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A COMPREHENSIVE THERMOECONOMIC DIAGRAM BASED ON BOTH SUBSYSTEM PRODUCTIVE PURPOSES AND PHYSICAL CONNECTIONS

Leandro Munhoz de Avellar
Marcelo Aiolfi Barone
Dimas José Rúa Orozco
Atilio Barbosa Lourenço
José Joaquim Conceição Soares Santos
Federal University of Espírito Santo, Avenida Fernando Ferrari 514, Goiabeiras, Vitória, Espírito Santo, Brazil
leandrom.avellar@yahoo.com.br, mabacz@gmail.com, dimas.rua@hotmail.com, atiliobl@gmail.com, jjcssantos@yahoo.com.br

Abstract. *Some thermoeconomic methodologies use productive diagram to represent the productive purpose and the interconnection of the subsystems in order to assess the cost of the internal productive flows and final products, and they do not assess the costs of the physical flows, although the productive flows are defined in relation to the physical flows. Furthermore, the subsystems are connected using productive flows and fictitious components, without considering the physical interconnection presented in the flow sheet. On the other hand, other thermoeconomic methodologies use the physical diagram and assess the cost of the internal physical flows only. This paper proposes a comprehensive thermoeconomic diagram in which both physical and productive internal flows are represented, the subsystems are connected using the same physical flows presented in the flow sheet and allows the assessment of costs of both physical and productive flows. The proposed comprehensive diagram avoids the arbitrariness due to the interconnection of subsystems using productive flows and fictitious components that do not exist in the flow sheet of the plant. The comparison of the exergetic and monetary unit cost, obtained using physical, productive and comprehensive diagrams, in a combined cycle cogeneration plant, show that the unit costs of both physical and productive flows using comprehensive diagram can be the same as the ones using conventional physical and productive diagrams, respectively.*

Keywords: *thermoeconomics, internal flow cost, physical diagram, productive diagram, comprehensive diagram*

1. INTRODUCTION

Thermoeconomics can be considered a new science which, by connecting Thermodynamics and Economics, provides tools to solve problems in complex energy systems, as for instance a rational cost assessment of the internal flows and final products of a plant, based on physical criteria. Various thermoeconomic methodologies have been developed, all of them having in common the cost, calculated from a rational basis (Second Law of Thermodynamics), for this purpose (Erlach et al., 1999).

In 1990s, the most systematic and widespread thermoeconomic methodologies developed until now (Frangopoulos, 1994; Tsatsaronis and Pisa, 1994; Valero et al., 1994a; von Spakovsky, 1994) were applied in a specific and previously defined thermal system, called CGAM problem (Valero et al., 1994b): Exergetic Cost Theory (Valero et al., 1994a), Exergoeconomics (Tsatsaronis and Pisa, 1994), Thermoeconomic Functional Approach (Frangopoulos, 1994) and Engineering Functional Analysis (von Spakovsky, 1994).

Later, when comparing these thermoeconomic methodologies, various authors (Abusoglu and Kanoglu, 2009; Cerqueira, 1999; Cerqueira and Nebra, 1999; Keshavarzian et al., 2017; Serra, 1994) have agree that there were two main groups of thermoeconomic methods: (a) assessment of the cost of the physical flows represented in a physical diagram (Tsatsaronis and Pisa, 1994; Valero et al., 1994a) and (b) assessment of the cost of the productive flows in a defined productive or functional diagram (Frangopoulos, 1994; von Spakovsky, 1994).

According to Lozano and Valero (1993), perhaps the fundamental limitation of the Exergetic Cost Theory, as it was originally formulated, consisted of defining the productive structure in relation to the same flows and component present in the physical structure, since the resulting difficulties lie mainly in the adequate treatment of the dissipative units and residues. In order to overcome this limitation another approach based on productive or functional diagram, called the Structural Theory of Thermoeconomics (Erlach et al., 1999; Lozano and Valero, 1993), was proposed. During the last ten years, some new thermoeconomic methodologies (Lourenço et al., 2015; Santos et al., 2009b), also based on productive or functional diagram, were proposed as consistent alternatives to deal with dissipative components and residues.

Aiming at the unification of the Exergoeconomic methodologies (AVCO approach and LIFO approach) proposed by Tsatsaronis and Pisa (1994), which were based on physical diagram, Lazzaretto and Tsatsaronis (2006) proposed a new thermoeconomic methodologies, called SPECO approach, based on physical diagram too. However, it should be mentioned that most thermoeconomic methodologies were founded based on productive diagram (Frangopoulos, 1994; Lourenço et al., 2015; Santos et al., 2009b; von Spakovsky, 1994) or was latter extended in order to deal with productive or functional diagram (Lozano and Valero, 1993).

Given a flow sheet of a thermal system, all thermoeconomic methodologies need to define a product and a fuel for each subsystem of the plant. Although the productive diagrams offer the advantage of showing clearly and graphically how the product of a given subsystem is distributed in order to be used as an input to another subsystem or as a final product of the plant, and it should be possible to evaluate all the flows of the productive diagram in relation to the state of the plant as defined by the physical diagram, the cost of the internal physical flows are not calculated with this model. Furthermore, in a productive diagram, the subsystems are connected using productive flows and fictitious components, without considering the physical interconnection presented in the flow sheet. This procedure can be more or less arbitrariness depending on the plant being analysed and depending on the interpretation of the analyst.

On the other hand, although a thermoeconomic model based on physical diagram avoids the arbitrariness related to the interconnection of the subsystems, this kind of diagram do not allow calculate the costs of the products and fuels at subsystem level, i. e., the costs of the internal productive flows (the purposes of the subsystems) are not calculated.

