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PRACTICAL APPROACHES FOR THE APPLICATION OF EXERGY COST THEORY TO ENERGY CONVERSION SYSTEMS

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Abstract

The Exergy Cost Theory (ECT) was proposed as a complete and formalized method to account for the exergy cost of system products, defining criteria for optimization and diagnosis purposes. In this paper, different practical approaches for the application of the Exergy Cost Analysis are presented and comparatively applied to the CGAM problem. An emphasis has been specially put on the possible approaches to define and to solve the system of exergy cost balances, including the definition of auxiliary relations and the reallocation of the exergy cost of residues.

It is found that the definition of the functional diagram and the numerical solution of the system through Input-Output analysis seems to be preferable with respect to other approaches.

1 Introduction

Over the last decades, environmental concerns related to the operation of energy conversion systems pushed research efforts in developing novel methodologies useful for the purposes of accounting and reducing energy-resources consumption.

According to the literature, particular attention has been devoted so far to Exergy, considered as a suited proxy for the quantification of resources consumption: *Exergy Analysis* (ExA) is widely adopted for the identification and the quantification of the thermodynamic irreversibilities, supporting analysts in reducing resources consumption of the analyzed energy conversion system [1–3]. The joint application of Exergy Analysis and economic principles leads to the definition of the so-called *Thermoeconomic Analysis* (TA) [2,4–6]. Thermoeconomic analysis can be adopted to evaluate different types of costs:

- *Exergy Cost Analysis:* introduced by *Valero* through the *Exergy Cost Theory* (ECT), it aims at evaluating the cost as the amount of exergy required by the system to produce its products (measured in J/J) [7,8];
- *Exergoeconomic Cost Analysis:* it is based on the same accounting rules and mathematical formulation of the Exergy Cost Analysis. However, it accounts for the economic cost of the

system products (measured in $/J) [9,10].

Both the methodologies are based on the same accounting structure and cost allocation rules. Beside the cost accounting purposes, one of the main goals of Thermoeconomics is the evaluation of the cost structure of the system products, understanding the cost formation process and thus introducing criteria and indicators for system design optimization and diagnosis [11].

There exist several practical approaches in the literature, to apply ECT to energy conversion systems [12,13]. In this paper, the Authors comparatively investigate possible ways to apply Exergy Cost Theory to one generic system, addressing practical approaches to account for the exergy cost of system products.

In the following, theoretical approaches to apply the ECT to a generic energy system are presented in subsection 2.1, practical techniques to solve such problem are showed in subsection 2.2, and the issue of reallocation of the exergy costs of residues is discussed in subsection 2.3. Finally, all of the introduced approaches are applied to the CGAM problem in section 3, and results discussed.

2 Exergy Cost Theory (ECT)

The *Exergy Cost Theory* (ECT) was proposed by *Valero* as a complete and formalized method aimed at evaluating the exergy costs of the products of energy systems. More specifically, ECT allows the analyst to understand the cost formation structure of such products, quantifying the relevance that internal irreversibilities have in increasing such costs, and defining criteria for optimization and diagnosis purposes [14].

Let us consider a generic energy system of Figure 1, formed by *n* components linked to each other and to the environment with *l* flows of energy or material interactions. The application of Exergy Cost Theory consists in the definition of a system of equations composed by *n exergy cost balances* (one for every component of the system) and *l-n auxiliary relations*. The latter are required to close and thus solve the system of equations, allowing the analyst to distinguish among productive components, whose main purpose is to generate a useful product, and dissipative components, that do not generate any final product but are responsible for disposing of the residues created during production.

