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Maintenance Strategy of a Preheat Train of a Crude Oil Distillation Unit Based on Exergy and Exergoeconomic Analysis

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Established or create new ones to plan the cleaning tasks of the heat exchangers. In this work, a maintenance strategy is developed for a preheating train under the Maintenance Centered on Energy Efficiency (MCEE) methodology, where it is sought to integrate the information of the principles of the second law of thermodynamics with economic variables to use parameters. The modification of the maintenance justification parameter (J) is proposed, adding two new maintenance indicators (W and X). Each one seeks to evaluate an essential criterion for the maintenance area: economic viability, technical feasibility, and benefits, toward the other exchangers in the network after cleaning a specific component. A criticality diagram and a criticality matrix are used. The heat exchangers are grouped into subassemblies, with the leading group consisting of the key heat exchangers (KHEX), the elements of which have a significant impact on the efficiency of the preheat train. For their part, the regions are composed of components whose performance is less considerable than that of the KHEX. In total, 34 maintenance activities will be carried out, distributed among the 25 interchanges of the network. The planning of a program of cleaning activities according to the maintenance strategy based on the methodology of the MCEE establishes a substantial scientific contribution due to the almost null existence of exergetic studies applied to the management of maintenance tasks and focused mainly on the preheating of trains. [DOI: 10.1115/1.4062713]

Keywords: maintenance, heat exchanger, preheat train, crude oil distillation unit, energy systems analysis

1 Introduction

Exergy is considered the valuable energy of a system under specific circumstances. This concept allows identifying how various limitations affect the performance of equipment. The introduction of economic variables in the exegetical analysis allows financial evaluations of each system component according to its performance, providing the necessary information to study the economic feasibility of the proposed improvements [1,2].

Ansarinasab et al. studied the origin of irreversibilities and their economic impact in a hydrogen liquefaction plant. The advanced exergetic analysis and exergoeconomics show that the heat exchanger network represents the highest rate of exergy destruction (10615.8 kW), equivalent to 60.08% of all the exergy destruction of the network. Likewise, the heat exchangers have the highest value regarding the cost rate of exergy destruction (534.34 US$/h), generated to a greater extent by the section corresponding to the avoidable-endogenous exergy destruction. In contrast, the inevitable-endogenous investment cost ratio is meager. The previous reveals that exchangers have enormous potential to improve system performance by reducing their avoidable exergy destruction by enhancing the performance of these components [3].

Rivero [4] conducted an exergoeconomic analysis in a crude oil distillation unit. The author incorporates a measure called "improvement potential" that relates the irreversibilities of a piece of equipment and its efficiency; this allows them to determine which systems are much more feasible to carry out improvement works. The results obtained by Rivero indicate that the production cost of the plant is 103.93×10^3 US$/h (823 million dollars per year in 2004), which is mainly associated with the costs of transforming the raw material since salaries, maintenance, administration, and other expenses are only US$232.56/h. In terms of potential for exergoeconomic improvement, the components with the most significant opportunity for intervention are the atmospheric and vacuum furnaces, the atmospheric and vacuum distillation towers, the atmospheric tower condenser, and the desalination system and the crude oil preheating train. Together, these elements produce an economic loss of 367 US$/h due to wasted exergy; however, if these elements are optimized, they can reduce the loss to 9 US$/h.

Maintenance is considered a set of methodologies, strategies, and activities meant to preserve an asset's useful life and optimal functioning (element used to generate value). This concept can be

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divided into two main branches: reactive maintenance and proactive maintenance.

Reactive maintenance is characterized by acting after a failure occurs in the equipment. This type of intervention leads to significant problems such as unforeseen stops in production, irreparable damage, work accidents, and increased maintenance costs. Proactive maintenance, unlike reactive, is focused on acting to prevent the appearance of failures. Therefore, it eliminates all the disadvantages of reactive maintenance and adds other benefits such as better organization in the maintenance department, increased availability, and useful life of the equipment, reduced spare parts inventory, and removed workload, among others [5]. This research explicitly addresses the processes considered proactive for assets.

TEMA (The Tubular Exchanger Manufacturers Association, Inc.) [6] divides the activities into online (online) and offline (offline) based on the complexity of the intervention. Online work consists of circulating fluids inside the exchanger without completely disconnecting them from the system to which it belongs. The second classification is focused on specialized mechanical cleaning. These activities are more effective but involve leaving the equipment out of service while they are carried out.

Most of the methods to establish the optimal cleaning moments usually make comparisons between the current performance of the equipment and the cost of maintenance; this type of strategy is implemented by Georgiadis et al. [7] and Georgiadis and Papageorgiou [8] in their studies on the reduction of efficiency in a network of heat exchangers; the solution is proposed through the optimization of the cost-benefit ratio of maintenance, restricting the variables to money and lost energy. With the help of linear programming, the results show how the performance of the heat exchanger decreases over time, implying the need to remove it from service to clean it to restore its performance.

Zubair et al. and Sheikh et al. [9,10] carried out a study on the performance and economic evaluation of the heat exchanger subject to fouling through the relationship between the accumulation of material and the global coefficient of heat transfer. Their results indicate the minimum intervention cost before the critical level of fouling occurs. But these strategies have shortcomings because they only consider the direct cost related to maintenance, leaving aside the indirect implications such as related economic losses such as the decrease in operating capacity, lost profits, or logistics costs.

Maintenance centered on energy efficiency (MCEE) emerges as a method for planning maintenance, seeking to preserve the condition of equipment through activities focused on eliminating or reducing the presence of malfunctions that generate inefficient use of energy. To achieve its mission, the MCCE carries out energy or exergetic studies to determine the origin of irreversibilities, consequences, and improvement opportunities. In addition, this methodology mixes economic variables to study the feasibility of the solutions proposed from the monetary sphere [11].

The research carried out by Yabrudy et al. [12] establishes a maintenance program centered on energy efficiency for the exchanger network under study. The economic-energy indicator "J" is introduced in the document, which compares the maintenance cost against the increase in the operating cost caused by the rise in fuel consumption due to the reduction in the heat transfer rate. Yabrudy et al. establish a criticality matrix created from the J indicator and the effectiveness, defined by the ratio between the current heat transfer rate and the optimal heat transfer rate (defined according to the design). This strategy allows evaluation of the priority of intervention in each component. The results made it possible to redirect the maintenance program toward the interchanges with the worst performance levels, which generated savings of around 150,000 dollars related to maintenance adequacy, loss of profit, and reduction in fuel consumption. Although the Yabrudy research sets a precedent in maintenance planning for interchange networks, in some aspects it is possible to obtain more precise information and make much more accurate decisions.

Given the above, this work aims to optimize the maintenance system through the following improvements:

- Heat exchangers go from being considered individual elements to being examined as components of a system, where the effects of a condition on a piece of equipment could benefit or harm the remaining elements and vice versa.
- Design, environmental, and operational constraints are included to gain insight into the potential for recovery rather than considering complete restoration regardless of restrictions.
- Irreversibilities are classified according to the possibility of being eliminated to understand how they affect operating performance and production costs and establish action plans.
- The economic losses caused by the increase in fuel consumption are taken as cumulative losses instead of instantaneous to have a record of the behavior over time, the heat transfer rate, or any other performance indicator.
- Specific values of the J^* indicator are assigned to each heat exchanger based on operational and maintenance considerations and the information obtained from the different analyses.