Bearing this in mind, this work shows and discuss a different thermoeconomic model, based on a comprehensive thermoeconomic diagram, which shows clear and graphically the product and fuel of the subsystem, as well as the physical interrelation among the subsystem, and allows assess the costs of both physical and productive internal flows of a thermal system, avoiding the arbitrariness related to the subsystem interconnections. For the sake of comparison, the exergetic and monetary unit costs of the internal flows and final products are calculated in a combined cycle cogeneration plant, as case study. In the final analysis, this paper aims at unifying both group of thermoeconomic methodologies by combining both physical and productive internal flows in a single and comprehensive thermoeconomic diagram in a single model.

2. THERMOECONOMIC MODELING

Thermoeconomic model is a set of equations which describes mathematically the cost formation process of the system final products, generally used for exergy and/or monetary costs of the external resources allocation to the final products and, consequently, for the assessment the exergetic unit cost and the monetary unit cost of both internal flows and final products, respectively.

Given the flowsheet of an energy system (Fig. 1), it is convenient to pick up a thermoeconomic model based on a diagram that reflect the productive purpose of the subsystems (products and fuels), as well as the interaction among them. All thermoeconomic methodologies need to define the productive purpose of the subsystems, as well as the distribution of the external resources throughout the system, which can be represented by means of a diagram (Figs. 2 to 5). Some thermoeconomic models are based on the physical diagram (Fig. 2) and others are formulated using a productive diagram (Fig. 3 and 4). In this work a model based on a comprehensive thermoeconomic diagram (Fig. 5) is presented.

No matter the physical or productive diagram is used for thermoeconomic model, in order to calculate the monetary unit cost of each internal flow and final products, the mathematical model for cost allocation, which is a set of cost equations obtained from the thermoeconomic balance in each subsystem of the diagram, is given by Eq. (1). The solution of this set of cost equation is the monetary unit costs of each internal flow and each final product. The monetary unit cost of a flow is the amount of external monetary unit required to obtain one unit of this flow, i.e., the monetary unit cost of a flow is a measure of the economic efficiency of the production process when producing this flow (Valero et al., 2006).

$$\sum (c_{out} \cdot Y_{out}) - \sum (c_{in} \cdot Y_{in}) = Z + c_F \cdot E_F \qquad (1)$$

In Eq. (1), c_{out} and c_{in} are unknown variables representing the monetary unit cost of the internal flows at the outlet and the inlet of each subsystems (in *$/kWh*), respectively; Y_{out} and Y_{in} represent the generic internal flows (in *kW*) at inlet and outlet of each subsystems, respectively, which can be assessed using any thermodynamic magnitude, such as, power (*P*), total exergy (*E*), negentropy (*S*), enthalpy (*H*), etc.; *Z* represents the external hourly cost of the subsystem due to the capital cost, operation and maintenance cost of each subsystem (in *$/h*); c_F is a known market unit cost of the external fuel exergy (in *$/kWh*) and E_F is the amount of the plant external fuel exergy consumption (in *kW*).

Since the number of internal flows is always greater than the number of subsystems, auxiliary equations are required. The thermoeconomic models based on productive diagram (Frangopoulos, 1994; Lourenço et al., 2015; Lozano and Valero, 1993; Santos et al., 2009b; von Spakovsky, 1994) consider that all internal productive flows exiting the same subsystem must have the same unit cost, since they were produced under the same resources and irreversibility. For the thermoeconomic models based on physical diagram (Lazzaretto and Tsatsaronis, 2006; Tsatsaronis and Pisa, 1994; Valero et al., 1994a), the criteria for auxiliary equations are the fuel and product principle. According to the fuel principle it is considered that a component uses a part of inlet flow exergy to produce a given product. Thus, the remaining part of the exergy inlet flow (which is one of the outlet flows) carries the same unit cost of the inlet flow. On the other hand, the product principle considers that all the outlet flows defined as products of the same subsystem have same unit cost.

By modifying Eq. (1) in order to formulate the cost equation balances to provide the exergetic unit cost (k_{out} and k_{in}) of each internal flow and final products of the diagram, Eq. (2) is obtained.

$$\sum(k_{out} \cdot Y_{out}) - \sum(k_{in} \cdot Y_{in}) = k_F \cdot E_F \quad (2)$$

The exergetic unit cost of a flow (in *kW/kW*) is the amount of exergy required to obtain one exergy unit of this flow. This cost is a measure of the thermodynamic efficiency of the production process generating this flow (Valero et al., 2006). In this case, Eq. (2), the hourly cost of the subsystem due to the capital cost, operation and maintenance must be neglected and replaced by zero ($Z = 0$) and the monetary unit cost of the external fuel exergy is replaced by the exergetic unit cost of the external fuel exergy, which is 1.00 *kW/kW*, because there is no exergy destruction before the productive process is performed (Valero et al., 2006). In this case, both the auxiliary equations and the internal flows or final products (Y_{out} and Y_{in}) remain the same as the ones used for the monetary unit cost calculations.

3. PLANT DESCRIPTION

The beauty of a theory is usually shown in the simplicity of its forms and the generality of its message, but its power resides in its capacity to solve practical cases (Lozano et al., 1993). Thus, in this paper, a simple gas and steam turbine combined cycle cogeneration plant, producing electric net power (W_{NET}) and useful heat (Q_U), is used to illustrate the application. In the flowsheet presented in Fig. 1, the plant is defined as having eight components: the air compressor (AC), the combustor chamber (CC), the gas turbine (GT), the electric generator (EG), the heat recovery steam generator (HRSG), the steam turbine (ST), the process unit (UP) and the pump (P). By using a combined gas and steam turbine cogeneration plant, this paper shows the capacity of thermoeconomics to deal with residues (the exhaust gases from the heat recovery steam generator), once that the achievement of functional products is inseparable from the generation of residues and all residues have a cost that must be allocated to the functional products (Torres and Valero, 2000).