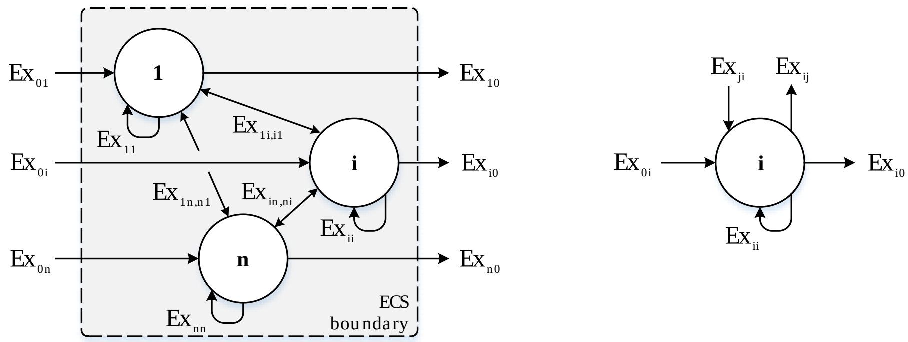

Figure 1.Physical structure of the generic energy system (left side) and focus on the generic ith component within the system (right side).Subscripts "ij" means: from component i to component j.

2.1 Practical approaches to define the Thermoeconomic problem

The general purpose of ECT is to allocate the consumption of exergy of the system to its useful products: therefore, the definition of the thermoeconomic system of equations depends on the purposes of each exergy flow, and thus it ultimately depends on the choice of the analyst.

The approaches to apply ECT can be first differentiated based on how the Thermoeconomic system of equations is defined: the exergy cost balance can be defined for each component according to the *Physical* and the *Functional* approach. A proper application of the two defined approaches to a same energy system is expected to provide the same results.

The *Physical approach* collects inlet and outlet flows of each component disregarding the purpose that such flows actually have in the system, expressing the conservation of the exergy cost. The purpose of each flow is thus defined by specifying appropriate auxiliary relations [15]. Therefore, this approach relies only on the physical structure of the system. On the other hand, the *Functional approach* distinguishes and collects physical flows entering and exiting each component based on the *Resource*, *Product* and *Loss* categories, according to their purpose. Therefore, some of the required auxiliary relations are actually embedded in the definition of such categories. With respect to the previous approach, the Functional approach relies on the so-called *functional diagram*, which redraws the physical structure of the system as a network of exergy interactions grouped as resources, products and losses. The functional diagram may require some fictitious components, called Junctions/branches, useful to distribute the exergy cost of multiple resources to different products [15–17]. The Physical and Functional approaches present the following advantages and drawbacks:

- In general, a proper definition of functional diagrams is not trivial. Therefore, in case of simple systems with few components, the Physical approach turns out to be simpler with respect to the Functional one, due to its reliance on the physical structure of the system.
- In case of complex energy systems with several components, Functional approach reduces the number of required auxiliary relations, thus simplifying the setup of the thermoeconomic problem with respect to the Physical approach;

Notice that, in both the Physical and the Functional approach it may be required to reallocate the exergy costs of losses and residues to the useful products of the system according to one defined criterion. Reallocation of losses is still a debated topic in the literature and widely accepted criteria have not been defined yet [18].

2.2 Practical approaches to solve the Thermoeconomic problem

The Thermoeconomic problem defined according to the aforementioned approaches can be practically solved by means of the *Direct method* and the *Input-Output method*.

Direct method. It consists in the direct numerical solution of the Thermoeconomic system of equations, and it can be carried out through any numerical solver (*Matlab*®, *EES*®, and so on). The Thermoeconomic system defined according to both the Physical and the Functional approach can be solved through the Direct method. Usually, a matrix notation can be used to formalize the Direct method, by means of the *Incidence matrix* introduced in relation (1) [2,13,15,19].

$$\left[\frac{\mathbf{I}(n\times l)}{\boldsymbol{\alpha}\left[(l-n)\times l\right]}\right]\cdot\mathbf{Ex}^*(l\times 1)=\begin{bmatrix}\mathbf{0}(n\times 1)\\ \boldsymbol{\omega}\left[(l-n)\times 1\right]\end{bmatrix}\quad\rightarrow\quad\mathbf{I}^*(l\times l)\cdot\mathbf{Ex}^*(l\times 1)=\mathbf{\Omega}(l\times 1)\tag{1}$$

$$\mathbf{Ex}^*(l\times 1)=inv\left[\mathbf{I}^*(l\times l)\right]\cdot\mathbf{\Omega}(l\times 1)\tag{2}$$

