

Article

Integrated Application of Dynamic Risk-Based Inspection and Integrity Operating Windows in Petrochemical Plants

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Abstract: The scientific and reasonable maintenance strategy is critical to ensure the continuous operation of stationary equipment in the petrochemical industry; both risk-based inspection (RBI) and integrity operating windows (IOWs) are effective for stationary equipment maintenance. In traditional static RBI, the risk is assumed to remain constant in whole inspection period, and the latest variations of medium and process parameters are not fed back into risk calculation. Thus, risk value may be overestimated or underestimated, leading to unexpected failures or excessive inspection. Integrated application of dynamic risk-based inspection (DRBI) and IOWs is an advanced direction for this problem. However, due to the complexity of dynamic interaction mechanisms and risk assessment algorithms as well as the deficiency of powerful software, industrial applications of DRBI and IOWs are still limited. By proposing improved dynamic risk indexes and real-time monitoring process parameters as well as utilizing them in DRBI assessment, this article proposes an integrated DRBI-IOWs method and develops a corresponding system. Further, the method and system are applied in a crude distillation unit. The results show that DRBI-IOWs provide direct and real-time insights into the actual risk and give early warning to the process parameter controls, which is important to control the equipment risk of sudden failures.

Keywords: integrity management; dynamic risk-based inspection (DRBI); integrity operating windows (IOWs); crude distillation unit; industrial application



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1. Introduction

The integrity of stationary equipment such as pressure vessels, pipelines, and storage tanks in petrochemical plants is important for reducing unplanned shutdowns to avoid losses [1–4]. Their continuous and reliable operation is closely related to the economic benefits and personal safety. Although the design and manufacturing play a significant role in their integrity, once the equipment is put into operation, proper inspection and maintenance should be carried out to control their failure risk [5–7].

Therefore, how to develop scientific and reasonable maintenance strategies is currently one of the most challenging for petrochemical plants. In recent years, preventive maintenance has been widely adopted and gradually replaced the previous corrective maintenance [8–11]. Preventive maintenance is further classified into two categories: time-based or rule-based and risk-based or condition-based methods [12–14]. The former is based on regulatory standards and conducts periodic inspection. For example, the periodic inspection strategy is mainly specified according to the supervision regulation TSG 21 in China [15]. Specific inspection content and methods are required in the regulation of pressure vessels. The inspection interval shall be determined based on the inspection results, which generally range from 3 to 6 years. However, due to the incongruence of rules, over inspection or insufficient inspection would occur in applying such methods. For the latter, risk-based inspection (RBI) has been developed by the American Petroleum

Institute [16,17], which provides effective inspection plans according to the damage mode and risk of equipment. Practice has proved that a well-structured RBI plan can mitigate risk and minimize shut-downs by focusing inspections and resources on critical risk elements, so to facilitate continuous operation and improve the integrity of equipment. For example, Hu et al. [18] developed an improved risk-based maintenance (RBM) approach based on the proportional age-reduction model for a petrochemical reforming reaction system, which considered imperfect maintenance to guarantee safety. Khan et al. [2] proposed an RBM approach by integrating a reliability approach and a risk assessment strategy to obtain an optimum maintenance schedule.

However, as stated in the literature [8,11,19], traditional RBI or RBM methods still have some intrinsic limitations:

- Applications of these methods mainly depend on static data from the previous periodic inspection history; the latest variations of process conditions are not fed back into the risk calculation.
- Risk value may be overestimated or underestimated due to the process parameter fluctuations, which may lead to unexpected failures or excessive inspections.
- Risk control and mitigation strategies provided by the RBI method, such as applying inspections and maintenance, cannot fundamentally reduce the probability of failure. A degradation with high damage rate may still occur due to process parameter deviations, which would account for catastrophic failure of the equipment.

To control the deviation of process parameters effectively, the integrity operating windows (IOWs) are developed in API 584 [20], which defines different boundary limits for process parameters to avoid the deviation. Lagad et al. [21] introduced an IOW application for a desalter in the crude unit to demonstrate the benefits of combining it with the RBI program. Kim et al. [4] developed the IOW and corrosion-control method in a crude distillation unit. An RBI-IOWs integrated approach and its framework were further proposed by Arena et al. [8], which provided a foundation for integrated applications of these two methods. These results indicate that IOWs are a good supplement to the RBI. By combining the two methods, the maintenance and risk mitigations actions can be constantly monitored and performed with real-time feedback, thus improving the equipment integrity.

Although the application of IOWs can limit the impact of process parameter fluctuations in a controllable range, it is necessary to dynamically assess the risk to develop more effective inspection strategies. In recent years, the concept of dynamic risk is proposed so that the risk profile can be updated with any given time according to the real-time monitored parameters [19,22,23], which facilitates the application of dynamic risk-based inspection (DRBI). A reliability-based DRBI model focused on risk indicators was proposed by Bhatia et al. [19] and applied in a process system. Other successful degradation-based DRBI approaches were proposed by Kim et al. [24] and Zeng et al. [25]. Detailed comparison and classification of the dynamic risk-assessment method refer to the publications [19,23,26]. These results showed that compared with a traditional static RBI method, DRBI provided direct and real-time insights into the actual risk, which would decrease the uncertainty of risk estimation and provide an accurate control of the system safety.