Different from a pure steam turbine cogeneration plant (*bottoming cycle*), in which the exhaust gases are released to the atmosphere directly from the subsystem where it is originated (the boiler), in a combined gas and steam turbine cogeneration plant, such gases are generated in the combustion chamber, but it is released to the atmosphere from the last subsystem in which such gases are used (heat recovery steam generator). The exhaust gases of heat recovery steam generator are residues of the system and their cost must be allocated to the final products.

On the other hand, different from a pure gas turbine cogeneration plant (*topping cycle*), in a combined gas and steam turbine cogeneration plant, in which a *topping* and a *bottoming* cycle are combined to produce both net power and useful heat, the heat recovery steam generator does not produce directly one of the final products of the overall cogeneration plant. In this case, the product of the heat recovery steam generator is the fuel of the *bottoming* steam cycle, i. e., the heat recovery steam generator acts as an interface between the *topping* and *bottoming* cycle.

The flowsheet of the combined gas and steam turbine cogeneration plant, in Fig. 1, allows dealing with residue allocation at the due to the gas cycle and evaluating the interconnection arbitrariness at the interface of the heat recovery steam generator (HRSG) between steam and gas cycles. At design point, the plant produces 3,581.01 kW of electric net power (W_{NET}) and 1,874.00 kW of useful heat (Q_U). The external fuel exergy consumption (Q_F) is 15,123.70 kW.

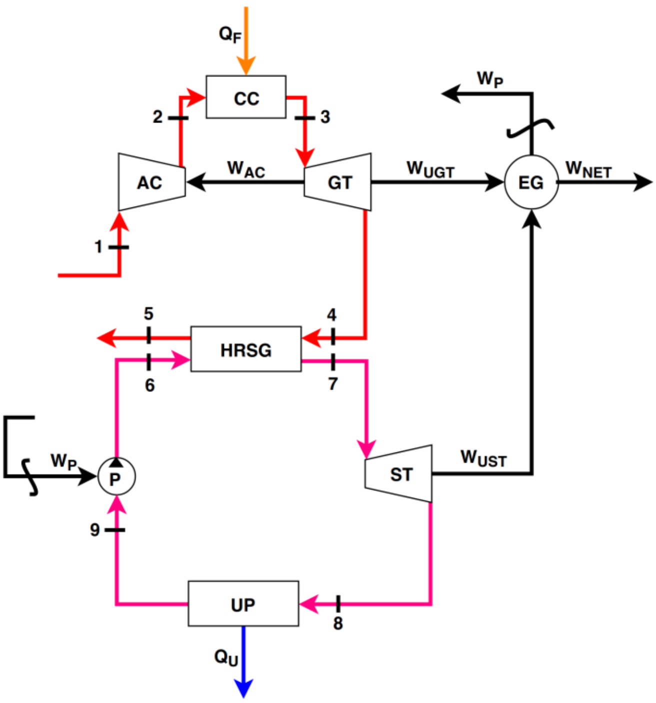

Figure 1. Flow Sheet of the analyzed combined cycle cogeneration plant.

The plant, represented in Fig. 1, generates 8,382.71 kW of gross power (W). The gas turbine (W_{GT}) generates 7,295.42 kW and the steam turbine (W_{ST}) generates 1,087.29 kW. The air compressor (W_{AC}) consumes 4,787.40 kW and the pump (W_P) consumes 14.30 kW to. Table 1 shows the main parameters and exergy of the working fluid streams.

Table 1. Parameters and Exergy of the Physical Streams representing de Plant Working Fluid

i	m (*kg/s*)	T (*ºC*)	p (*bar*)	E (*kW*)
1	23.24	25.00	1.01325	0
2	23.24	230.20	5.1040	4,358.90
3	23.24	850.00	4.8480	1,3135.58
4	23.24	537.30	1.0207	5,012.59
5	23.24	151.10	1.0132	488.61
6	3.19	60.70	26.01	30.13
7	3.19	330.00	25.0	3,404.75
8	3.19	136.00	2.0	1,895.46
9	3.19	60.20	1.013	21.46

This case study, the thermodynamic model called cold air-standard is used. In this thermodynamic model, combustion does not exist and, therefore, combustion gases do not exist. Air is the only working fluid and the combustion process in the chamber is represented by an exergy addition. In addition, the specific heat of the air remains constant in any state of the cycle with a value equal to 1 kJ/(kg.K). The air is considered ideal gas whose constant is equal to 0.287 kJ/(kg.K). In Table 2 is shown the external hourly costs of cogeneration system. The external fuel cost assumed is 6.91 $/MWh.

Table 2. Subsystem External Hourly Costs due to Capital, Operation and Maintenance Costs.

Components and Productive Units	External Hourly Costs ($/h)
Air Compressor (AC)	16.03
Combustion Chamber (CC)	5.72
Gas Turbine (GT)	21.75
Heat Recovery Steam Generator (HRSG)	13.74
Steam Turbine (ST)	2.80
Pump (P)	0.60
Electric Generator (EG)	6.17

In thermoeconomics, given the flowsheet of an energy system and the thermodynamic model, it is convenient to pick up a thermoeconomic model, generally based on a diagram, reflecting the process of cost formation of the overall system.