2 Materials and Methods

The crude distillation unit's preheating train is designed to transfer heat to 150,000 barrels daily from the heat surplus of crude oil fractions leaving the unit. The heat exchanger network comprises 25 shell and tube exchangers, shown in Fig. 1. This equipment carries out a regenerative process, where the fractions obtained by distillation give up heat to the crude oil before entering the furnace. This process increases the plant's energy performance, operating costs, and environmental impact to be reduced.

The fractions (derivatives) obtained during the distillation process are the following:

- heavy vacuum gas oil (HVGO);
- medium vacuum gas oil (MVGO);
- atmospheric gas oil (AGO);
- heavy diesel (HDIESEL);
- vacuum residue (VR).

Figure 2 allows us to understand how the decay in the performance of the heat exchanger network affects fuel consumption since if the train outlet temperature is below the optimum temperature (316 °C), the atmospheric furnace will demand more fuel than what is stipulated because 316 °C is the maximum possible temperature depending on the temperatures of the currents and the efficiency of the *HEX* according to the design conditions. Lower temperatures also imply more signific fouling in the oven (and, therefore, an increase in maintenance) and a lower profit margin for the business.

It is, therefore, essential to monitor the behavior of the preheating train, to verify if its energy-saving function is fulfilled, or if maintenance shutdown is needed to recover its performance (as close as possible to design specifications).

2.1 Exergy Destruction in Heat Exchangers. Calculating the total exergy destruction and its parts is the starting point for establishing the maintenance strategy focused on maintaining a highly cost-effective mode of operation for the heat exchanger network. The specific details of the exergy destruction balances in the equipment, the conditions for calculating each type, and their results have been explained and published previously by Fajardo et al. [13].

In the system under study, exergy destruction is the valuable energy not used during the heat exchange between the hot fluid and the crude oil [1].

Given the restrictions in the manufacturing processes and the operating and environmental conditions, reducing the exergy destroyed to zero is impossible. Consequently, there is a portion of exergy destruction of an unavoidable nature ($\dot{E}_{D,k}^{UN}$) [14].

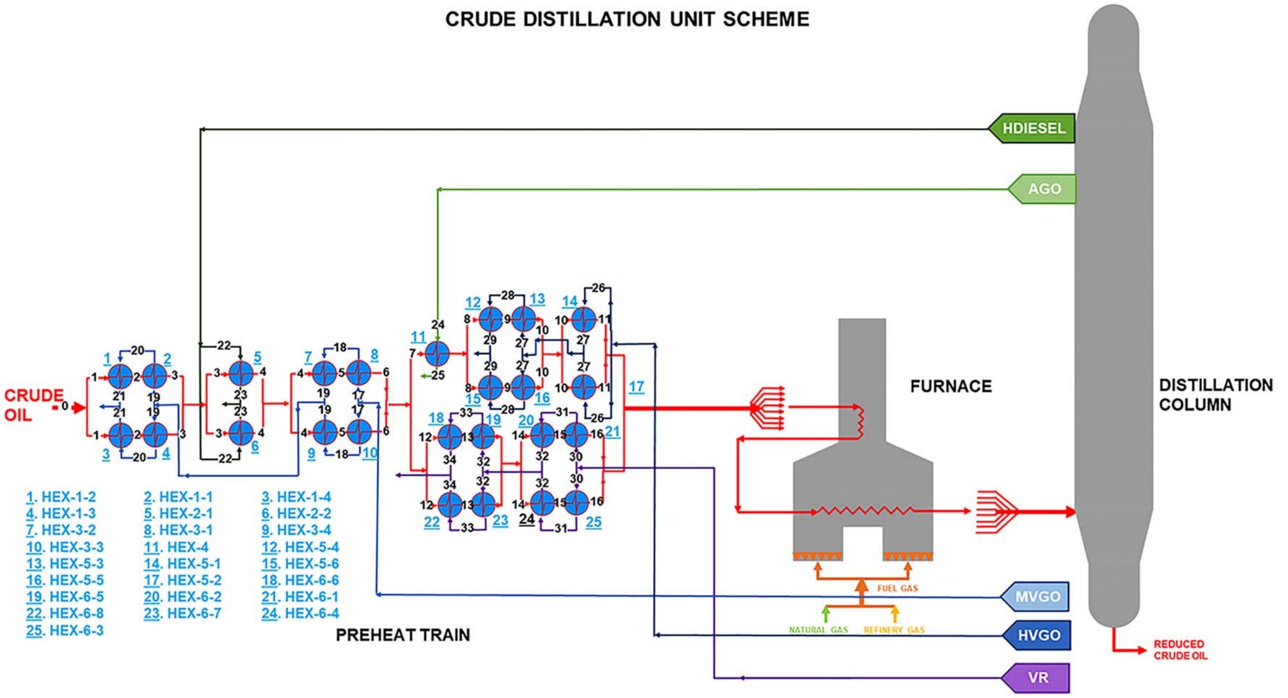


Fig. 1 Scheme of preheat train of the crude distillation unit [12]

The avoidable destroyed exergy ($\dot{E}_{D,k}^{AV}$) is that in which the improvement works will have effective results. In exchangers, the reduction in performance associated with avoidable malfunctions is related to a phenomenon known as fouling. This process consists of the accumulation of unwanted materials such as suspended solids, insoluble salts, and even algae on the internal surfaces of the heat exchanger, inducing resistance to heat transfer [15,16].

In addition, the origin of the reduction in the performance of component k can be caused by inefficiencies of the machine itself, grouped in the destruction of endogenous exergy ($\dot{E}_{D,k}^{EN}$), or by inefficiencies present in other elements whose effect manifests itself in component k; then, the destruction of exogenous exergy ($\dot{E}_{D,k}^{EX}$) in element k is caused by the remaining components [17].

The combination of these concepts leads to a deeper understanding of the system:

- The unavoidable-endogenous exergy destruction ($\dot{E}_{D,k}^{UN,EN}$) is the part of the wasted exergy that cannot be reduced due to the limitations of the k component.
- The unavoidable-exogenous exergy destruction ($\dot{E}_{D,k}^{UN,EX}$) is the section of the destroyed exergy that cannot be decreased due to limitations in the other elements of the system.
- The avoidable-endogenous exergy destruction ($\dot{E}_{D,k}^{AV,EN}$) can be reduced by improving the performance of component k.
- The avoidable-exogenous exergy destruction ($\dot{E}_{D,k}^{AV,EX}$) can be reduced by improving the efficiency of the other system components.

In heat exchangers, the performance associated with fouling can be reduced or eliminated through maintenance activities depending on the type of activity to be carried out and the specific condition of the equipment [12,18]. Therefore, it is essential to establish an optimal maintenance strategy that leads to significant improvements in network efficiency.