The matrix $\mathrm{I}^*(l\times l)$ is called *Cost matrix*: it is obtained by juxtaposing the *Incidence matrix* $\mathrm{I}(n\times l)$, which defines how the flows and components are connected, and matrix $\alpha[(l-n)\times l]$ which represents the auxiliary relations. The Cost matrix is then multiplied by the *Exergy Cost vector* $\mathrm{Ex}^*(l\times 1)$, which collects the unknown total exergy costs of all the l streams. The closure for this system is made by the vector $\mathbf{\Omega}(l\times 1)$, composed by the empty vector $\mathbf{0}(n\times 1)$, which represents the conservation of the total exergy costs for all the components, and vector $\boldsymbol{\omega}[(l-n)\times 1]$, a numerical arrangement required to set auxiliary relations. The solution of the system of equations (1) can be simply performed through relation (2). Notice that the structure of such matrices may change, depending on the adopted approach to define the Thermoeconomic problem, either Physical or Functional. More details and applications of the Direct method can be found in literature [2,15,19].

Input-Output method. This method was originally conceived by *Leontief* for the analysis of the structure of national economies, investigating direct and indirect relations among the sectors of the economy [20,21]. The Input-Ouptut method can be adopted to account for environmental burdens of economic activities. Recently, it has been also used in the fields of Thermoeconomics and *Industrial Ecology* [12,22,23]: inded, its numerical structure makes it suited for the application of the Exergy Cost analysis.

To implement the Input-Output method, the Physical approach cannot be adopted, because the functional diagram of the system must be defined in advance. In line with the traditional formulation of the Input-Output method available in the literature [24], the exergy production balance for all the *n* components of the system in a given time frame can be written in matrix form, as in relation (3).

$$\mathbf{x}(n\times 1)=\mathbf{Z}(n\times n)\cdot\mathbf{i}(n\times 1)+\mathbf{f}(n\times 1) \tag{3}$$

The amount of exergy produced by each component is collected in the *total production vector* $\mathrm{x}(n\times 1)$. Endogenous transactions of exergy produced by all the components are collected in the *transaction matrix* $\mathrm{Z}(n\times n)$: each one of its elements represents the amount of products of the *i*th component provided as a resource to all the other *j*th components (Ex_{ij}). The *final demand vector* $\mathrm{f}(n\times 1)$ collects the amount of exergy delivered outside the physical boundaries of the system as the useful product. Finally, the *resources vector* $\mathrm{R}(1\times n)$ collects the amount of exergy directly provided as resource to each component from outside the system boundaries. The *Resource-Product table* (RP table) is usually defined as the assembly of matrices and vectors Z, f, x and R.

Based on the exergy production balance (3), the exergy cost balance can be written as in relation (4): for each component, the total exergy cost of its products equals the total exergy cost of resources taken from other components plus the exergy directly taken from outside system boundaries. By simple matrix manipulations, the specific and total exergy cost vectors, respectively $\mathrm{ex}^*(n\times 1)$ and $\mathrm{Ex}^*(n\times 1)$, can be obtained as in relation (5). Notice that matrix $\mathrm{U}(n\times n)$ is the Identity matrix of order *n*.

$$\hat{\mathbf{x}}\cdot\mathbf{ex}^* = \mathbf{Z}^{\mathrm{T}}\cdot\mathbf{ex}^* + \mathbf{R}^{\mathrm{T}} \tag{4}$$

$$\mathbf{ex}^* = inv\left[\mathbf{U}-\left(\mathbf{Z}\cdot\hat{\mathbf{x}}^{-1}\right)^{\mathrm{T}}\right]\left(\mathbf{R}\cdot\hat{\mathbf{x}}^{-1}\right)^{\mathrm{T}} \quad ; \quad \mathbf{Ex}^* = \hat{\mathbf{f}}\cdot\mathbf{ex}^* \tag{5}$$

Further theoretical details and applications of the Input-Output method can be retrieved in literature [12,22]. Notice that Direct method accounts for the exergy cost of the *l* products/outputs of each component, while Input-Output accounts for the exergy cost of *n* system products, one for each component.

