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Article

Estimation of Shutdown Schedule to Remove Fouling Layers of Heat Exchangers Using Risk-Based Inspection (RBI)

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Abstract: Oil and Gas plants consist of a set of heat exchangers, which are used in recovering the waste heat from product streams to preheat the oil. The heat transfer coefficient of exchangers declines considerably during the operation period due to fouling. Fouling in heat exchangers is a complex phenomenon due to the acceleration of many layers of chemical substances across tubes of heat exchangers resulting from chemical reactions and surface roughness. In this paper, the fouling process was determined as a critical failure in the heat exchanger. Failure is an accelerated fouling layer across the heat exchanger tubes, which can be the reason for the clogging of tubes. Hence, a risk assessment was conducted using the Risk-Based Inspection (RBI) approach to estimate the probability of fouling in heat exchangers. The results showed that the RBI approach can be used successfully to predict the suitable time to shut down the plant and conduct the fouling cleaning process.

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Keywords: fouling process; maintenance; cost of maintenance and RBI approach

1. Introduction

In general, any processing plant consists of a large number of critical and non-critical equipment that run continuously to fulfil the operating requirement. These pieces of equipment undergo periodically or non-periodically planned maintenance on the short or long time during their life cycle, taking a risk factor into account to avoid any defect or failure that may cause disastrous consequences during the normal operation of the plant. Therefore, the critical pieces of equipment cannot be subject to inspection and maintenance activities unless the plant is under an entire shutdown to conduct the maintenance activities. Maintenance is a philosophy resulting from a variation of its implementation from a company to another due to several aspects such as an economic aspect, the geographical conditions, and process configuration. Sahoo [1] indicated that a shutdown philosophy is scheduled maintenance of the plant to minimize downtime to maximize the efficiency of a plant. For instance, many processing companies have used turnaround terminology rather than shutdown terminology to execute maintenance activities of critical equipment. Levitt [2] stated that “a shutdown is a melting pot in accelerated time, which means that people will be operating at or near their limits”.

A planned shutdown is one of the biggest activities of maintenance for any processing plant in terms of manpower, materials, time, and costs. Emiris [3] stated that shutdown is primarily proactive maintenance because all facilities of the plant are out of service to perform inspections, repairs, replacements, and modification periodically, thus rendering this maintenance of paramount importance to avoid any threat that can have a significant effect on the reliability and efficiency of the system. Plant shutdown normally

depends on the maintenance activities related to the critical equipment pieces [4]. Heat exchangers are one of the critical equipment pieces and a vital indicator to estimate the interval and duration of the shutdown.

Many critical failures overlapped on each other in heat exchangers, which require more time to identify them using RBI. Six critical failures in heat exchangers are identified: clogged flow due to fouling layers, leakages, vibration due to misalignment, internal and external corrosion, and cracks of the shell due to exceeding design pressure and allowed temperatures. A fouling layer is considered as the common failure in the heat exchangers that pose the highest risk with comparing to other failures based on the RBI approach. Fouling is the accumulation of undesirable particles on heat transfer surfaces [5] that appear as layers on a heat transfer surface that contribute to the reduction of the conductivity of heat transfer inside of tubes during the lifetime of the heat exchanger.

The fouling process is an unavoidable process and, hence, most of the industrial equipment are overdesigned in terms of the heat transfer area to meet the efficiency requirements. In thermal desalination plants, for example, the heat transfer areas are overdesigned with an allowable 20% to 25% excess, increasing by about 30% of the total cost of the thermal equipment [6]. Moreover, the fouling process may lead to an unexpected shutdown of plants due to fluctuation of pressures and temperatures or equipment vibration.

It is necessary to maintain heat exchangers by inspecting them during regular periods (shutdown maintenance) to remove fouling that helps in accelerating the corrosion rate and hinders the flowing fluid in the interior tubes or on a heat transfer surface [7].

A cleaning of fouling is a dominating activity in the maintenance of heat exchangers to restore the efficiency of equipment and mitigate any threat that may occur during the normal operation of the plant. The cleaning of fouling requires many devices and tools and much people power to contribute to the total removal of fouling and the reducing of risk.

To remove deposits across tubes of heat exchangers, mechanical and chemical techniques (Routine Maintenance) can be applied during normal operation of equipment (Figure 1); however, it is necessary to shut down equipment to execute maintenance activities to avoid increased fouling layers, which may result in unexpected consequences on humans and infrastructure of a plant.