4. CONVENTIONAL THERMOECONOMIC DIAGRAMS

Conventionally, the thermoeconomic models for cost allocation are formulated based on physical or productive diagram. Differences notwithstanding, no matter the kind of diagram used, the methodologies have some remarkable similarities. The division of the system into subsystems is one of them, but perhaps the most important is the need to define the products and fuels for each of those subsystems. The product and fuels can be defined as the increase or decrease in the thermodynamic magnitude (exergy) of a stream, respectively, mechanical and electric power, external fuel consumption and final useful products and raw stream materials.

Table 3 shows the subsystem fuels and products. For the sake of simplicity and to avoid disagreements, the thermodynamic magnitude used in this paper, to describe the fuels and the product of the subsystems, is total exergy.

Table 3. Definitions of the Fuels and the Products.

System and Subsystems	Fuel		Products		Residue
	Physical	Productive	Physical	Productive	
Air Compressor (AC)	W_{CA}	W_{CA}	$E_2 - E_1$	$E_{2:1}$	-
Combustion Chamber (CC)	E_C	E_C	$E_3 - E_2$	$E_{3:2}$	-
Gas Turbine (GT)	$E_3 - E_4$	$E_{3:4}$	W_{TG}	W_{TG}	-
Heat Recovery Steam Generator (HRSG)	$E_4 + E_5$	$E_{4:5}$	$E_7 - E_6$	$E_{7:6}$	E_5
Steam Turbine (GT)	$E_7 - E_8$	$E_{7:8}$	W_{UTV}	W_{UTV}	-
Pump (P)	W_P	W_P	$E_6 - E_9$	$E_{6:9}$	-
Processing Unit (UP)	$E_8 - E_9$	$E_{8:9}$	Q_u	Q_u	-
Electric Generator (EG)	$W_{UTG} + W_{UTV}$	$W_{UTG} + W_{UTV}$	$W_P + W_{NET}$	$W_P + W_{NET}$	-

The products and fuels of the subsystem, in Table 3, are total exergies of internal flows and final products that represent electric power, and useful heat (presented in the flowsheet) or the exergy added to and removed from the working fluid in a subsystem. Each productive flow is defined based on a physical flow or based on the difference between two physical flows. The productive flows that represent the exergy added to and removed from the working fluid ($E_{j:k}$) are always exergy variations between two physical flows (E_j and E_k).

Nowadays, there is a certain degree of agreement and unification related to the procedure to define the product and fuel at subsystem level. A general, systematic and didactic procedure can be found in Lazzaretto and Tsatsaronis (2006): (i) the product is defined to be equal to the sum of all the exergy of energy streams generated in the subsystem plus all the exergy increases between inlet and outlet of the respective material streams that are in accord with the purpose of the subsystem; and (ii) the fuel is defined to be equal to all the consumed exergy of energy streams supplied to the subsystem plus all the exergy decreases between inlet and outlet of the respective material streams minus all the exergy increases (between inlet and outlet) that are not in accord with the purpose of the subsystem.

4.1 Physical Diagram

Figure 2 shows the physical diagram of the analyzed combined cycle cogeneration plant. The physical diagram (Fig. 2) can be considered a simplification of the flow sheet (Fig. 1), in which the subsystems are defined and represented.

Serra (1994) showed that, no matter the cost equation balance is based on physical or productive flows and diagrams, if there is a consistent definition of the physical units and its fuel and products, as well as the same treatment to the cost of external irreversibility (residues), all methodologies presents equal results for the final product costs.

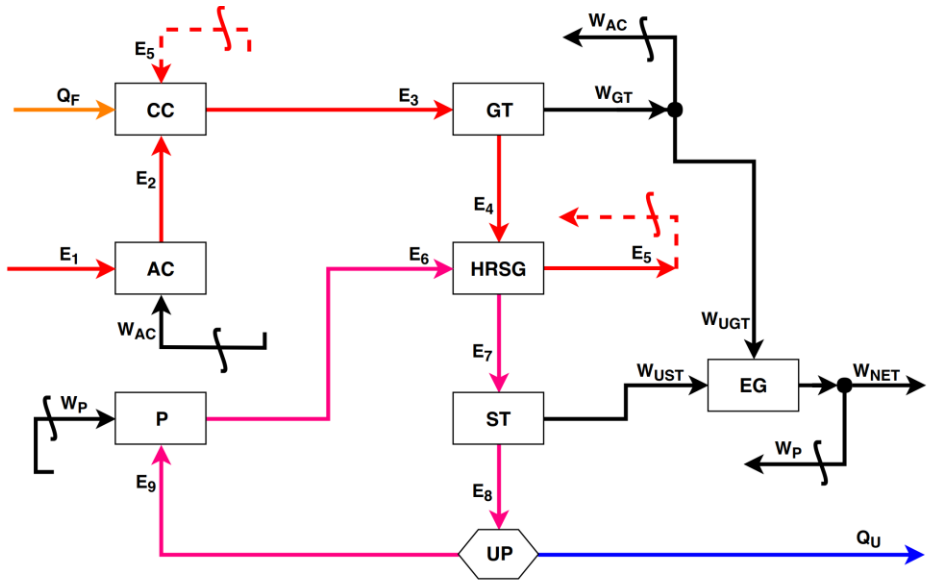

Figure 2. Physical Diagram of the analyzed combined cycle cogeneration plant

Thus, given the physical diagram, for each subsystem, it is possible to write, respectively, the monetary or exergetic cost balances, according to Eq. (1) and Eq. (2), and the auxiliary equations based on fuel and product principle. The fuel principle attributes the same unit cost for streams representing working fluid: air/gases (E_3, E_4 and E_5) and water/steam (E_7, E_8 and E_9). The product principle attributes the same unit cost for streams representing mechanical power (W_{AC} and W_{UGT}) and electrical power (W_P and W_{NET}). The solution of the set of cost equations allows calculating the exergetic or monetary unit cost of each internal flow and final product. In Fig. 2, the residues (E_5) are allocated to the combustion chamber, where it was originated, as proposed by Torres and Valero (2000) and by Lazzaretto and Tsatsaronis (2006).