To sum up, the Direct and the Input-Output methods present the following characteristics:

- Both methods are different formalizations of a same problem: therefore, results of the application of a same system should be the same;
- The Direct method always requires the definition of auxiliary relations, based on the purpose of each flow. On the other hand, the application of the Input-Output method implicitly includes all auxiliary relations, simplifying the definition of the Thermoeconomic system;
- The Direct method is well established and widely accepted to account for the exergy costs of system products. On the other hand, the Input-Output method has been mainly applied to

account for environmental burdens of products of national economies. However, in recent years, many applications of advanced Input-Output methods appeared in the field of Industrial Ecology, such as Material Flow Analysis, Life Cycle Assessment, and so on [25,26]. Therefore, one advage in using Input-Output method for the application of Exergy Cost Theory resides in the opportunity to expand the boundaries of the analyzed system, encompassing its supply chains. More details about the use of Input-Output method for such purpose can be found in literature [27,28].

2.3 Reallocation of the Exergy Cost of residues

Residual flows can be defined as all the unwanted and unavoidable outputs of a system [18]. Literature related to Thermoeconomic analysis deals with the treatment of residual flows in several ways. The simplest method consists in setting the specific exergy cost of residues equal to zero: this approach results in an unfair evaluation of the exergy costs of system products, since the cause of irreversibilities is charged upon the last productive component of the system [29]. Another approach debated in literature consists in the *reallocation of the exergy cost of residues* among the useful products of the system. To perform such reallocation process, it is required to understand the formation process for the exergy cost of such losses and to reallocate such costs among the productinve components contributing to the generation of such losses. Since the identification of such formation process requires the role of each component within the system to be known, the Physical approach described in subsection 2.1 does not provide enough information for this purpose.

Therefore, the reallocation process is performed by defining the Thermoeconomic system according to the Functional approach, and by allocating such costs based on the proportionality criterion proposed by Valero [17,18].

3 Application of Direct and Input-Output methods to the CGAM problem

The CGAM problem has been employed in literature as a test case study for a number of applications in Thermoeconomic analysis and optimization [30]. It consists in a cogeneration plant composed by five components: air compressor (AC, 1), air pre-heater (APH, 2), combustion chamber (CC, 3), gas turbine (GT, 4) and heat recovery steam generator (HRSG, 5). At design conditions, the plant depicted in Figure 2 supplies 30 MW of net electric power and 14 kg/s of saturated steam at 20 bar. More information about the CGAM problem can be found in literature [31].

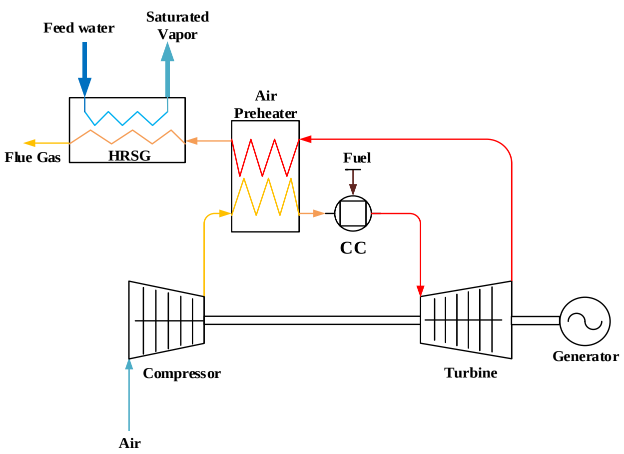

Figure 2. CGAM plant configuration and properties

Thermodynamic properties of all the streams have been listed in Table 1. From such properties, the physical exergy is computed except for the fuel of CC in which chemical exergy of the methane is assumed equal to its Lower Heating Value.