Despite the significant efforts in developing RBI, IOWs, DRBIs, and integrated approaches, their industrial applications are still limited. This is mainly attributed to the industrial applications not only depending on expert experience in process and corrosion, but also relying on available software tools. To realize the dynamic risk assessment and process control by using the DRBI and IOW methods, the following aspects should be considered:

- The DRBI model and DRBI-IOWs integrated methodology need to be further investigated. Although the RBI-IOWs-integrated approach has been proposed in reference [8], a more accurate risk profile and tendency should be established to enable a more effective maintenance and management. It means that the real-time monitored parameters should not only be controlled within the IOW limits, but also should be used to assess the risk dynamically for inspection strategy development.

- A carefully designed software system with real-time data collection and preset calculation logic should be developed to apply the integrated method. Although commercial software for RBI applications was well developed, such as DNV's Synergi Plant V5.6 and Lloyd's All Assets Platform REV04, the functions of dynamic data interaction and risk calculation are still in development.
- Developed software system should be compatible, robust, and reliable, which is available for different plants, processes, loops, and corrosion mechanisms to achieve the consistency of risk trends and the monitored dynamic indicators.

This study proposes a DRBI and IOW integrated method and develops a corresponding system. Meanwhile, a case study for the application of DRBI and IOWs is conducted on a crude distillation unit. The results provide a good example and technical foundation for the integration application of DRBI and IOWs, which plays an important role in the development of condition-based proactive maintenance in petrochemical plants.

2. Integrated Method of DRBI and IOWs

The risk-calculation process and models for a traditional static RBI are elaborated in API 581 [17] in America and GB/T 26610 [27] in China. Critical issues for DRBI are introducing time variable and dynamic monitoring parameters in risk calculations; this article proposes an improved dynamic risk index to perform dynamic risk assessment, which is demonstrated in following section. Other calculation processes and models for DRBI are similar to RBI, and concrete process and models refer to API 581 [17] and GB/T 26610 [27]. For process parameter control, a fundamental framework and step for IOW are developed in API 584 [24]. In this article, the IOW parameters are real-time monitored and any unexpected fluctuations deviated for IOW boundary limits are captured. Moreover, the real-time dynamic monitored parameters are directly utilized in DRBI assessment. Furthermore, risk mitigation measures or inspection maintenance plans are performed through IOW warnings to ensure the risk is within an acceptable level, thus realizing the integration of DRBI and IOWs.

Specifically, the risk is defined as the multiplication with probability of failure (POF) and consequence of failure (COF), where POF is believed to be dynamically variation with the monitored parameters, while COF is relatively quasi-static unless the fluctuations of operation temperature and pressure are significant and have a great impact on leakage rate, which is similar with the publication [19]. When calculating the POF, the generic failure frequency (GFF) model [17] is selected, and the impact of dynamic monitored parameters on POF is considered with the damage prediction model. The GFF model can be represented as:

$$P_f(t) = gff_{Total} \cdot D_f(t) \cdot F_{MS} \quad (1)$$

where $P_f(t)$ is consequence of failure, gff_{Total} is generic failure frequency, $D_f(t)$ is damage factor, and F_{MS} is facility management factor. To better recognize the foregoing method, the stepwise procedures and details are further summarized in following section.

Step 1. Obtaining basic risk assessment data with the general requirements of API 580 and API 581 [16,17]. The potential damage mechanisms are identified according to API 571 [28]. Further, dividing the corrosion loops according to technological process analysis. Corrosion loops are important in the DRBI and IOW integrated method, which are closely related to identifying the damage mechanisms and establishing relationships between monitoring data and corresponding equipment.

Step 2. Defining dynamic monitoring indicators for DRBI based on the corrosion loops and related damage mechanisms, which should be enabling dynamically monitored by in situ sensors or regular samplings. Three types of monitoring parameters are included in this study: the medium composition data from a laboratory information management system (LIMS), e.g., total acid number (TAN), sulfur (S) content, and chlorine (Cl^-) content; the process operation parameters from the distributed control system (DCS), e.g., operation temperature and flow velocity; and last the wall-thickness data from corrosion monitoring system (CMS), e.g., online ultrasonic measurement of thickness at a fixed position. These

parameters should be carefully screened, especially considering that most parameters have little impact on risk; thus it is critical to confirm which parameters are required for risk assessment.

Step 3. Associating the monitoring parameters with each specific equipment in the corrosion loops. Furthermore, establishing the correlation between monitoring data and damage-prediction models according to standards such as API 581 [17] and API 939-C [29], etc. Then, the corrosion rate or cracking sensitivity are automatically updated by a computer system. The wall thickness monitoring data provide another alternative approach to calculate the measured short-term or long-term corrosion rates r_{dt} , which can be used in the absence of damage prediction models. The r_{dt} is expressed as:

$$r_{dt} = \frac{t - t_T}{T_T - T_0} \quad (2)$$

where t is the nominal thickness, t_T is the latest monitored minimum wall-thickness, T_T is the assessment time point, and T_0 is the latest wall thickness monitoring time point.