2.2 Key Heat Exchangers and Regions. According to several studies [19–21], among others, there are heat exchangers whose

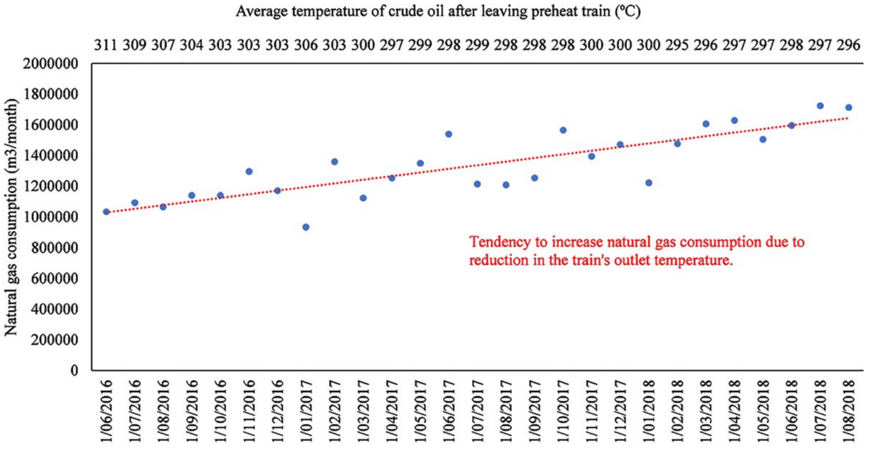


Fig. 2 Correlation between train outlet temperature, natural gas consumption, and time elapsed

individual performance has a much more significant impact on the global efficiency of the heat exchanger network. These components are known as Key Heat Exchangers (KHEX) and are generally characterized by presenting the highest improvement opportunity rates. Therefore, they are components in which it is feasible to prioritize optimization activities to improve the network's performance.

In this research, to define if a heat exchanger is categorized as a KHEX, the avoidable exergy destruction is used as a selection parameter, together with a rule to limit the number of heat exchangers chosen to 20% of the entire network. Also, components whose irreversibility has adverse effects on KHEs will not be considered worthy of being categorized as critical; they will be designated as a source of inefficiency of the KHEX under consideration.

The term regions or areas is a maintenance strategy whose operation consists of grouping those heat exchangers that are not a KHEX. A region includes similar components in compliance with maintenance indicators and spatial location, like shown in Fig. 3, the latter being the most important criterion when assigning the corresponding region. The number of regions to create is limited to a maximum of five heat exchanger groups due to the business rules established by the company.

The main advantage of using regions is the possibility of carrying out a routine of group cleaning activities to save on economic expenses related to logistics and services and reduce the number of lost profits.

2.3 Maintenance Indicators. In maintenance, the indicators are numbers that let to the quantification of the behavior of a system and help in making decisions about the preventive or corrective actions to be carried out on that system. These indicators allow evaluating the progression over time of asset management and defining the best path for the continuous improvement of the maintenance department.

Maintenance indicators vary according to the company's objectives, strategies, and action plans. However, these indicators are based on efficiency, cost-benefit, safety, regulatory compliance, asset performance, and downtime. When companies define maintenance indicators consistent with their situation and need, they can increase production, reduce costs, improve safety, and increase overall efficiency.

In general, the maintenance criteria established in an industrial plant can come from several maintenance strategies. Therefore, the maintenance department must know how to use the tools provided by each method and identify the weaknesses and strengths to establish the most suitable maintenance plan possible.

The MCEE is closely related to Reliability Centered Maintenance (RCM). The RCM is based on ensuring optimal equipment operation and identifying all possible causes of a system failure using cause-and-effect relationships. After identifying all the possible causes, the best maintenance strategy to eliminate the faults can be determined [22]. The MCEE and the RCM base their maintenance tasks on proactive tasks, as they seek to determine the root cause of equipment failures and correct them as early as possible once the intervention is justified.

In addition, maintenance centered on energy efficiency can complement other maintenance methodologies, such as Risk-Based Inspection (RBI). This procedure determines and evaluates the risks that may compromise the integrity of the equipment or infrastructure. In the RBI, the risks are categorized according to their severity; based on this strategy, action plans are established to discuss the integrity of the assets [23]. Nevertheless, the RBI does not consider the efficiency of the elements within its field of action, which is why the MCEE can be included in the maintenance plans.

Since the above, the MCEE maintenance indicators should not be seen as unique and definitive decision criteria for equipment maintenance, but rather as complementary strategies that seek to improve performance through the use of energy from the field of maintenance management.

2.3.1 Indicator W. Considering that it is not possible to recover all the valuable energy that equipment wastes and that, in addition, this percentage varies in each asset [24]. It is convenient to establish a metric that identifies components with the most significant potential for improvement concerning all system elements. In this work, it is proposed to establish a direct relationship between the technical feasibility of a maintenance intervention of component *k* and the

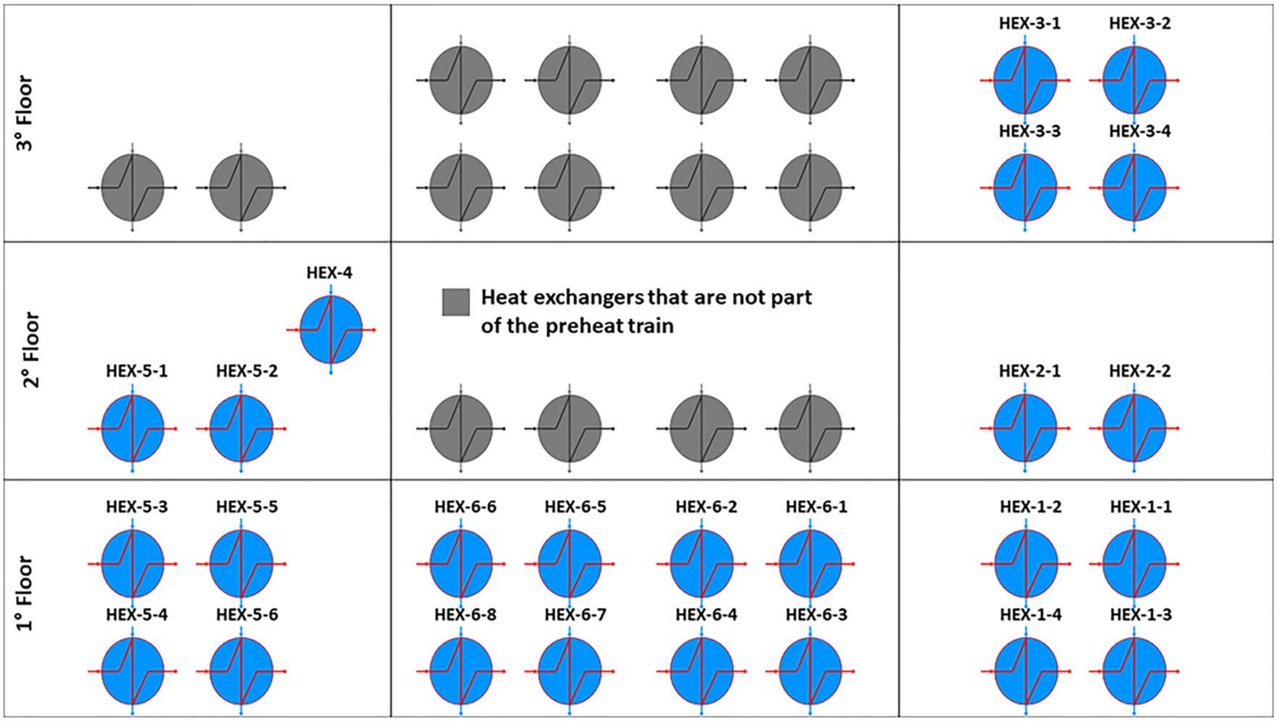


Fig. 3 Location of heat exchangers at the unit

avoidable-endogenous exergy destruction caused by this component.