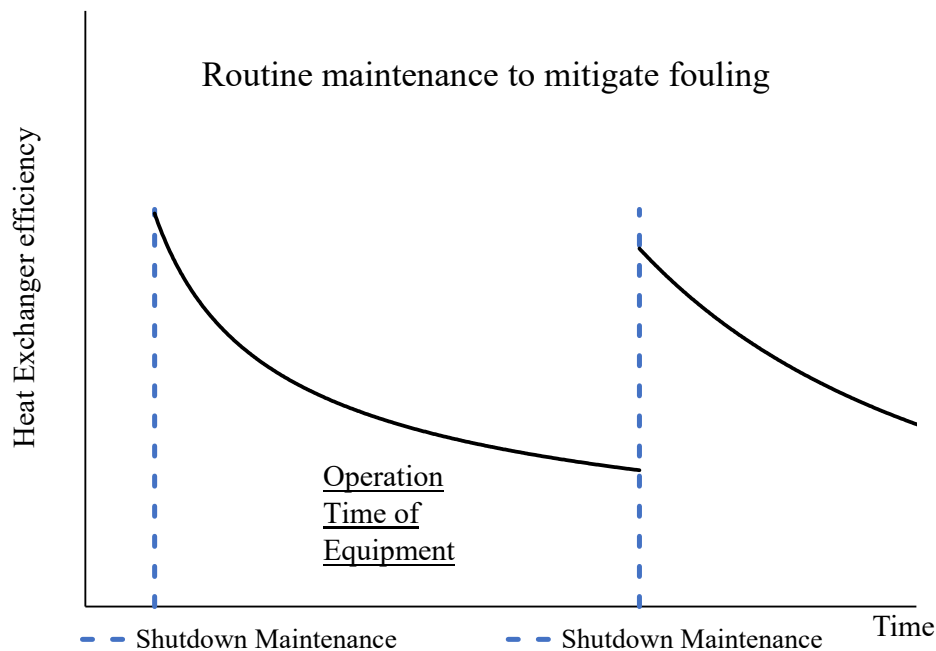


Figure 1. The optimum time for removing tubes' fouling.

However, the cleaning process of heat exchangers or any piece of equipment is very costly due to the shutdown period of the plants and the cost of cleaning materials and labor. The cleaning cost of a single heat exchanger may vary between \$700 and \$1000 [8]. Hence, selecting the optimum time to shut down the plants and choosing the best strategy may result in a significant reduction in cleaning costs.

There are several publications in the literature focused on scheduling problems due to their great impact on the cost of routine maintenance in many industrial processes. Most of the scheduling problems focused on when and how to clean the fouling. While some studies addressed the optimization of the cleaning period, others focused on the number of interval cleaning actions. Minimizing the cleaning cycle period based on the cleaning method or maximizing the operating time before the next shutdown may reduce the total cost of routine maintenance.

Khan and Zubair [9] developed an optimization model based on risk-based performance analysis. Two fouling models, specifically, exponential and a power-law fouling rate, were incorporated into the main model. The cost related to the reduction in the cleaning time was examined by considering cost savings related to a reduction in the effectiveness, pumping power cost, anti-foulant cost, and cleaning cost. Their results showed an increase in the optimum dimensionless cost by around 21 for the power-law fouling model and around 14% for the exponential fouling model. However, the risk level experienced a dramatic decrease, from 0.5 to 0.01. Pogiatzis et al. [10] presented a mixed-integer nonlinear programming (MINLP) model to solve a scheduled cleaning optimization problem. The optimal schedule consists of the time interval at which the cleaning action is taking place and the cleaning mode in each chosen time interval. Ishiyama et al. [11] presented a first-order aging model to identify the optimum cleaning scheduling considering the cleaning methods based on the nature of the fouling layer. Biyanto et al. [12] developed an optimization model to optimize the interval cleaning schedule of heat exchangers' networks within a period of 44 months, using particle swarm optimization. The optimization of cleaning schedule results showed a saving of 23% of maximum potential savings.

Licindo et al. [13] developed an optimization model to predict frequent cleaning action and the time in which the exchanger must be cleaned. To validate the results of the model, four heat exchangers were used in their study and the results showed that the efficiency of the heat exchangers was maintained at nearly 90% of the maximum energy recovery. Elsholkami et al. [14] used operating process data to estimate the fouling rate and then used these data to develop an optimization model to optimize the cleaning cycle period. By using mathematical optimization techniques and real data, a saving of almost \$30,000 was achieved. Di Pretoro et al. [15] optimized the cleaning procedure duration for heat exchangers by minimizing the time average losses under uncertain operating conditions. To achieve their objectives, a fouling kinetic model and two different cleaning techniques, namely, chemical and mechanical techniques were used successfully to assess the optimum cycle period.