4.2 Productive Diagram

All thermoeconomic methodologies need to define the productive purpose (products and fuels) of the plant, at both system and subsystem levels. Some of them uses a productive diagram to represent the product and fuel at subsystems level, as well as the interconnection among the subsystems. Since, in conventional productive diagrams, the subsystems are connected using internal productive flows (fuels and products) and fictitious components (junctions and separators), without considering the interconnection of the subsystem using the same physical flows presented in the flow sheet of the plant, this interconnection can involve arbitrariness. The interconnections are more or less arbitrariness, depending on the preference and interpretation of the analyst. According to Lozano and Valero (1993), the way in which we define the productive diagram is a key point in thermoeconomics, which has been proved by Cerqueira and Nebra (1999).

Despite the above-mentioned arbitrariness, given a productive diagram, the mathematical model can be systematically formulated. The mathematical model for monetary or exergetic cost allocation is obtained by formulating cost equations balance in each actual and fictitious subsystem of the productive diagram, according to Eq. (1) and Eq. (2), and the auxiliary equations consider that the productive flows exiting the same separator (bifurcation) have the same unit cost.

In a productive diagram, the fictitious units (junctions and bifurcations) receives the product of the subsystems that increase the exergy of the working fluid and convert these productive flows into fuels to the subsystems that reduce the exergy of the working fluid (respectively). Due to the arbitrariness that generally occurs in this steep, this paper analyses two different arrangements for the productive diagrams representing the same combined cycle cogeneration plant.

4.2.1 Arrangement 1

The first arrangement for the productive diagram of the analyzed plant, which graphically depicts its cost formation process, is presented in Fig. 3. The external resource is the fuel exergy (Q_F) and the products are the electrical net power (W_{NET}) and the useful heat (Q_U). The rectangles are the actual subsystems or actual productive units. The rhombus and the circles are fictitious productive units called junction (J) and bifurcation (B), respectively. Each productive unit of has inlet and outlet arrows, that represent its fuels (or resources) and products, respectively. This kind of productive diagram is the most usual by the thermoeconomic practitioners (Colombo et al., 2017; Santos et al., 2009a; Serra, 1994), in which there are different exergy junctions and bifurcations for the topping gas cycle and the bottoming steam cycle. In this kind of productive diagram, the heat recovery steam generator (HRSG) acts as an interface between both cycles.

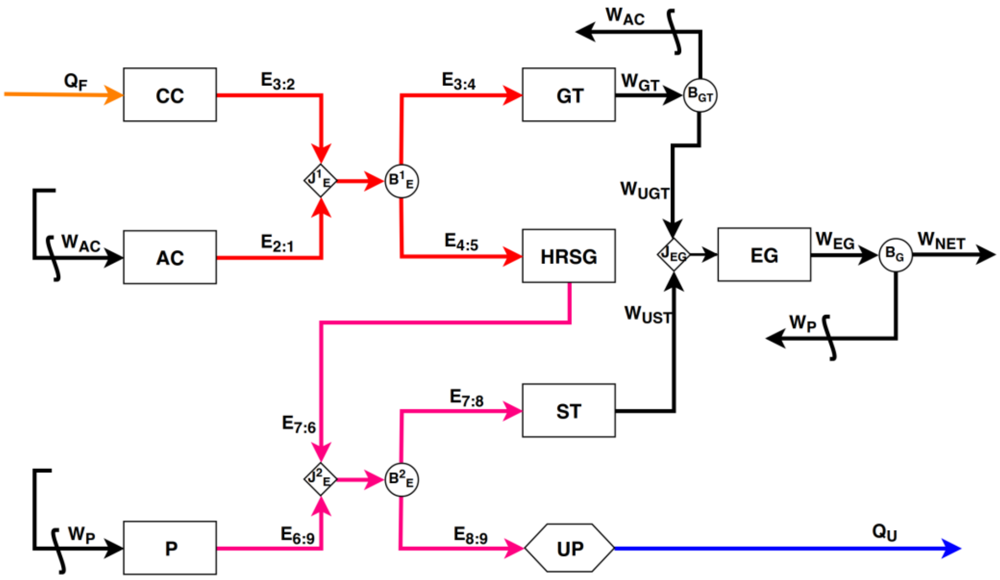

Figure 3. Arrangement 1 for Productive Diagram of the analyzed the combined cycle cogeneration plant

By using this productive diagram, the residue cost (the cost of stream 5, which represents the exhaust gases) the residue cost is not calculated, but it is implicitly and indirectly allocated to the net power and useful heat proportionally to the fuel of the subsystems fuelled by the combustion gases generated in the combustion chamber ($E_{3:4}$ and $E_{4:5}$), i.e., to the gas turbine and to the heat recovery steam generator, respectively. This allocation is done throughout the bifurcation (B_{1E}). The auxiliary equations attribute the same unit cost for the flows exiting the same bifurcation. In this productive diagram, the productive flows exit four bifurcations: gas cycle working fluid ($E_{3:4}$ and $E_{4:5}$), steam cycle working fluid ($E_{7:8}$ and $E_{8:9}$), gas cycle mechanical work (W_{UGT} and W_{AC}) combined cycle electrical work (W_{NET} and W_P).