Step 4. Calculating the dynamic risk by using the GFF model as mentioned above. The corrosion thinning damage index A_{rt1} of astatic RBI in GB/T 26610 [27] is expressed as:

$$A_{rt1} = \frac{ar}{t} \quad (3)$$

where a is service time, r is corrosion rate, and t is nominal thickness. By introducing the time variable and the effect of dynamic monitoring data on corrosion rate, the improved dynamic risk index A_{rt2} is corrected as:

$$A_{rt2} = \frac{[(t - t_T) + r_d \times (T - T_0)]}{t} \quad (4)$$

where r_d is the predicted corrosion rate obtained by the damage prediction model (r_{dp}) or measured value (r_{dt}) in step 3. The application of t_T ensures that the calculation results do not deviate significantly from the actual situation. In addition, the residual corrosion life of the equipment is dynamically calculated based on API 510 [30] and API 570 [31] for developing inspection and maintenance strategies. The monitoring data are used instead of static data; the residual life T_r is obtained as:

$$T_r = \frac{t_T - t_{\min}}{r_d} - (T - T_0) \quad (5)$$

where $t_{\min}$ is the required thickness calculated by design formulas and allowable stress at operating temperature.

Step 5. Establishing the reasonable IOW control boundary limits. Once the monitoring parameters in DCS, LIMS, and CMS exceed the IOW limits, the predetermined risk mitigation actions are taken until the risk is effectively controlled. This process will form a closed-loop in dynamic risk assessment and effectively control the process parameter boundary.

3. Development of Integrated DRBI and IOW Systems

With the foregoing proposed method and logic models, this study develops a highly integrated DRBI and IOW software system (Dynamic Risk Assessment and Intelligent Warning System for Complete Units V1.0). Figure 1 indicates the software framework and function modules. There are six functional modules, including basic data management, monitoring data management, damage identification and diagnosis, dynamic risk assessment, residual life prediction, and risk mitigation modules.

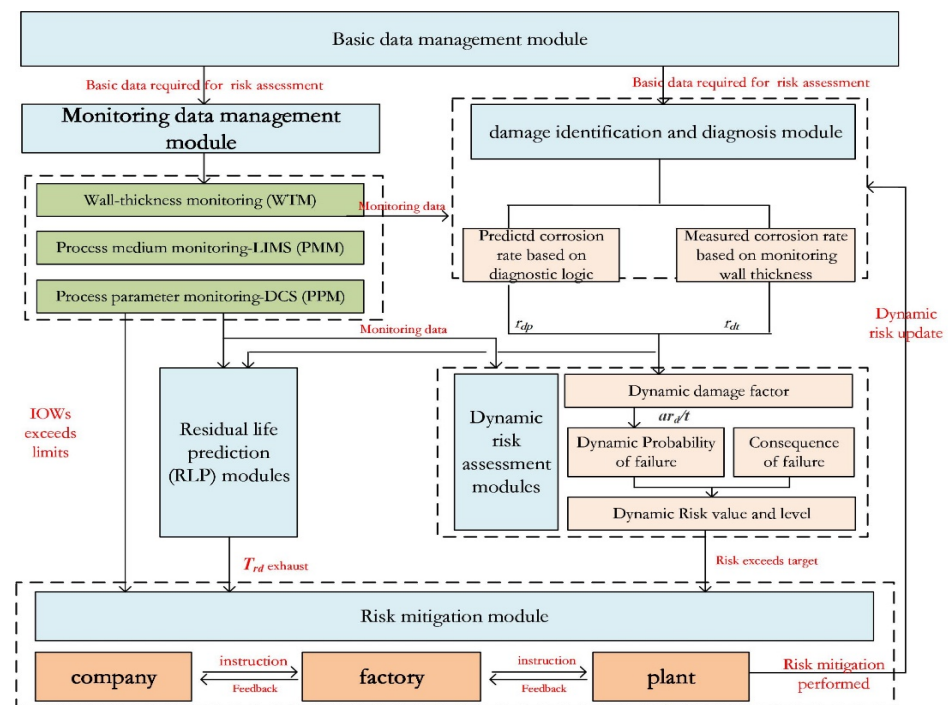


Figure 1. Framework and function modules of the developed DRBI-IOWs system.

The basic data management module is similar to other commercial RBI software, such as DNV's Synergi Plant V5.6 and Lloyd's All Assets Platform REV04. This module stores static data required for risk assessment, including the construction data, process data, historical operation data, material, and the medium database; of this, the material and medium database are closely related to the risk assessment accuracy. The powerful material and medium database are built in this system. There are more than 1500 materials in the material database, which are further divided into 54 material categories (carbon steel, 300 series stainless steels, etc.) and 93 subcategories (304 stainless steels, 316 stainless steels, etc.). The medium database includes more than 900 typical petrochemical media associated with their chemical performance data.