In this paper, the Risk-Based Inspection (RBI) approach was used to estimate the probability of fouling in heat exchangers by the mean of risk assessment and, hence, the maximum operating time before shutting down the plant for fouling cleaning was determined. The losses' cost due to the consequence of equipment failure was estimated.

2. Material and Methods

Fouling layers would lead to an increase in temperature and then would increase corrosion and leakage. Acceleration of these layers depends on the chemical properties of the fluid flow and the operating temperature [16]. Many induced effects resulting from the difference in the inlet and outlet temperatures of process streams cause accumulated layers of fouling in heat exchangers [17]. However, the most well-known techniques that can be used to mitigate or remove accumulated fouling across tubes' bundle in heat exchangers are as follow:

- *On-line cleaning method* generally uses the cleaning of tubes when the equipment is online to need no disassembly of exchangers. Examples of this technique are the use of the sponge rubber balls, upstream filtration, chemical additives, antiscalant, inhibitors, soot blowing, Jet cleaning, reversing flow, and passing brushes for cleaning of tubes to continue their operational function and to avoid any mandated downtime that can occur during the normal operation of the plant. There is no assurance of this technique that all the fouling layers could be removed sufficiently.
- *Off-line cleaning method* uses the cleaning when the equipment is off-line of service for its disassembly, to have access to the inside tubes. This method uses chemical solutions, a liquid jet, steam, air-jet, drilling, scrapers of tubes, and blasting to remove all fouling layers to restore equipment to the normal state. This technique includes the extra cost associated with the assembly and disassembly of a heat exchanger.

Figure 2 shows the relationship between expecting fouling resistance and time. It determines the stages of growing fouling during the life cycle of heat exchangers, which explains an increase of fouling linearly with time. The initiation period for cleaning fouling may be negligible due to a relatively small number of fouling layers. During this period, it was found that the fouling layers were slowly accumulated. Therefore, the initiation period may not be needed to perform monitoring, inspections, and maintenance activities to mitigate the fouling layers.

The initiation of fouling layers may be rapid due to the severe operating conditions of exchangers accompanied by a modest rate of deposits, resulting from the chemical reactions. Ignoring this stage is considered a beginning of risk based on the RBI. Therefore, in this stage, it is necessary to start with the mechanical technique to mitigate these layers.

The fouling layers occur in three indicators to mitigate the fouling layers. The fouling profile increases with time but not linearly, and then it decreases gradually and asymptotically to reach a steady state. This process can be achieved by increasing fluid flow velocity and surface temperature. Removal of the fouling is not done without shutdown maintenance actions. Georgiadis and Papageorgiou [18] stated that heat exchangers must

be shut down to carry out their maintenance after the regular time of operation process. Sikos and Klemeš [16] also reported that cleaning of heat exchangers is not done online. Therefore, it is done by removing all fouling layers that prevent the movement of the fluid, cleaning tubes, and replacing corroded tubes to obtain maximum heat transfer [19].

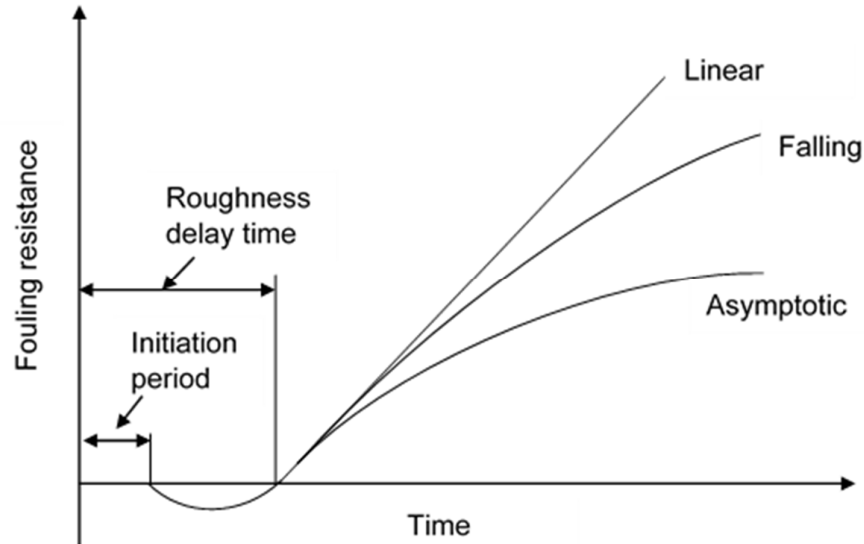


Figure 2. Expected types of fouling curves.