Using the parameter W in Eq. (1), it is possible to contrast the endogenous avoidable exergy destruction of heat exchanger k against the total average endogenous avoidable exergy destruction.

This indicator helps to identify in which heat exchangers the cleaning activities would cause a more significant impact on the efficiency of the network and to evaluate the technical viability of the cleaning, given that the maintenance activities will not have the expected effect if the heat exchanger is applied to malfunctions of an unavoidable nature or caused by malfunctions of other heat exchangers in the network

$$W=\frac{\dot{E}_{D,k}^{AV,EN}}{\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}} \tag{1}$$

where n represents the total number of heat exchangers.

For the W parameter, the degree of criticality is classified as Low (L), Medium (M), or High (H) from Eqs. (2)–(4):

Low (L) for heat exchangers with the lowest values

$$\left(W<\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}-\sigma_W\right) \tag{2}$$

Medium (M) for Heat exchangers with average values

$$\left(\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}-\sigma_W\leq W\leq\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}+\sigma_W\right) \tag{3}$$

High (H) for Heat exchangers with the highest values

$$\left(W>\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}+\sigma_W\right) \tag{4}$$

σ_W represents the standard deviation of the endogenous avoidable exergy destructions of all heat exchangers and is determined by Eq. (5)

$$\sigma_W=\sqrt[2]{\frac{\sum_1^n\left[\dot{E}_{D,k}^{AV,EN}-\frac{\sum_1^n \dot{E}_{D,k}^{AV,EN}}{n}\right]^2}{n}} \tag{5}$$

2.3.2 Indicator J^*. Due to the fact that one of the most important aspects for companies is the economic feasibility of all the decisions that are made, the maintenance interventions proposed under the method of the MCEE must have a solid justification regarding the economic convenience of the activity. Most of the monetary justifications usually make a comparison between the current cost of operation under the current performance of the equipment and maintenance [7,8].

The KPI "J" proposed by Yabrudy in Ref. [12] and expressed in Eq. (6) makes a contrast between the increase in the cost of production due to a decrease in the rate of heat transfer (measured from the rate of design) against the cost of carrying out maintenance and the associated lost profits (if any).

However, the measures proposed in Eq. (6) arise through an instantaneous balance, which means that it does not consider the history of associated losses since the exchanger begins to decline in its performance. In addition, when performed through energy analysis, it is assumed that all the available energy can be used, ignoring the various limitations that can reduce the functionality of the heat exchanger [25,26]

$$J=\frac{(\dot{Q}_{ref}-\dot{Q})C_e}{\sum C_{mtto}+lp} \tag{6}$$

It is essential to mention that although "J" considers it the optimal efficiency based on the design data, this efficiency may not be achieved (even if maintenance is done) if significant changes are made in operating parameters such as environmental conditions.

The exergoeconomic maintenance indicator J^* (Eq. (7)) arises from modifications made to parameter "J," focused on solving the observations expressed previously. In J^*, all the energy variables are transformed into exergy variables to take advantage of the second law studies explained in Sec. 2.1.

J^* allows determining the economic feasibility of the intervention. This maintenance indicator involves the accumulated financial losses related to the exergetic cost generated in the atmospheric furnace (fuel consumption) caused by a reduction in the efficiency of the exchanger k against the expense incurred in carrying out a specific type of maintenance to recover the optimal efficiency, given the present constraints

$$J^*=\frac{C_c\int_0^t(\dot{E}_{\dot{Q}_{ref}}-\dot{E}_{\dot{Q}})dt}{\sum P_{mtto}+Lp} \tag{7}$$

where C_c is the exergetic cost of the fuel used in the furnace, $\sum P_{mtto}$ is the sum of all costs associated with maintenance, and Lp is the loss caused by lost profits, listed in Table 1. C_c (Eq. (8)) is intrinsically associated with the chemical exergy of the fuel, the higher heating value (HHV), and the purchase price of the fuel (P_c), whose value is $2.606*10^{-6}\ \frac{USD}{kJ}$ for natural gas, according to The Wall Street Journal [27].

$$C_c=P_c\frac{\mathrm{HHV}_c}{e_c^{ch}} \tag{8}$$

According to Ahmadi and Dincer [2], the chemical exergy of gaseous fuels is the higher heating value multiplied by a factor

Table 1 Distribution of maintenance: categories, scope, costs, and lost profits

Tipo	Category	Work	Time (days)	Maintenance costs			Loss profits	
				Manpower $\left(\frac{USD}{m^2}\right)$	Spare parts (USD)	Logistics & Services (USD)	Total $\left(\frac{USD}{day}\right)$	Partial $\left(\frac{USD}{day}\right)$
J_A^*	Major Maintenance Off site	Complete disassembly of the exchanger, mechanical cleaning and replacement of deteriorated parts.	15–25	84.24	$0.1\mathrm{PEC}_k$	Depending on the location of the interchange and the place of execution of each activity	It is subject to the situation	500
J_B^*	Intermediate Maintenance On Site	Easy mechanical cleaning	1	39.39	–	According to heat exchanger location	–	–
J_C^*	Minor Maintenance Online	Chemical cleaning	0.5	16.05	–	According to heat exchanger location	–	–

that varies according to the type of fuel; for natural gas, it is determined by Eq. (9)

$$e_c^{ch} = 0.985\mathrm{HHV_c} \tag{9}$$

For the preheating train under investigation, there are three types of indicators J^*: J_A^*, J_B^*, and J_C^* whose difference lies in the kind of activity to be carried out, and therefore, in the total amount of costs, the details of the types of maintenance are summarized in Table 1.

It is important to define the threshold for the exergoeconomic maintenance indicator J^*; according to the exchanger to be evaluated, the type of maintenance to be performed, the economic losses incurred, and the expense incurred during maintenance.

Once the predefined value is reached or exceeded, it is considered acceptable to carry out routine maintenance (from the economic point of view) to define the threshold of each J^*; according to the exchanger and other conditions, the behavior of endogenous avoidable exergy destruction will be used in conjunction with business management policies, to ensure that the maintenance tasks are in accordance with the objectives and company policies.

For the J^* indicator, the degree of criticality is classified as Low (L), Medium (M), or High (H) from Eqs. (10)–(12):

Low (L) for heat exchangers with zero compliance (totally clean)

$$\left(\frac{J^*}{Threshold} = 0\right) \tag{10}$$

Medium (M) for heat exchangers with average values

$$\left(0 < \frac{J^*}{Threshold} = 0{,}5\right) \tag{11}$$

High (H) for heat exchangers that meet or exceed the threshold

$$\left(\frac{J^*}{Threshold} \geq 1\right) \tag{12}$$

2.3.3 Indicator X. In addition to technical and economic feasibility, it is also essential to determine which exchanger can benefit the remaining elements the most after performing routine maintenance.