4.2.2 Arrangement 2

Figure 4 shows the second arrangement for the productive diagram of the analyzed plant. This kind of arrangement were proposed by Modesto and Nebra (2006), in which there is no difference in the treatment between the gas and steam cycle subsystems. There is a pair of fictitious units (junctions and bifurcations) that receives all the product of the all subsystems that increase the exergy of the working fluid and convert these productive flows into fuels to all the subsystems that reduce the exergy of the working fluid (respectively), no matter the working fluid is air/gas or water/steam. In this arrangement, the auxiliary equations also attribute the same unit cost for the flows exiting the same bifurcation. In this productive diagram, the productive flows exit three bifurcations: gas and steam cycle working fluid ($E_{3:4}$, $E_{4:5}$, $E_{7:8}$ and $E_{8:9}$), gas cycle mechanical work (W_{UGT} and W_{AC}) combined cycle electrical work (W_{NET} and W_P).

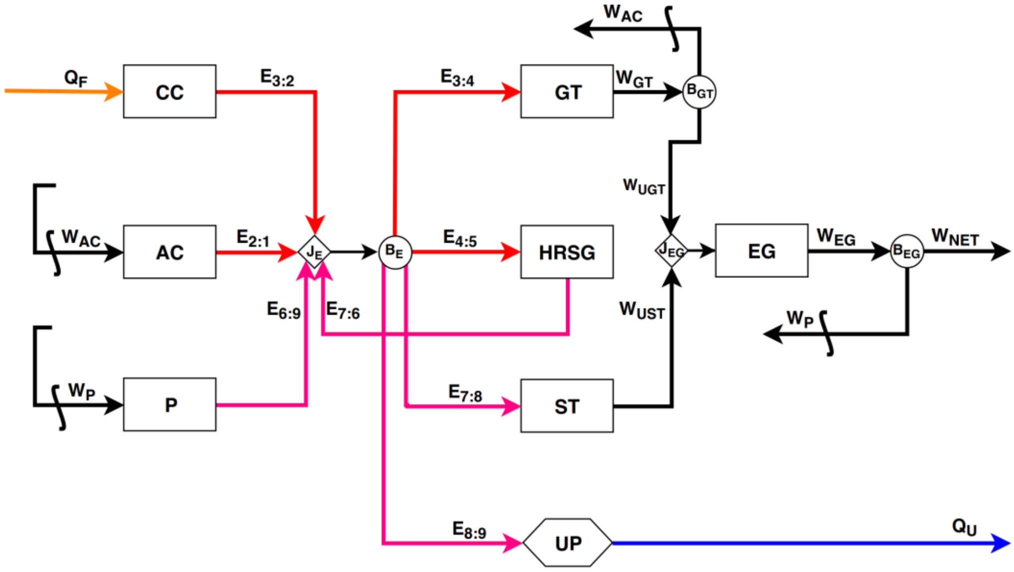

Figure 4. Arrangement 2 for Productive Diagram of the analyzed combined cycle cogeneration plant

By using this productive diagram, the residue cost is not allocated implicitly to the subsystems fuelled by the combustion gases generated in the combustion chamber (gas turbine and to the heat recovery steam generator) only, but also part of the residue cost is implicitly and directly allocated to subsystems fuels by the steam generated in the heat recovery steam generator (the steam turbine and the process), proportionally to the fuels of both productive units ($E_{7:8}$ and $E_{8:9}$). In this case, the allocation of the residue cost is done throughout the bifurcation (B_E).

5. COMPREHENSIVE THERMOECONOMIC DIAGRAM

The comprehensive diagram preserves the main characteristics of both physical and productive diagrams. From the first, the subsystems are connected using the same flows present in the flow sheet. From the second, the product and fuels of each subsystem are presented in the diagram. Figure 5 is a combination of the concept of both physical and productive diagram in a comprehensive thermoeconomic diagram representing the analyzed combined cycle cogeneration plant.