Any activity without applying shutdown maintenance cannot remove all fouling layers, which justifies the widespread adoption of shutdown maintenance in real maintenance of heat exchangers. The response of fouling with time can be linear, falling, accelerating, or saw-tooth. However, linear fouling response is the most common type in this piece of equipment, which constantly occurred due to the temperature of the deposit with the flowing fluid remains.

3. Cost of Removing Fouling

The fouling removing of heat exchangers is considered expensive in terms of time, labor, and materials due to the larger deposit of mass accumulated through the tubes. Therefore, all heat exchangers that represent high risk should be shut down and moved to inspection and maintenance activities to restore the plant to its normal performance level and prolong the expectancy of life of the heat exchangers [18]. On the other hand, the economic effects resulting from the fouling of heat exchangers have become costly in terms of inspection, maintenance, and production loss, particularly in the processing plant, which runs continuously under harsh operational conditions. Equation (1) presents the costs imposed due to the fouling cleaning process [9].

$$TC = (FC + VC) \times MD \quad (1)$$

where TC is the Total cost of the cleaning process per cycle of maintenance duration; FC is the fixed cost that tends to increase due to the production losses resulting from the shutdown units; VC is the variable cost associated with repair, replacement, cleaning fouling; and MD is Maintenance Duration.

4. Risk-Based Inspection Approach (RBI)

Due to severe consequences that may occur, resulting from fouling layers in heat exchanger tubes, Risk-Based Inspection (RBI) is presented. The RBI approach usually serves industries that require high safety to avoid the high risk during operational periods, especially the oil, gas, petrochemical industry due to high pressure, fluctuating

temperatures, and corrosion in piping, vessels, reactors, heat exchangers, and tanks [20]. In TAM (Turn Around Maintenance), the major challenge is to implement the RBI approach to determine and assess pieces of equipment that can be a cause for a rise in risk, with integrating the reliability approach to determine the reliability and failure rate of a plant and reduce the total operating costs and environmental damage. Therefore, most of the processing plants focus on RBI techniques due to the complexity of the processes that require higher availability and reliability [21].

The RBI approach is being applied to determine the high-risk equipment for reducing the risk of consequences in the operational process resulting from fluctuated pressure, temperatures, and corrosion rate. The assessment of the RBI approach is to address risks of critical equipment in terms of safety and environmental and economic aspects to mitigate the expected level of risk. Therefore, the risk matrix is an effective method of representing the probability of fouling (*PoF*) and consequence of failure (*CoF*) categories [22], as given in Equation (2).

$$ER = PoF \times \sum CoF(\$) \quad (2)$$

where *ER* is the estimated risk, *PoF* is the probability of fouling, and *CoF* is the cost due to the consequence of failure (more details of this cost can be found in Equation (4)).

5. Results and Discussions

5.1. Risk Matrix

Table 1 shows the potential impact of the fouling layers in the tubes of heat exchangers on the system in terms of increasing the coefficient of loss of heat transfer and energy consumption of heat exchangers, according to the operation specifications. Table 1 is designed to determine the critical equipment that requires major maintenance due to the accumulation of fouling layers through the tubes of heat exchangers.

Table 1. Effect of fouling thickness on the efficiency of the heat exchanger.

Risk Level	Risk Criteria	Decision
	Insignificant risks	The equipment is in no need for maintenance. Thus, it is necessary to remove it from the current maintenance list.
	Acceptable risks	The equipment requires a mechanical technique to mitigate the accelerated fouling layers. However, it is no need for maintenance activities.
	Expected risks	The equipment needs mechanical techniques to reduce the fouling layers. However, it is no need for maintenance activities.
	Unacceptable risks	The heat exchanger requires a chemical technique to clean the fouling layers. Thus, it is necessary to shut down the unit completely to perform maintenance activities of the heat exchanger.
	Catastrophic risks	Unexpected failure and degradation.

The risk matrix is one of the proposed tools in this study to contribute to the analysis and selection of critical equipment that has the highest risk. Table 1 shows a five-by-five risk matrix that includes two directions. The bottom left corner represents the lowest risk and the top right corner represents the highest risk.