Table 1. Thermodynamic properties of the CGAM plant

Stream	Mass Flow Rate [kg/s]	Temperature [K]	Pressure [bar]	Exergy Rate (Physical) [MW]
Air (Compressor inlet)	91.28	298.15	1.01	0.0
Air (Compressor outlet)	91.28	603.74	10.13	26.9
Air (APH outlet)	91.28	850.00	9.62	39.7
Flue gas (CC outlet)	92.92	1520.00	9.14	107.3
Flue gas (Turbine outlet)	92.92	1006.16	1.10	41.6
Flue gas (APH outlet)	92.92	779.78	1.07	21.5
Flue gas (HRSG outlet)	92.92	426.90	1.01	2.2
Water (HRSG inlet)	14.00	298.15	20.00	0.0
Water (HRSG outlet)	14.00	485.57	20.00	12.8
Methane (Fuel)	1.64	298.15	12.00	85.0

3.1 Definition of the Thermoeconomic problem

The Thermoeconomic problem is defined for the CGAM system based on the Physical and the Functional approach and it is shown in **Error! Reference source not found.**. The former implies the identification of 12 material and energy streams and 5 components, thus 7 auxiliary relations are required. The latter approach lead to the identification of 11 streams and 6 components, therefore 5 auxiliary relations are needed. Notice that the number of streams and components identified the Physical approach equals the real number of streams and components of the analyzed system (see **Error! Reference source not found.**, left side). On the other hand, the Functional approach defines different numbers of flows and components, depending on the shape of the functional diagram (see **Error! Reference source not found.**, right side). In the present case, the fictitious component 6 is defined to collect and thus distribute the flows of resources and products among all the other components. Notice that, with respect to other components, junction/branch 6 does not contribute in increase the specific exergy cost of its products.

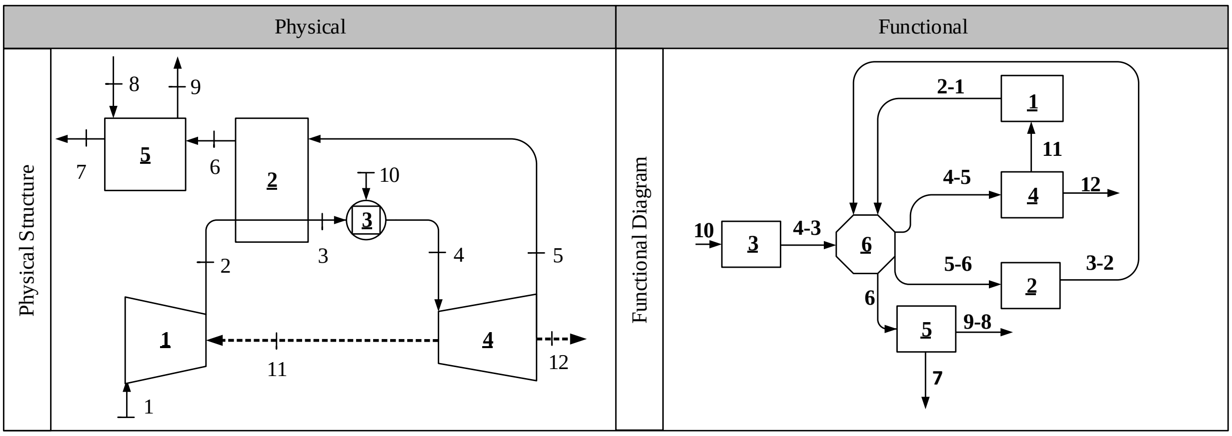

Figure 3. Definition of the Thermoeconomic problem

As stated in subsection 2.1, application of the Functional approach implicitly defines some auxiliary relations with respect to the Physical approach. In the present case, such impicit auxiliary relations are mainly referred to the by-product of the components. As an exapmle, fuel of the GT is presented as (4 - 5) in the Functional approach, which implicilty considers stream number 5 as a byproduct of the GT. The same could be interpreted for the APH.