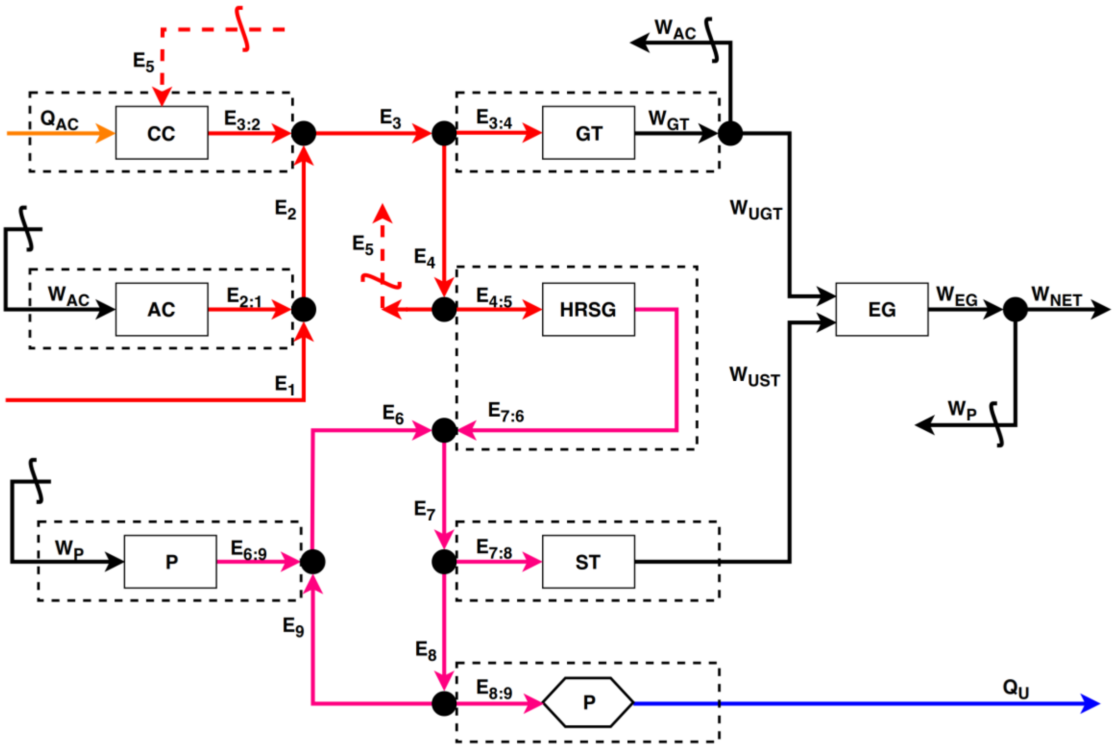

Figure 5. Comprehensive Diagram of the analyzed combined cycle cogeneration plant

The comprehensive thermoeconomic diagram, in Fig. 5, shows clear and graphically the product and fuel of the subsystems, as well as the interrelation among the subsystems, by combining both physical and productive internal flows in a single diagram. However, in this comprehensive thermoeconomic diagram, there are no the fictitious subsystems, called junction (J) and bifurcation (B), and the subsystems are interconnected using the same physical exergy flows presented in the flow sheet. In the comprehensive diagram, in Fig. 5, each subsystem acts as both a productive unit (continuous line) and as a component (dotted line) combining the characteristic of both productive and physical diagram, respectively. Lazzaretto and Tsatsaronis (2006) introduced the concepts of productive unit and component. However, these authors do not use the concept of productive unit for cost calculation using productive diagrams.

The mathematical model for exergetic and monetary cost allocation is obtained by formulating cost equations balance in each subsystem of the comprehensive diagram, according to Eq. (1) and Eq. (2). However, each subsystem allows formulating two cost equation, one the productive unit boundary and other at a component boundary. The auxiliary equations of comprehensive diagram are formulated at the component boundary as well as in the physical diagram. The fuel principle attributes the same unit cost for some working fluid streams: air/gases (E_3, E_4 and E_5) and water/steam (E_7, E_8 and E_9). The product principle attributes the same unit cost for streams representing mechanical power (W_{AC} and W_{UGT}) and electrical power (W_P and W_{NET}). The solution of the set of cost equations allows calculating the exergetic or monetary unit cost of each internal flow and final product. In Fig. 5, the residue (E_5), as a physical flow, it is allocated to the combustion chamber, where it was originated, as the procedure used in the physical diagram presented in Fig. 2.

Compared to the conventional productive or functional diagrams, the comprehensive thermoeconomic diagram has the advantage of allowing calculate the cost of each internal physical flows of the system, not the cost of internal productive flows only. Furthermore, in the comprehensive diagram the subsystems are connected using the same physical flows of the flowsheet, avoiding the arbitrariness related to the interconnection using the criticized fictitious subsystems (junctions and separators). Compared to the conventional physical diagrams, the comprehensive diagram has the advantage of allowing calculate the cost of each internal productive flows, not the cost of internal physical flows only.

6. INTERNAL FLOWS AND UNIT COST RESULTS

Table 4 and 5 shows the values of the physical and productive flows (in *kW*) of the four kinds of diagrams analyzed, as well as their respective exergetic unit cost (in *kW/kW*) and monetary unit cost (in *$/kWh*), respectively. These unit costs were obtained by solving the set of cost equations defined by considering each of the diagram shown in: Fig. 2 (physical), Fig. 3 (productive - arrangement 1), Fig. 4 (productive - arrangement 1) and Fig. 5 (comprehensive), respectively.

Table 4. Exergy and Exergetic Unit Costs

Flow	Value (kW)	Exergetic Unit Cost (*kW/kW*)			
		Diagram			
		Physical	Productive 1	Productive 2	Comprehensive
E_1	0.00	0.00	-	-	0.00
E_2	4,358.90	2.53	-	-	2.53
E_3	13,135.58	2.07	-	-	2.07
E_4	5,012.59	2.07	-	-	2.07
E_5	488.61	2.07	-	-	2.07
E_6	30.13	3.33	-	-	3.33
E_7	3,404.75	2.78	-	-	2.78
E_8	1,895.46	2.78	-	-	2.78
E_9	21.46	2.78	-	-	2.78
$E_{2:1}$	4,358.90	-	2.53	3.00	2.53
$E_{3:2}$	8,776.68	-	1.72	1.72	1.84
$E_{3:4}$	8,122.99	-	2.07	2.46	2.07
$E_{4:5}$	4,523.98	-	2.07	2.46	2.07
$E_{7:6}$	3,374.62	-	2.77	3.29	2.77
$E_{7:8}$	1,509.29	-	2.78	2.46	2.78
$E_{8:9}$	1,874.00	-	2.78	2.46	2.78
$E_{6:9}$	8.67	-	4.71	5.00	4.71
Q_F	15,123.70	1.00	1.00	1.00	1.00
W_{TG}	7,295.42	2.77	2.77	2.94	2.77
W_{AC}	4,787.40	2.30	2.30	2.73	2.30
W_{UTG}	2,508.02	2.30	2.30	2.73	2.30
W_{UTV}	1,087.29	3.85	3.85	3.41	3.85
W_P	14.30	2.86	2.86	3.03	2.86
W_{NET}	3,581.01	2.86	2.86	3.03	2.86
Q_U	1,874.00	2.78	2.78	2.46	2.78