The monitoring data management module is critical for dynamic indicator management and IOW functional realization. There are three sub-modules, i.e., process medium monitoring (PMM), process parameter monitoring (PPM), and wall-thickness monitoring (WTM) modules, which respectively interact with enterprise's LIMS, DCS, and CMS data. Due to the discrepancies between different data sources, monitoring data management module needs to be customized and developed according to interface features of enterprise's aforementioned systems. The information from in situ sensors is processed in this module to facilitate subsequent damage diagnosis and risk assessment. Furthermore, the IOWs and predetermined risk mitigation response actions are set for monitoring parameters. When the monitoring parameters exceed the limit, they will be displayed and warned with response actions in risk mitigation module.

In the damage identification and diagnosis (DID) module, the corrosion rate and damage sensitivity are quantitatively predicted. For some scenarios lacking mechanism knowledge, the expert-estimated or measured corrosion rate is allowed to be used. The diagnosed corrosion rate and damage sensitivity are sent to the dynamic risk assessment module.

In the dynamic risk assessment and residual life prediction modules, once receiving related parameters from the DID and WTM modules, dynamic risk indexes and residual life will be calculated. Thus, the dynamic risk and residual life are updated and displayed in real time by setting the updated frequency in the system.

Finally, the early warning of high risk, insufficient life, and monitoring parameters exceeding the IOW boundary are displayed in the risk mitigation module, which allows

different managers and operators from the company, factory, and plant to instruct risk mitigation measures step by step. Meanwhile, inspection and maintenance strategies are automatically generated, including the inspection time point and effective method, replacement plan, etc. These strategies can be fed back to the enterprise resource planning (ERP) system until the risk is effectively controlled.

The user interface of the DRBI-IOWs system is shown in Figure 2, which inherits the advantages of traditional static RBI systems in human–computer interaction, such as device tree retrieval, batch data input, calculation and generation of maintenance plans, statistical analysis, and other functions. In addition, the system developed in this article also has some unique features, such as:

- More than 100 default values for evaluation data, which is convenient for engineering personnel users.
- Preset process, medium template, automatic damage diagnosis.
- Display of dynamic risk curve with traceability of risk calculation history.
- Three-level (company, factory, and plant) warning interface, which facilitates feedback on risk control actions.

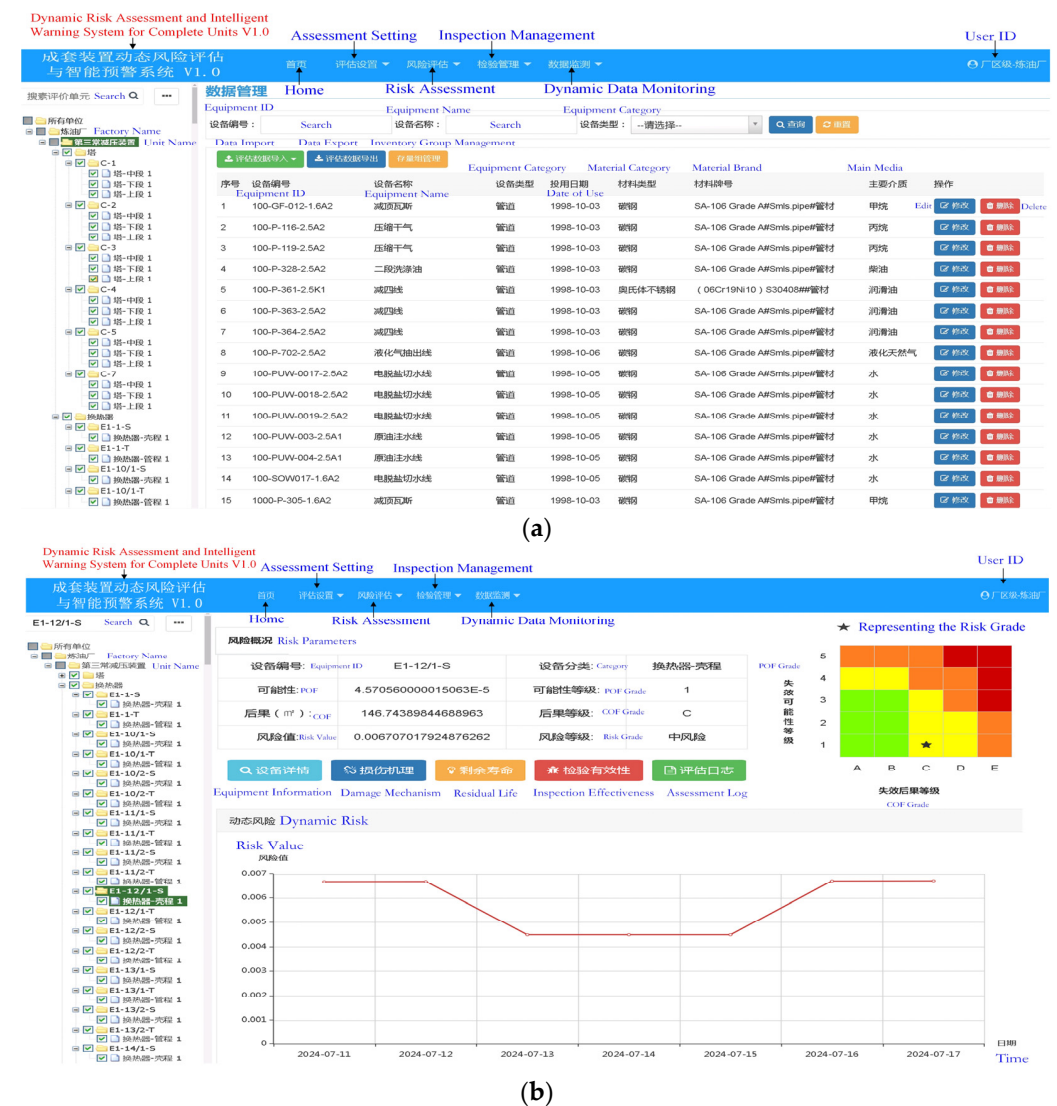


Figure 2. The user interface of the DRBI-IOWs system with (a) basic data management and (b) risk assessment results displayed.