3.2 Application of the methods and computation of the exergy costs

To solve the TE problem with the Direct method, *EES®* (Engineering Equation Solver) software has been utilized, while for the Input-Output method, Microsoft Excel was employed.

In Table 2, the Thermoeconomic parameters of the CGAM problem for both approaches solved by Direct method are presented, including reallocation of the residual flow in the bottom part of the table. It has been mentioned in subsection 2.3 that the reallocation requires formation process of the residual flow to be known, which only functional diagram can provide.

As expected, with the Direct method, the results of the analysis are the same for the Physical and the Functional approach. In the bottom part of Table 1, the exergy cost of the residual flow of the HRSG has been reallocated according to the functional diagram of the system. As can be inferred from Table 2, without performing reallocation of the residual flow (i.e. setting specific exergy cost of such flow equal to zero), the exergy cost of the residue will be charged on the the HRSG, which is the last productive component. Conversely, according to the Functional approach, the HRSG is not considered as the only component responsible for production and disposal of such residual flow. Therefore, the reallocation process based on the Functional approach distributes the exergy cost of the residual flow among the components involved in the production of such residue. It is notewhorty that an unproper reallocation of the exergy costs of the residues may produce *over*- and *underestimated* exergy costs of useful products (consider the specific exergy cost of the GT and HRSG before and after the reallocation).

Table 2 . Results for standard technique (TE parameters)

Equipment	$Ex_D[i]$ [kw]	$ex_F^*[i]$ [kw/kw]	$ex_P^*[i]$ [kw/kw]	$Ex_{D-F}^*[i]$ [kw]	$Ex_{D-P}^*[i]$ [kw]
Physical approach, ***Direct*** method					
AC	1093	1.74	1.81	1895	1972
APH	7366	1.53	2.42	11299	17793
CC	17441	1.00	1.26	17441	21947
GT	7602	1.53	**1.74**	11661	13189
HRSG	6536	1.53	**2.58**	10024	16869
Functional approach, ***Direct*** method					
AC	1093	1.74	1.81	1895	1972
APH	7366	1.53	2.42	11299	17793
CC	17441	1.00	1.26	17441	21947
GT	7602	1.53	**1.74**	11661	13189
HRSG	6536	1.53	**2.58**	10024	16869
Junction	-	1.53	1.53	-	-
Functional approach, ***Direct*** method (**Reallocated**)					
AC	1093	1.84	1.91	2009	2090
APH	7366	1.63	2.56	11974	18856
CC	17441	1.00	1.26	17441	21947
GT	7602	1.63	**1.84**	12357	13977
HRSG	6536	1.63	**2.34**	10623	15275

Junction	-	1.63	1.63	-	-

In Table 2, Ex_D is the *Exergy destruction*, ex^*_F is the *specific exergy cost of the fuel*, ex^*_P is the *specific exergy cost of the product* for each component, Ex^*_D is the *Exergy cost of exergy destruction*.

Table 3 represents the TE parameters of the same system, defined by the Functional approach and solved by Input-Output method, considering the reallocation of residues. As can be inferred by comparing bottom part of Table 2 with Table 3, results of Direct and Input-Output methods coincide for the system defined by Functional approach.

