energy [kJ]	P	Pressure [kPa]
a	Specific Helmholtz energy [kJ/kg]	Q	heat exergy
cmp	Compressor	S	Entropy [kJ/K]

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cnd	Condenser	s	Specific entropic [kJ/kgK]
E	Physical exergy	T	Temperature [°C or K]
evp	Evaporator	TEC	Theory of the exergetic cost
F	Flow work [kJ]	trb	Turbine
H	Enthalpic term [kJ]	U	Internal energy [kJ]
h	Specific enthalpy [kJ/kg]	v	Specific volume [m³/ kg]
Ir	Irreversibility	vlv	Valve
k	Exergetic unit cost [kW/kW]	Y	thermodynamic magnitudes
LD	Localized physical exergy disaggregation	$\dot{m}$	Mass flow [m³ /s]
η	Efficiency		

Subscript

0	Environmental conditions	M	Mechanical component
cnd	Condenser	out	Outlet
evp	Evaporator	ph	Physical
F	Fuel	T	Thermal component
i	Internal flow	rb	Turbine
in	Inlet	vlv	Valve

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