4. Application of Integrated Method and System

A crude distillation unit (CDU) is one of the most important and typical units in the petroleum refinery industry. In June 2023, the developed DRBI and IOWs system was deployed in a petrochemical company in China and applied to its CDU. With a production capacity of 4 million tons per year, this CDU has been serviced over 25 years and is in normal operation currently.

Figure 3 exhibits the implementation route for the application of DRBI and IOWs method in this industrial CDU. There are 34 corrosion loops, which are divided. More than 900 monitoring parameters from LIMS and DCS are analyzed, and 46 medium and 12 process parameters as well as 455 wall-thickness monitoring points are established. The sampling frequency for dynamic monitoring parameters in LIMS and DCS is once a day, while the data updating frequency in the DRBI-IOWs is also set as once a day. It should be pointed out that sampling frequency for wall-thickness data in the CMS system varies for different equipment, which is determined according to the practical situation. The typical corrosion loops and corresponding monitoring parameters are listed in Table 1. For instance, in the tower top loops, main damage mechanisms are hydrochloric acid and ammonium salt corrosion, which corresponds the dynamic indicators of Cl^- content, pH, and temperature; in the tower bottom system, the main mechanisms are high-temperature sulfur and naphthenic acid corrosion, and the dynamic indicators are S content, TAN, temperature, and flow rate.

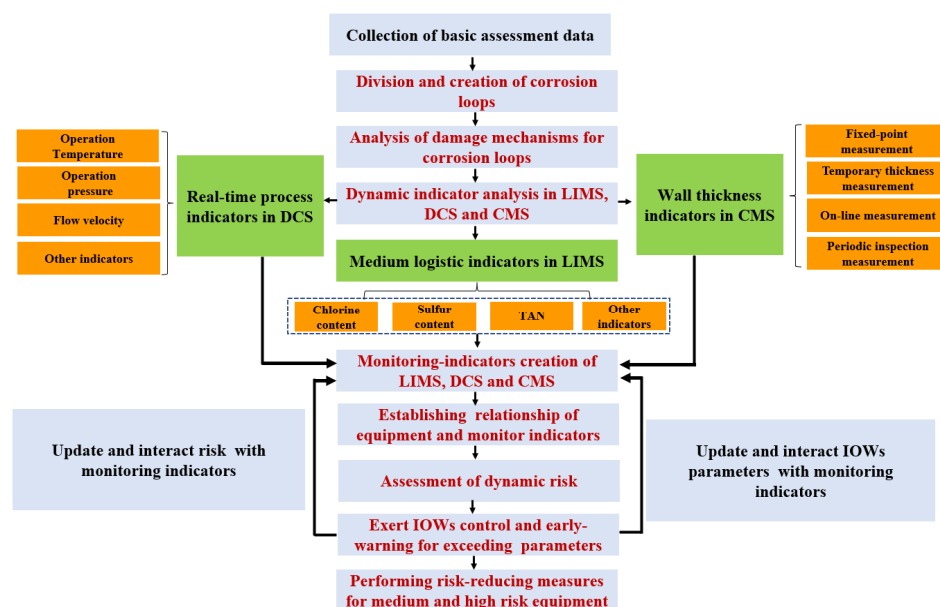


Figure 3. Implement route of integrated DRBI and IOW method in the CDU.

To demonstrate the integrated effect of DRBI and IOWs, three pieces of equipment in the prefractionator bottom oil-gas circuit and atmospheric tower overhead circuit were taken as the examples. Table 2 shows the critical parameters for risk assessment of the selected equipment. Considering the figures with screenshot for CDU in system are unclear, it should be noted that the figures related to monitoring parameters and dynamics risk profile in next section are redraw based on exported data from DRBI and IOW system.

Table 1. Typical corrosion loops and corresponding dynamic indicators in the CDU.