Table 5. Exergy and Monetary Unit Costs

Flow	Value (kW)	Monetary Unit Cost (*$/MWh*) Diagram			
		Physical	Productive 1	Productive 2	Comprehensive
E_1	0.00	0.00	-	-	0.00
E_2	4,358.90	30.44	-	-	30.44
E_3	13,135.58	19.21	-	-	19.21
E_4	5,012.59	19.21	-	-	19.21
E_5	488.61	19.21	-	-	19.21
E_6	30.13	57.03	-	-	57.03
E_7	3,404.75	30.06	-	-	30.06
E_8	1,895.46	30.06	-	-	30.06
E_9	21.46	30.06	-	-	30.06
$E_{2:1}$	4,358.90	-	30.44	37.72	30.44
$E_{3:2}$	8,776.68	-	12.56	12.56	13.63
$E_{3:4}$	8,122.99	-	19.21	25.16	19.21
$E_{4:5}$	4,523.98	-	19.21	25.16	19.21
$E_{7:6}$	3,374.62	-	29.82	37.80	29.82
$E_{7:8}$	1,509.29	-	30.06	25.16	30.06
$E_{8:9}$	1,874.00	-	30.06	25.16	30.06
$E_{6:9}$	8.67	-	123.81	128.17	123.81
Q_F	15,123.70	6.91	6.91	6.91	6.91
W_{TG}	7,295.42	30.40	30.40	32.96	30.40
W_{AC}	4,787.40	24.37	24.37	31.00	24.37
W_{UTG}	2,508.02	24.37	24.37	31.00	24.37
W_{UTV}	1,087.29	44.30	44.30	37.50	44.30
W_P	14.30	33.11	33.11	35.75	33.11
W_{NET}	3,581.01	33.11	33.11	35.75	33.11
Q_U	1,874.00	30.06	30.06	25.16	30.06

The unit costs in Tab. 4 and 5 confirm that the unit cost of the final products (useful heat and net power) can be the same, no matter the kind of diagram, when the same treatment is dispensed to cost of residues, if the subsystem productive purposes are defined accordingly and if the interconnection are made rationally. Bearing this in mind, we can conclude that perhaps, in this case, the arbitrariness affected the results obtained using the productive diagram (arrangement 2). However, the comprehensive diagram proposes a procedure allowing accomplish all these steeps, based on a general and systematic rule, based on physical and rational basis (thermodynamics and economics).

The results also show that, besides the unit cost of the final products (useful heat and net power), the unit costs of both internal physical and productive flows obtained using this comprehensive diagram can be also the same as the ones obtained, separately, using the conventional physical and productive diagram (arrangement 1), respectively.

Although, for the sake of simplicity, in this work, the thermodynamic magnitude used is total exergy (E), it should be mentioned that the comprehensive diagram can be applied no matter the thermodynamic magnitude (Y), since most internal productive flow ($Y_{j:k}$) is always the deference between two internal physical flows (Y_j and Y_k).

7. CONCLUSIONS AND CLOSURE

This work presented and discussed the concepts and the fundamentals of a thermoeconomic model, based on a comprehensive thermoeconomic diagram, which shows clear and graphically the productive purpose of the subsystem (product and fuel), as well as the interrelation among the subsystems, and allows assess the unit costs of both physical and productive internal flows of the system. This paper showed that a comprehensive thermoeconomic diagram takes all the advantages of both conventional physical and productive diagrams using a single diagram.

For the sake of exemplification and numerical comparison, the exergetic and monetary unit costs of the internal flows and final products were calculated using a combined gas and steam turbine cogeneration plant. The results showed that the unit cost of the internal physical and productive flows obtained using the comprehensive diagram can be the same as the ones obtained using the conventional physical and productive diagrams, separately. However, the advantage is that all these results can be obtained using a single and comprehensive thermoeconomic model, which is not possible using a thermoeconomic model based on productive or physical diagram only. Thus, this paper contributed to the unification of two group of thermoeconomic methodologies that differs mainly in the kind of diagram (physical or productive) used to formulate the cost equations, which can be formulated using this comprehensive thermoeconomic diagram.

Once that nowadays the thermoeconomic methodologies have achieved a certain advance in the unification and agreement related to a systematic procedure to the treatment of the residues and to define fuels and products at the subsystem level, the comprehensive diagram avoid the use of the criticized fictitious units (junctions and bifurcations) generally used in the conventional productive diagram in order to interconnect the subsystems. At this point, the comprehensive diagram, here presented, reduces this arbitrariness, by connecting the subsystems using the same physical flows as in the flow sheet. Related to the treatment of the residues and allocate its cost to the final products, as in a physical diagram, their costs are calculated and explicitly allocated to the subsystem in which they were originated. In other words, the residues are recirculated and internalized in the system throughout the subsystem in which they were originated. In a conventional productive diagram, the cost of the residues is not calculated, and it is allocated implicitly to the final products throughout one or more subsystems, depending on the productive diagram arrangement used.

Although, in this work, the results confirm that, no matter the thermoeconomic methodology, if the productive purpose (fuel and product) of the subsystem are the same, and the interconnection among the subsystem is consistently defined, the cost of the final product will be unavoidable the same, it should be pointed that, although the certain degree of agreement related to a systematic procedure to define fuels and products at the subsystem level, the interconnection among them still more or less arbitrariness in the conventional productive diagram. This arbitrariness is avoided by using the comprehensive thermoeconomic diagram, in which the subsystems are connected using physical flows.

In the final analysis, we can say that this paper also showed that we can take all the advantages of both productive and physical diagrams by considering the comprehensive diagram, overcoming the limitations of these conventional diagrams, separately, and avoiding the criticism related to the arbitrariness involved in the productive diagrams.

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