Table 3. Results for Input-Output technique (TE parameters)

Functional approach, ***Input-Output*** method, (**Reallocated**)					
Equipment	$Ex_D[i]$ [kw]	$ex^*_F[i]$ [kw/kw]	$ex^*_P[i]$ [kw/kw]	$Ex^*_{D-F}[i]$ [kw]	$Ex^*_{D-P}[i]$ [kw]
AC	1093	1.84	1.91	2009	2090
APH	7366	1.63	2.56	11974	18856
CC	17441	1.00	1.26	17441	21947
GT	7602	1.63	**1.84**	12357	13977
HRSG	6536	1.63	**2.34**	10623	15275

4 Conclusions

In this paper, a comparison has been performed between different methods for Thermoeconomic analysis of the ECS applied on the CGAM case study.

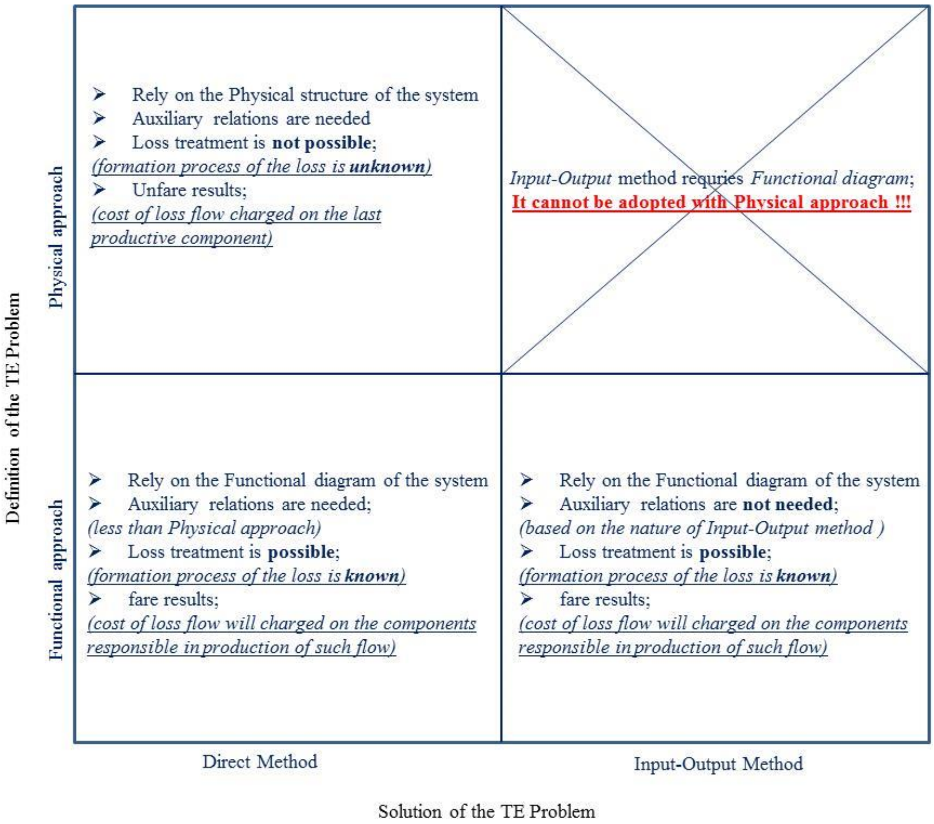

Figure 4. Summary and highlights of discussed methodologies

Two approaches have been introduced to define the Thermoeconomic system of equations, and two methods have been presented to solve the TE problem. Main advantages, drawbacks and peculiarities of the combinations of the proposed approaches are resumed in Figure 4.

It is found that the application of Direct and Input-Output methods to the Thermoeconomic problem defined by means of the Functional approach provide the same results.

Moreover, it has been shown the proper exergy cost reallocation of the residues prevents over- and under evaluation of the exergy cost of the useful products. Such reallocation process is more fair once the TE problem defined the by means of Functional approach.

Authors believe the Input-Output method not only reduces the complexity level of the analysis, but also provides an opportunity to expand the domain of the analysis towards the application of exergy life cycle assessment.

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