A risk matrix must reflect a company's risk criteria, as it differs significantly from one company to another. A Five-by-five risk matrix is used to determine zones of risk in *PoF/CoF* configuration. The estimated Risk in the Very High zone must be immediately considered due to the high in both *PoF* and *CoF*, resulting from fouling layers across tubes of in heat exchanger. The 5/E means that fouling layers are rated very high. At this level, the plant must be shut down to implement maintenance activity to remove total layers of fouling.

Twenty pieces of heat exchangers are distributed on a risk (5 × 5) matrix based on the *PoF* and *CoF* to identify pieces that pose the highest risk on the production, operating

assets, and environmental issues. Table 2 shows that five pieces of exchangers are rated in the very-low-risk zone, nine pieces of exchangers are located in a low-risk zone, four pieces of exchangers are classified in a moderate risk zone, one piece of equipment is rated in the high zone, and one equipment is rated in the very-high-risk zone. This means that 19 pieces of exchangers rated between low (L) and high risk (H) should be excluded and add one piece located in a very-high-risk zone to be estimated risk (ER).

Table 2. The risk matrix of the likelihood of fouling in heat exchangers.

		CoF (\$)				
		A	B	C	D	E
Estimated Risk (ER)		≤300,000	300,000–600,000	600,000–900,000	900,000–1,200,000	1,200,000–1,500,000
		5	0.8–1	M	H	H
4	0.6–0.8	L = 2	M = 2	M = 1	H = 1	VH = 1
3	0.4–0.6	L = 2	L = 3	M = 1	M	H
2	0.2–0.4	VL = 2	L = 2	L	M	H
1	0.1–0.2	VL = 2	VL	L	L	M
Rating	PoF	Very Low	Low	Medium	High	Very High

5.2. Probability of Fouling (PoF)

This factor is necessary to estimate exposure time and failure frequency for each piece of equipment to determine the probability of the failure associated with corrosion and fluctuating temperatures. Risk assessment of equipment degradation mechanisms should be taken into consideration to avoid their growth rates due to the acceleration of fouling layers and fluctuating temperatures. The assessment of risk should be comprehensive to identify the risk level and mitigate or avoid it [23]. Thodi et al. [24] assessed risk to determine the optimum replacement of components in the offshore plants based on the fouling probability and consequences of failure for pipelines.

The probability of fouling can be ranked through the risk matrix as follows:

1. Very Unlikely
2. Unlikely
3. Possible
4. Probable
5. Highly Probable.

PoF is the difference between removing (R) and measuring effectiveness (M) to the difference between removing (R) and fouling effectiveness (F). This can be expressed as presented in Equation (3).

$$PoF = \frac{R - M}{R - F} \quad (3)$$

For a single heat exchanger, the values of PoF resulting from Equation (3) for a period of 600 days with an interval of 30 days are presented in Table 3. From Table 3, two points to be aware of are the following:

- To execute a shutdown maintenance activity of a heat exchanger, PoF value should be closed to or equal to 1, which indicates high fouling.
- Before a maintenance activity is executed on the heat exchanger, M should be very close to F values.

Table 3. Probability of Fouling in the heat exchanger [25].

Interval Number	Time (Days)	R	M	F	PoF
1	30	0.241	0.215	0.168	0.35
2	60	0.283	0.257	0.218	0.40
3	90	0.355	0.305	0.248	0.46
4	120	0.394	0.332	0.275	0.52
5	150	0.373	0.347	0.329	0.59
6	180	0.397	0.363	0.344	0.64
7	210	0.432	0.409	0.387	0.51
8	240	0.48	0.425	0.403	0.71
9	270	0.512	0.488	0.442	0.34
10	300	0.452	0.433	0.401	0.37
11	330	0.493	0.467	0.442	0.51
12	360	0.535	0.501	0.476	0.57
13	390	0.665	0.633	0.615	0.64
14	420	0.698	0.667	0.645	0.58
15	450	0.717	0.696	0.671	0.45
16	480	0.765	0.716	0.701	0.76
17	510	0.784	0.737	0.725	0.79
18	540	0.829	0.768	0.753	0.80
19	600	0.867	0.815	0.813	0.96

5.3. Consequence of Failure (CoF)

In this stage, the consequence of failure is identified according to the tragic damages caused by failures of equipment. These consequences can be determined in terms of the following:

- ✓ Explosion or fire effects on buildings and plants.
- ✓ The toxic material effects resulting in any equipment failure or degradation can lead to fatalities or injuries due to overpressure and fluctuating temperatures. Therefore, compensation costs will be very high [26].
- ✓ Effect on the production.
- ✓ The threat to the environment.
- ✓ An unplanned shutdown can lead to lost production.