No.	Corrosion Loops	Damage Mechanisms	LIMS Indicators	DCS Indicators	CMS Indicators
1	Crude oil circuit before desalting	Hydrochloric acid corrosion	pH, Cl [−] content	Temperature	Wall thickness
2	Crude oil circuit after desalting	Hydrochloric acid corrosion	pH, Cl [−] content	Temperature	Wall thickness
3	Prefractionator top oil-gas	Hydrochloric acid-ammonium salt corrosion	pH, Cl [−] content	Temperature	Wall thickness
4	Prefractionator bottom oil-gas	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
5	Atmospheric tower overhead circuit	Hydrochloric acid-ammonium salt corrosion	pH, Cl [−] content	Temperature	Wall thickness
6	First-line circuit of atmospheric tower	Hydrochloric acid corrosion	pH, Cl [−] content	Temperature	Wall thickness
7	Second-line circuit of atmospheric tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
8	Third-line circuit of atmospheric tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
9	Atmospheric tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
10	First-line circuit of vacuum tower	Hydrochloric acid-ammonium salt corrosion	pH, Cl [−] content	Temperature	Wall thickness
11	Second-line circuit of vacuum tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
12	Third-line circuit of vacuum tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
13	Fourth-line circuit of vacuum tower	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness
14	Vacuum tower bottom	Sulfidation-naphthenic acid corrosion	S content, TAN	Temperature, flow rate	Wall thickness

Table 2. Critical parameters of examples for dynamic risk assessment of the CDU.

Equipment ID	250-P-106-2.5A2	E1-2/1-T	C-1-Bottom
Equipment name	Second-branch crude oil line	Tube-side of heat exchanger	Prefractionator bottom
Corrosion loop	Prefractionator bottom oil-gas	Atmospheric tower overhead circuit	Prefractionator bottom oil-gas
Operation temperature (°C)	255	124	250
Operation pressure (MPa)	1.75	0.7	0.08
Nominal thickness (mm)	8	28	14
Diameter (mm)	250	900	3800
Length/height (m)	47.5	2	2.85
Material brand	SA 106 Gr A	SA 106 Gr A	SA 106 Gr A
Main medium	Typical crude oil	Naphtha	Typical crude oil

Figure 4 indicates comparison of the static and dynamic risk variation for the 250-P-106-2.5A2 pipeline. In traditional static RBI, the underlying assumption is that risk remains constant and acceptable in whole inspection period; the latest variations of the process conditions are not fed back into the risk calculation. Thus, risk value may be overestimated or underestimated due to the process parameters fluctuations, which may lead to unexpected failures or excessive inspection. However, process parameters fluctuations generally vary inevitably and exert significant effects on risk variation, which may

account for the unexpected failure of equipment. Compared with the static risk profile, the real-time dynamic risk variation is displayed and any risk fluctuations can be captured accurately, which provides direct insights into the actual risk and decreases the uncertainty of risk assessment.

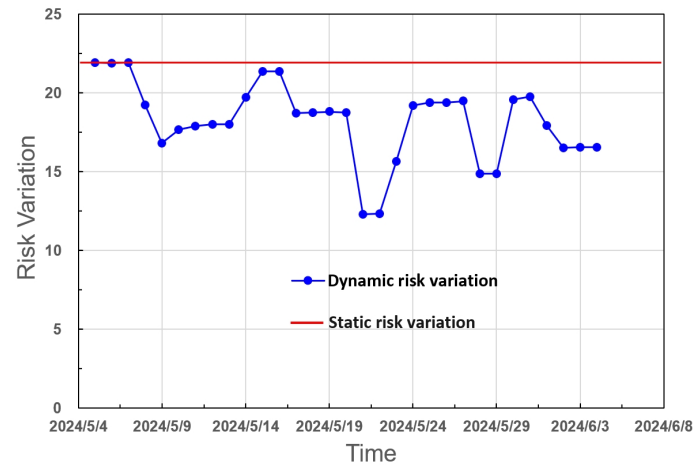


Figure 4. Variation in dynamic risk with time for the 250-P-106-2.5A2 pipeline.

The underlying reasons for dynamic risk variation are confirmed by analyzing the related monitoring indicators. As shown in Table 1, the damage mechanism of 250-P-106-2.5A2 is high temperature sulfidation-naphthenic acid corrosion and the corresponding dynamic indicators are S content, TAN, and flow velocity. Figures 5a and 6a illustrate the time-dependent trends of S content and TAN, respectively. To match the time interval of risk variation in Figure 4, the local-enlarged distribution diagrams of S content and TAN are, respectively, depicted in Figures 5b and 6b. The variation tendencies of dynamic risk are totally consistent with the S content while there is no directly corresponding relationship between risk profile and TAN, which suggests the risk variation is mainly dominated with S content rather than TAN. It is noted that the flow volume data in the system remains constant from January 2024 and has no effect for the risk variation in Figure 4.