It is possible to use the information obtained from the avoidable-exogenous mexogen analysis to determine the heat exchangers whose irreversibilities cause more avoidable exergy destruction to the other exchangers within the network [13]. This formulation quantifies the effects of particular maintenance from the point of view of each component of the heat exchanger network.

The indicator X, formulated in Eq. (13), represents the ratio between the sum of all avoidable effects caused by element k to each remaining component (element r) and the total avoidable induced impacts by all heat exchangers

$$X = \frac{\sum_{r=1\ r\neq i}^{i-1} \dot{E}_{D,i}^{AV,EX,r+}}{\dot{E}_{D,total}^{AV,EX,+}} \tag{13}$$

Therefore, indicator X identifies which heat exchanger can benefit the remaining exchangers to a greater extent after performing routine maintenance on the equipment.

It is essential to mention that the sum is only allowed for positive values of exogenous exergy destruction since negative values imply deteriorating the condition of one team to benefit another [24]. Therefore, the inevitable-exogenous rates of a negative nature are discarded for the calculations related to the X indicator. This reason is based on the fact that said the strategy would also affect the predecessor equipment of the component to which irreversibilities are added. Consequently, it would cause an increase in the destruction of exogenous exergy of the exchangers in which have incidence.

The main difference between the maintenance indicators W and X is that the first determines the convenience of carrying out maintenance from the point of view of the equipment to be intervened (element k). In contrast, the second evaluates the relevance of said maintenance activity from the perspective of the remaining components.

For the X parameter, the degree of criticality is classified as Low (L), Medium (M), or High (H) from Eqs. (14)–(16):

Low (L) for heat exchangers with the lowest values

$$\left(X < \frac{\sum_1^n X}{n} - \sigma_X\right) \tag{14}$$

Medium (M) for heat exchangers with values close to the average

$$\left(\frac{\sum_1^n X}{n} - \sigma_X \leq X \leq \frac{\sum_1^n X}{n} + \sigma_X\right) \tag{15}$$

High (H) for heat exchangers with the highest values

$$\left(X > \frac{\sum_1^n X}{n} + \sigma_X\right) \tag{16}$$

where σ_X represents the standard deviation of the X values of all heat exchangers and is determined with Eq. (17)

$$\sigma_X = \sqrt[2]{\frac{\sum_1^n \left[X - \frac{\sum_1^n X}{n}\right]^2}{n}} \tag{17}$$

For practical purposes, it is necessary to establish a simple method that allows the maintenance department to determine the equipment and the cleaning to be carried out according to the information collected from the maintenance indicators. Given the above, in this work, a criticality diagram and a criticality matrix are proposed to facilitate substantially analyzing the data obtained.

2.4 Criticality Diagram and Criticality Matrix. Criticality is essential in maintenance to direct the maintenance plan. Identifying the most critical assets allows for establishing priorities when focusing the resources and efforts necessary to carry out maintenance activities and, on the other hand, helps to quantify the severity of the consequences caused by equipment failure.

A critical analysis is an easy-to-use and understood technique in which relative ranges are arranged to represent a condition and its associated consequences. In these cases, the aim is to minimize the frequency of failures and the related effects at a particular level and a general level through considerations of aspects such as associated costs, safety, environment, operability, and maintainability.

The degree of priority will determine, in turn, the intensity and frequency with which we should provide maintenance to an asset.

Through the values obtained in the indicators W, J^*, and X, it is possible to build a criticality diagram to quickly inspect each exchanger's performance and its effects within the network.

The information reflected in the diagram can be expanded if a criticality matrix is used, allowing the field of vision to be developed without losing simplicity when summarizing the data.

Through this strategy, intervention priority ranges are established apart from the criteria of the HKEX. Consequently, this method allows evaluation of the individual and group behavior (regions) of the exchangers.

Furthermore, due to the cleaning frequencies, for some short periods, the KHEX will not have a significant effect within the network because their performance has been restored with some maintenance activity, but this equipment will regain its importance as it increases (again) the formation of fouling within the equipment.

Then, the criticality diagram and matrix can become a helpful tool when establishing intervention priorities when there is no clear vision of the KHEX or their impact within the network is relatively like other equipment.

Figure 4 and Table 2 outline the operation of each of the maintenance scheduling tools. Its sections include elements and results by way of explanation. These do not strictly comply with the number of heat exchangers or the analysis results.

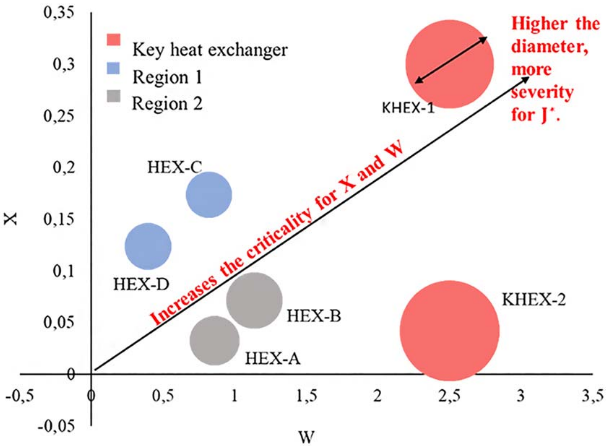


Fig. 4 Criticality diagram

Table 2 Criticality matrix designed

Exchanger	W	J_A^*	J_B^*	J_C^*	X
HEX-A	L	M	M	M	H
HEX-B	M	L	L	L	H
HEX-C	H	H	H	H	H
HEX-D	L	M	M	M	H
HEX-E	H	H	H	H	L
HEX-F	H	M	M	M	L
HEX-G	L	L	L	L	L
HEX-H	L	L	L	L	L
HEX-I	L	L	L	L	H

Figure 4 illustrates the criticality diagram prepared to represent the information. The values of indicator X are listed on the ordinate axis, while W occupies the abscissa axis. <> Each circle represents a heat exchanger whose location is determined from the results obtained in indicators W and X.

The size of the circle in Fig. 4 is directly related to the percentage of compliance (current value over threshold) of the type of J^* that is being evaluated, while the color of the circle is related to its condition (KHEX) or to the region to which it belongs. Therefore, intervention priority is determined by looking for the most prominent circles furthest to the right and up.

For the case of the criticality matrix in Table 2, the values obtained in each indicator are listed for each heat exchanger, including the results of all types of J^*.

Unlike the criticality diagram, the matrix allows the feasibility of all types of maintenance to be jointly evaluated. This option translates into an advantage when considering advancing some type of maintenance due to a special condition such as a plant shutdown (allowing the avoidance of loss of profit).

In the criticality matrix case, the intervention priority is established by looking for the heat exchangers with the most significant number of parameters with high criticality.

3 Results and Discussion

3.1 Key Heat Exchangers and Regions. It is possible to group each component of the heat exchanger network into subsets [20]. As explained previously, this will facilitate the management of the maintenance program and reduce logistics requirements and the demand for specialized services.