Consequently, the category of a qualitative approach can be ranked through the risk matrix as follows [27].

- (1) The heat exchanger is working. No impact on the production and human factor. The total cost may be less than \$300,000.
- (2) Routine maintenance of heat exchanger with minimum impact of risk on the production and human factor: total cost may be between \$300,000–\$600,000.
- (3) A slowdown of fouling layers in tubes, but the unit is running normally; risk on the production and human factors are starting to increase. The total cost may be between \$600,000 and \$900,000.
- (4) Accelerating in fouling layers. The plant should be shut down to execute maintenance activities to avoid high-risk impacts on the production and human factors. The total cost may be between \$900,000 and \$1.2 million.
- (5) Fouling layers lead to unexpected shutdown of a plant with maximum impact on the production and human factors. Total cost may be between \$1.2 million and \$1.5 million.

The financial and human losses and system and environmental damage should be taken into account to combine *CoF*, which can be determined as presented in Equation (4):

$$CoF = (F_L + H_L) + (S_D + E_D) \quad (4)$$

where CoF is the consequence of failure, F_L is the financial losses, H_L is the human losses, S_D is system damage, and E_D is the environmental damage.

The costs of losses and the damage due to the consequence of failure (CoF) are presented in Table 4.

Table 4. CoF analysis of fouling in heat exchangers [23,27].

15	Time Lost: (Day)
2233	Loss rate (\$/h)
0.25	Damage radii (km)
5	Environmental damage radii (km)
1400	Asset density (\$/m ²)
26	Number of employees close to unit
75,400	Environmental loss (\$/km ²)
20,000	Human health loss (\$/employee)
0.2	Population distribution factor
0.1	Importance factor
803,880	1. System damage
274.75	2. Financial losses
104,000	3. Human losses (Compensation cost due to loss of life or injuries)
591,890	4. Environment damage
1,500,044.75	CoF (1 + 2+3 + 4)

In addition, an acceptable risk (AR) is presented to compare with ER , as expressed in Equation (5)

$$ER \leq AR \quad (5)$$

The AR varies from one company to another based on operational conditions and economic aspects [23]. AR criteria for heat exchangers is assumed to be equal to or less than \$100/h as a maximum [26]. Hence, for $ER \leq \$100/h$, the operational time before shutting down the plant for TAM can be calculated as follows:

$$\text{Operational time} = \frac{PoF \times CoF}{ER} = \frac{0.96 \times \$1,500,000}{100 \text{ \$/h}} = 14,400 \text{ h} \quad (6)$$

Based on the determined results for PoF and ER , the plant must be shut down after 14,400 operational hours to conduct TAM and avoid any threat associated with the plant.

6. Conclusions

Routine Maintenance has a practised, systematic approach to mitigate risk during the normal operation of equipment. RBI application of fouling layers across tubes has become an applicable approach in oil and gas plants to avoid dangerous consequences resulting from plant shutdown to conduct maintenance activities. Thereby, the objective of the study associated with determining a critical failure in the heat exchangers and assessing risk using the RBI approach was achieved by removing the fouling layers.

The results in this study illustrated that fouling is the crucial indicator of the beginning of risk appearing in heat exchangers. Consequently, the mechanical technique that is used during the normal operation state of the unit may not be effective to clean heavy deposits in the long term. Therefore, the total shutdown of a unit is regarded as a necessary evil over the years to perform a chemical technique in order to remove hard and heavy deposits. In general, any fouling at the heat exchanger must be cleaned on regular scheduling to return the unit to its normal operational state. Based on RBI, the plant/unit

must be shut down once every 14,400 h to remove the fouling layers to avoid any threat related to the processing plant. These findings provide a close match compared to the results obtained by Hameed et al. [28], as they estimated the shutdown interval once every 13,000 h for an LNG plant. These results may support further work in the improvement probability of fouling for exchangers in other industrial environments, which run under harsh operation conditions resulting from overpressures and fluctuating temperatures.

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Nomenclature

AR	Acceptable risk
CoF	Consequence of failure
ER	Estimated risk
E _D	Environmental Damage
F	Fouling effectiveness
FC	Fixed cost
F _L	Financial Losses
H _L	Human Losses
M	Measuring effectiveness
MD	Maintenance Duration.
PoF	Probability of fouling
R	Removing
RBI	Risk-based inspection
S _D	System Damage
TAM	Turnaround maintenance
TC	Total cost of cleaning process per cycle of maintenance duration.
VC	Variable cost

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