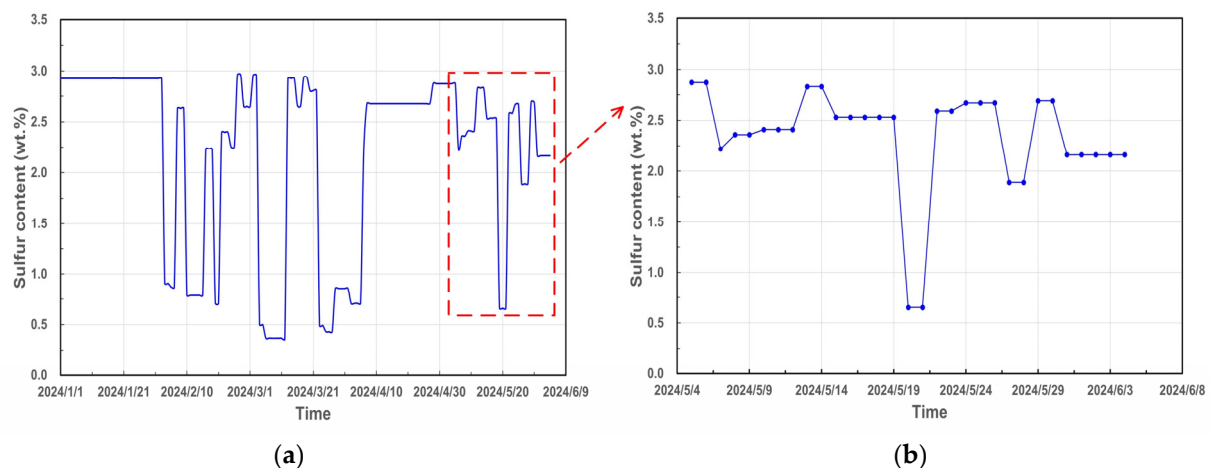


Figure 5. Variation in S content with time for 250-P-106-2.5A2 pipeline of (a) and (b) the local-enlarged diagram.

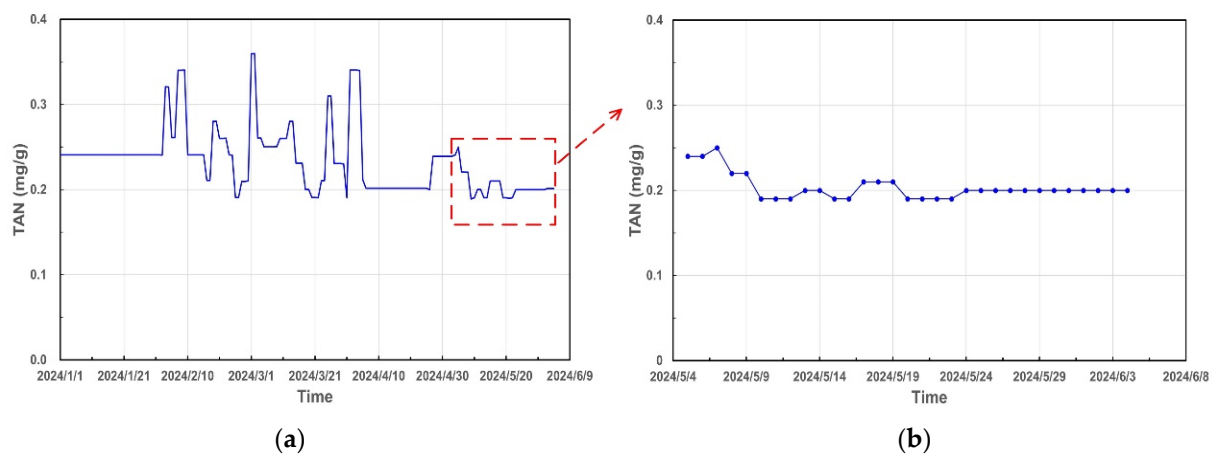


Figure 6. Variation in TAN with time for 250-P-106-2.5A2 pipeline of (a) and (b) the local-enlarged diagram.

Figure 7 presents the static and dynamic risk variation for the tube-side of the heat exchanger E1-2/1-T. Different to the dynamic risk of the 250-P-106-2.5A2 pipeline with several short horizontal lines, the risk of heat exchanger E1-2/1-T varies almost every day to display a high frequency fluctuation. Obviously, it is the dynamic indicators related to the equipment that dominate the variation. This result also demonstrates that it is extremely necessary to revise traditional static RBI with the DRBI method, thus acquire a more accurate risk profile to control the risk of sudden failures.

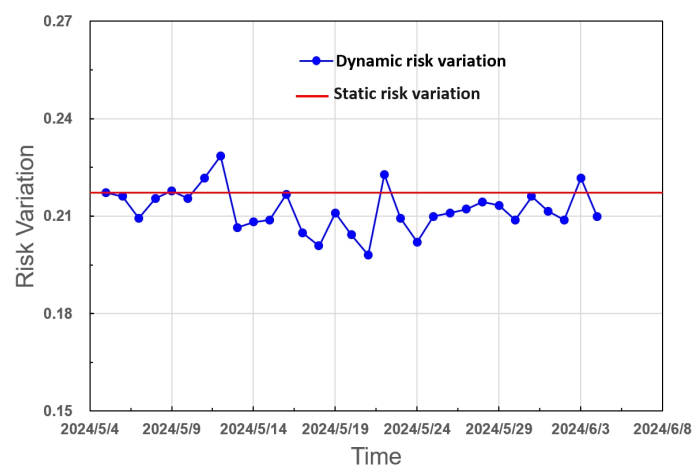


Figure 7. Variation in dynamic risk with time for the tube-side of heat exchanger E1-2/1-T.