The first subset comprises the KHEX, whose members have been previously defined: HEX-2-1/2, HEX-4, and HEX-5-1/2, as well as everything related to them. The exergy destruction calculations involved.

Table 3 Subassemblies: key heat exchangers and regions

Key heat exchanger	Region 1	Region 3	Region 5	Region 6
HEX-2-1/2	HEX-1-1/3	HEX-3-1/3	HEX-5-3/5	HEX-6-1/3
HEX-4	HEX-1-2/4	HEX-3-2/4	HEX-5-4/6	HEX-6-2/4
HEX-5-1/2	↓	↓	–	HEX-6-5/7
			–	HEX-6-6/8
Impact	HEX-2-1/2	HEX-4	–	–

The criteria to establish the regions are very varied and depend exclusively on the objective set. Therefore, the regions can be modified according to convenience. For this research, the formation of the regions is focused on grouping the teams that impact the KHEX, followed by spatial proximity.

- Region 1 includes HEX-1-1/3 and HEX-1-2/4; Region 1 elements are responsible for 60% of the exogenous exergy destruction of HEX-2-1/2, 40. The remaining percentage is distributed among the network interactions. Therefore, no more exchangers are included in this region.
- Region 3 contains HEX-3-1/3 and HEX-3-2/4. These teams contribute 66% to the exogenous destruction of HEX-4.
- Region 5 groups HEX-5-3/5 and HEX-5-4/6 are grouped by proximity. The HEX-5-4/6 stands out for its possible optimization potential in terms of investment costs.
- Region 6 groups the HEX-6-1/3, HEX-6-2/4, HEX-6-5/7, and HEX-6-6/8. They are selected due to their proximity. They do not present significant relevance according to the current analysis.

Table 3 summarizes the established subsets and their members for the HEN.

3.2 Indicators *W* y *X*. The HEX-5-1/2, Fig. 5, stands out for having the highest values of W, with an average magnitude of 1.58. Therefore, they are the equipment whose individual cleaning will contribute the most to improving the operating performance of the preheating train.

The mean values of W for HEX-2-1/2 and HEX-4 are 0.54 and 0.35, respectively. These low amounts, compared to HEX-5-1/2, are due to the external effects suffered by HEX-2-1/2 and HEX-4. Therefore, it is very convenient to link the cleaning activities in HEX-2-1/2 with those of Region 1 (waverage = 1.10) and for HEX-4 with Region 3 (waverage = 1.28).

The results of the parameter X (Fig. 6) place the HEX-2-1/2 heat exchanger as the equipment with the highest incidence on the rest of the remaining elements. For this element, the average value of X is around 0.24. Consequently, HEX-2-1/2 is responsible for more than 24% of the negative interactions in the heat exchanger network.

In second place is Region 1, whose elements have a mean of 0.16—followed by Region 3 with an average value of 0.09. In fourth place, is the HEX-4 with an average X of 0.07. Regions 5 and 6 do not present significant differences since their value is around 0.04.

The incidence relationships in the heat exchanger network are fully explained in Ref. [13]. In particular, X is always equal to zero for HEX 5-1/2 and HEX 6-1/3. This means that cleaning the heat exchangers does not benefit other equipment because these elements are at the end of the preheating train.

3.3 J^* Indicator Thresholds. Figure 7 illustrates the data obtained for HEX-4, where it is observed that there is no significant increase in avoidable-endogenous exergy destruction for the optimal moments proposed by Yabrudy [12].

Occasionally from J_c to J_B there is an increase of zero kW. It is not possible to quantify the growth in J_B to J_A because the J_A criterion fails to be met in the model proposed by Yabrudy et al. [12].

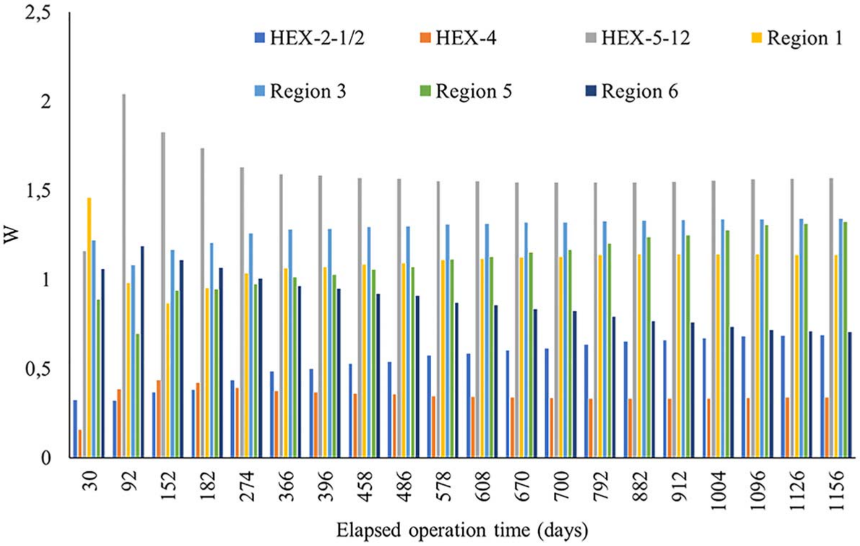


Fig. 5 Behavior of *W* indicator according to the elapsed time of operation

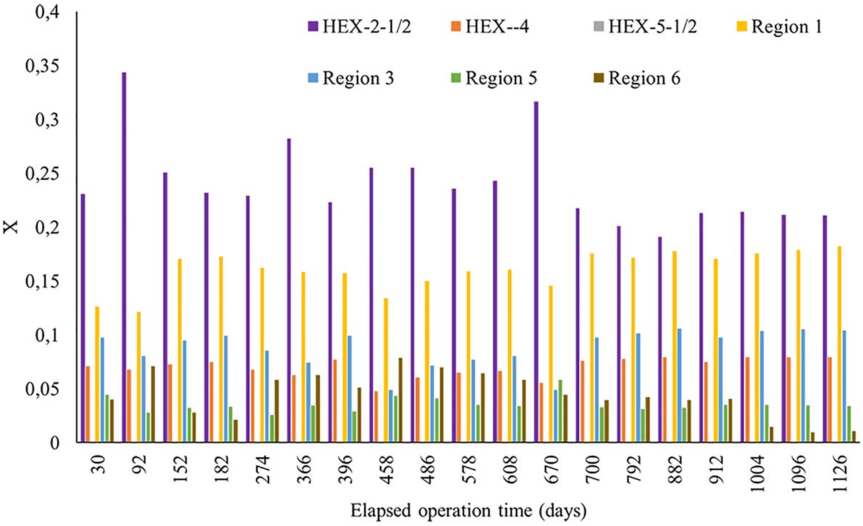


Fig. 6 Behavior of *X* indicator according to the elapsed time of operation

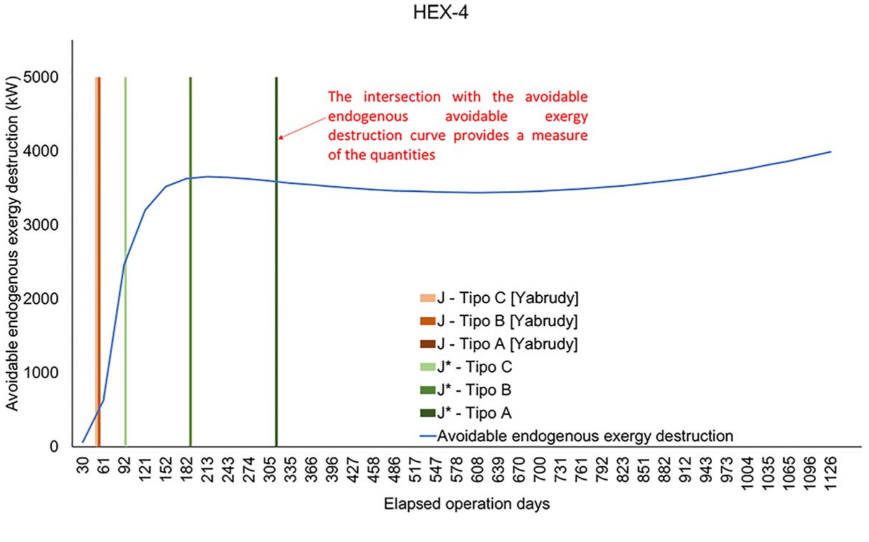


Fig. 7 Behavior of avoidable-endogenous exergy destruction and assigned values of indicators *J* and *J**—**HEX-4**

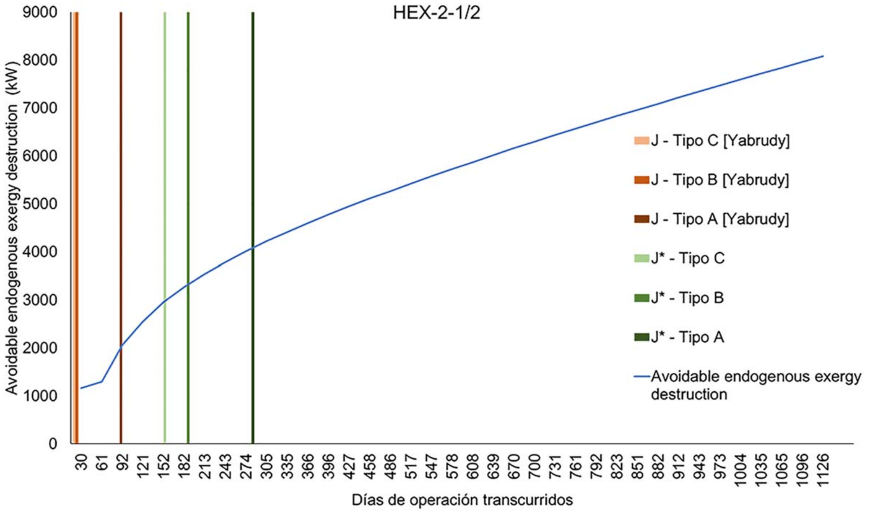


Fig. 8 Behavior of avoidable-endogenous exergy destruction and assigned values of indicators *J* and *J—HEX-2-1/2**

Taking into account the above, the threshold values of J^* for HEX-4 are designated based on the premise that the longer the interval between maintenance activities, the more difficult it will be to eradicate fouling due to the coking process [18].

Figure 8 shows that for HEX-2-1/2 there are significant differences in avoidable-endogenous exergy destruction according to the J values. However, when compared with the slope presented by the plot of $\dot{E}_{D,k}^{AV,EN}$, it is possible to increase the minimum feasibility values to maximize profit. Specifically, the avoidable-endogenous exergy destruction that increases between J_C^* and J_A^* is 1057.75 kW.

Following the strategies used in HEX-2-1/2 and HEX-4, threshold values of J^* are assigned to each heat exchanger (Table 4).

3.4 Planning of Maintenance Activities. Listed below are a series of considerations when scheduling cleaning tasks:

- The planning of maintenance activities only applies to heat exchangers that meet the above criteria. Unless another maintenance strategy indicates otherwise, the maintenance planner must decide based on his experience and knowledge of this type of situation.
- The duration of the cleaning work should not exceed 30 calendar days.
- Maintenance activities are planned in such a way as to eliminate all avoidable inefficiencies in the equipment of interest.
- Efforts should be made to maintain simultaneously cover all the equipment affected by the cleaning routines.
- If several types of maintenance are justified, the most robust maintenance will be chosen unless a restriction does not allow it.
- When major maintenance is justified, J_A^* will be approved for scheduling and execution when, if, and only if considered by management based on business considerations (reliability, production, and quality, among others).
- In the event of loss of profit, the time required for economic recovery must be granted before starting maintenance activities.
- It is designated as point zero (start of operation) on 06/01/2022. As of this date, projections will be made to establish the planning of activities for the year 2023.

Table 4 Maintenance thresholds

	Threshold		
Assets	J_A^*	J_B^*	J_C^*
HEX-1-1/3	7	10	19
HEX-1-2/4	6	8	13
HEX-2-1/2	5	7	8
HEX-3-1/3	3	5	11
HEX-3-2/4	2	3	5
HEX-4	3	5	9
HEX-5-1/2	2	5	10
HEX-5-3/5	3	5	8
HEX-5-4/6	6	5	3
HEX-6-1/3	10	14	16
HEX-6-2/4	3	5	8
HEX-6-5/7	4	5	7
HEX-6-6/8	3	5	7

Based on the results of the criticality diagram (Fig. 9), it is decided to prioritize the HEX-2-1/2 for the first quarter of 2023, considering compliance with the J_B^* indicator and its impact on the rest of the network elements. For better results, cleaning activities must be carried out parallel to the HEX-1-1/3 and HEX-1-2/4 heat exchangers.

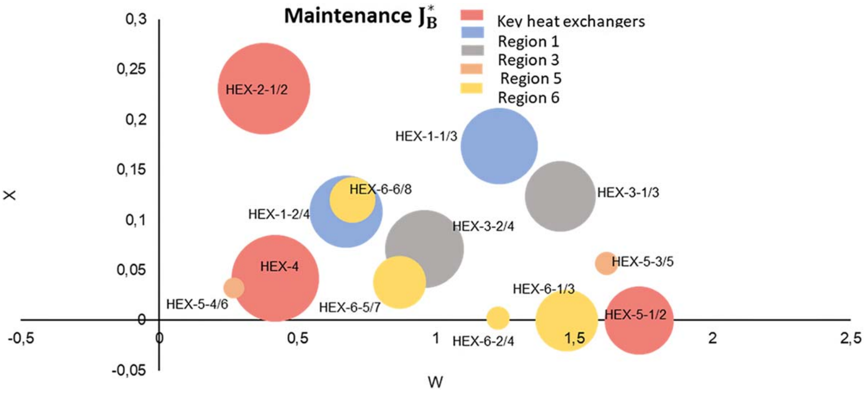
For the second quarter, maintenance activities will be focused on the HEX-4 and HEX-5-1/2, due to their economic justification and their high technical feasibility, respectively. It was decided to work on HEX-3-1/3 and HEX-3-2/4 before cleaning activities on HEX-4 to eliminate adverse external effects on this exchanger.

Before evaluating the maintenance indicators for the third quarter of 2023, it is decided to start the third quarter with a chemical wash for the KHEX, whose last maintenance exceeds 60 days (HEX-1-1/2 and HEX-4) given that KHEX are components with rapid compliance with maintenance parameters.

Taking into account the results obtained for the second half of the third quarter (Table 5) it is decided to include chemical washes in Regions 1 and 3 because the exchangers of these zones become key pieces for the network performance when the KHEX are they find clean.

For the same quarter, intermediate maintenance routines are established for the exchangers of Region 6 since they occupy the second place in terms of justification of the maintenance indicators. Finally, for the fourth quarter, HEX-5-3/5 and HEX-5-4/6 will be cleaned.

The schedule presented in Table 6 shows the maintenance activities to be carried out according to the month of the year and the heat exchanger. In total, 34 maintenance activities will be carried out, distributed among the 25 heat exchangers in the network. The



Criticality diagram for the first quarter of year 2023

Table 5 Criticality matrix for the third quarter of the year 2023

Assets	W		J_A^*		J_B^*		J_C^*		X	
HEX-1-1/3	0.827	M	9.07	H	22.70	H	59.33	H	0.248	H
HEX-1-2/4	0.698	M	6.90	H	17.27	H	45.12	H	0.137	H
HEX-2-1/2	0.000	L	0.05	M	0.12	M	0.32	L	0.000	L
HEX-3-1/3	0.717	M	6.63	H	16.60	H	43.38	H	0.185	
HEX-3-2/4	0.559	L	5.37	H	13.45	H	35.15	H	0.110	M
HEX-4	0.000	L	0.00	L	0.00	L	0.00	L	0.000	L
HEX-5-1/2	0.000	L	0.00	L	0.00	L	0.00	L	0.000	L
HEX-5-3/5	1.936	H	11.18	H	28.00	H	73.17	H	0.047	L
HEX-5-4/6	0.642	M	8.44	H	21.13	H	55.23	H	0.030	L
HEX-6-1/3	1.692	H	25.68	H	64.29	H	168.02	H	0.000	L
HEX-6-2/4	1.157	H	10.27	H	25.72	H	67.20	H	0.002	L
HEX-6-5/7	0.982	M	9.42	H	23.59	H	61.65	H	0.038	L
HEX-6-6/8	0.791	M	7.14	H	17.87	H	46.69	H	0.204	H

Note: Low, L; Medium, M; High: H.

Table 6 Maintenance planning for the preheating train for year 2023

Maintenance schedule for the preheat train												
	I Trimester			II Trimester			III Trimester			IV Trimester		
ASSETS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HEX-1-1	B							C				
HEX-1-2	B							C				
HEX-1-3		B						C				
HEX-1-4		B						C				
HEX-2-1	B						C					
HEX-2-2		B					C					
HEX-3-1				B					C			
HEX-3-2				B					C			
HEX-3-3				B					C			
HEX-3-4				B					C			
HEX-4					B		C					
HEX-5-1						B						
HEX-5-2						B						
HEX-5-3												
HEX-5-4											B	
HEX-5-5											B	
HEX-5-6												
HEX-6-1								B				
HEX-6-2								B				
HEX-6-3								B				
HEX-6-4								B				
HEX-6-5									B			
HEX-6-6									B			
HEX-6-7									B			
HEX-6-8									B			

letters included in each cell are directly related to the type of maintenance to be performed, then:

The programming of maintenance activities for the year 2023 does not include major activities (J_A^*) due to the company's reliability policies and production projections for 2023.

Maintenance preserves the continuity of flow in the system. A type J_A^* maintenance involves removing the equipment from the network for an average time of 20 days (while maintenance is being carried out). During this period, the crude oil and the hot fluid circulate entirely within the exchanger parallel to the equipment in operation. So, if there is a fault in the parallel exchanger, the production process could be stopped, generating economic losses for the company. This implication indicates that the decision to carry out major activities does not depend exclusively on the point of view of the MCEE. Management agreements of the company must support it.

Generally, it can be established that after one year of uninterrupted operation, all heat exchangers in the network justify class A maintenance from the point of view of the MCEE.

4 Conclusion

This research takes as a case study a preheating train of a crude oil distillation unit, where maintenance indicators are created or modified for the heat exchanger network cost-efficiency. The results obtained in this case study indicate the following:

- The introduction of the maintenance indicators W and X constitutes a substantial contribution to maintenance management, allowing the use of the information from the different analyses to evaluate the technical feasibility and the benefits to external components before a maintenance activity. The HEX-5-1/2 exchanger is the equipment with the highest technical justification, while the HEX-2-1/2 generates the highest traces of adverse effects on the rest of the network elements.
- The modification made to the exergoeconomic maintenance indicator J^* translates into a better relationship between the economic and the process variables (translated into the exergetic field). Consequently, it is possible to improve the economic evaluation of the exchangers. Regarding the preheating train under study, the HEX-2-1/2 and the HEX-4 are the fastest equipment that exceeds the threshold values for each type of maintenance type.
- Given its general concept, W, J^*, and X can be applied to any system, regardless of the operating characteristics, the types of maintenance, or the associated costs. However, the reference values must be adjusted, taking into account the particular configuration of the system, the incidence of the assets, the variation in prices (operation and maintenance, among others), and the objectives set by the company.
- The use of the values obtained in the W, J^*, and X indicators to build the criticality diagrams and the criticality matrix constitutes an essential tool for maintenance planning because it allows prioritizing the heat exchangers and the cleaning based on exergetic and exergoeconomic criteria.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

e = specific exergy $\left(\frac{\mathrm{kJ}}{\mathrm{kg}}\right)$
t = time (days)
J = indicator J (−)
W = indicator W (−)
X = indicator X (−)
$\dot{E}$ = exergy (kW)
$\dot{Q}$ = heat transfer rate (kW)
C_c = exergetic fuel cost $\left(\frac{\$\mathrm{USD}}{\mathrm{kJ}}\right)$
C_e = energy cost $\left(\frac{\$\mathrm{USD}}{\mathrm{kJ}}\right)$
P_c = fuel purchase price $\left(\frac{\$\mathrm{USD}}{\mathrm{kJ}}\right)$
Lp = lost profit (US$)

Abbreviations

AGO = atmospheric gas oil
HDIESEL = heavy diesel
HEX = heat exchanger
HEN = heat exchanger network
HHV = higher heating value $\left(\frac{\mathrm{kJ}}{\mathrm{kg}}\right)$
HVGO = heavy vacuum gas oil
KHEX = key heat exchangers
KPI = key performance indicator
MCEE = maintenance centered on energy efficiency
MVGO = medium vacuum gas oil
PEC = estimated asset price (US$)
PHT = preheat train
TEMA = Tubular Exchanger Manufacturers Association
VR = vacuum residue

Greek Symbols

ε = exergy efficiency
η = energy efficiency
σ = standard deviation (−)
y = exergy destruction ratio

Subscripts

A = major maintenance
AV = avoidable
B = intermediate maintenance
C = minor maintenance
CH = chemical
D = destruction
EN = endogenous
EX = exogenous
k = k component
n = total number of assets
r = r component (remnant)
Ref = reference
UN = unavoidable
$*$ = modified

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