The damage mechanism for E1-2/1-T is hydrochloric acid-ammonium salt corrosion, but there is no corresponding corrosion rate prediction algorithm currently; this issue will be elaborately discussed in following section. Consequently, hydrochloric acid corrosion is regard as the main mechanism and the corresponding dynamic indicator is pH or Cl^- content and temperature. Considering the pH can be converted with Cl^- content, the conversion exists a clear error; thus, the pH is preferred to assess risk. Figures 8–10 indicate the variation in Cl^- , pH, and operation temperature with time for E1-2/1-T. As shown in Figure 8, the pH is slightly fluctuating in the interval of (7.0, 8.0), and which exerts weak impact for dynamic risk. Accordingly, Figure 10 shows that the variation in operation temperature is obvious. Because the temperature is extremely sensitive to the corrosion rate of hydrochloric acid, which thus dominates the dynamic risk variation. Different from the foregoing 250-P-106-2.5A2 pipeline, there is no distinct corresponding tendency

between risk variation and dynamic indicators, which are mainly attributed to a greater pH or operation temperature, leading to the opposite variation tendency for risk.

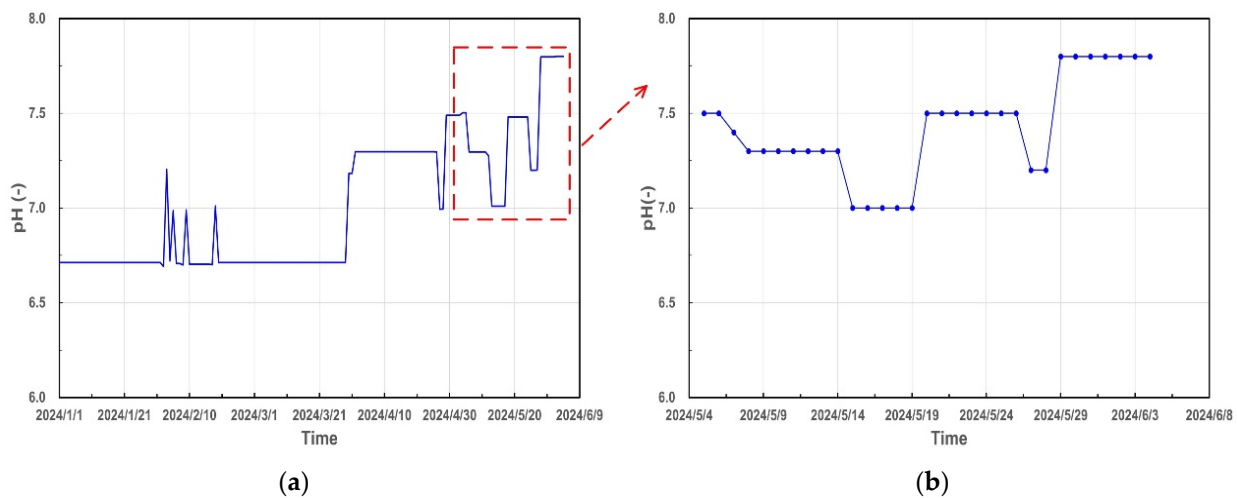


Figure 8. Variation in pH with time for tube-side of heat exchanger E1-2/1-T of (a) and (b) local-enlarged diagram.

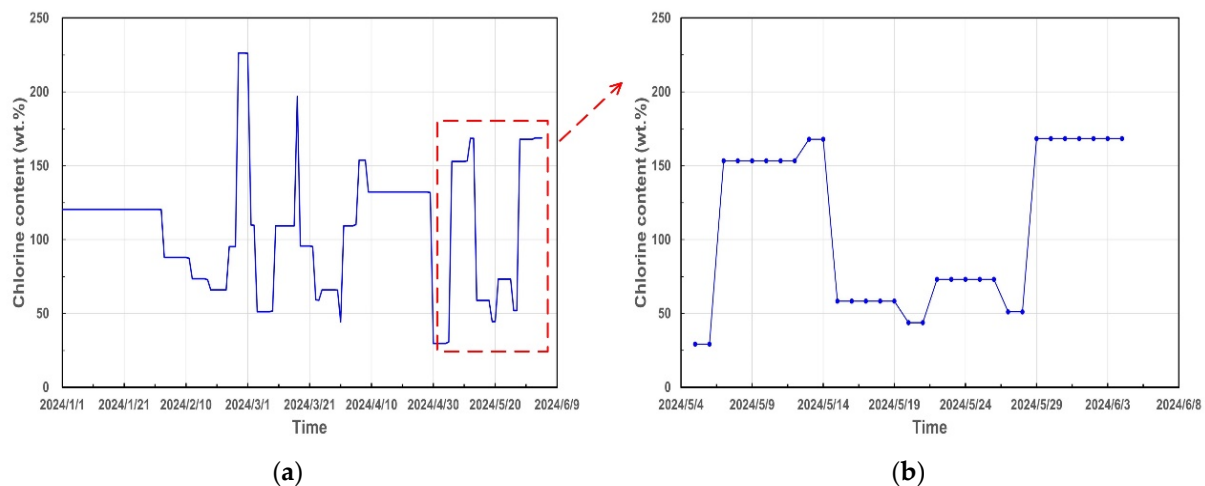


Figure 9. Variation in Cl^- content with time for tube-side of heat exchanger E1-2/1-T of (a) and (b) local-enlarged diagram.

The above examples demonstrate that once the dynamic risk assessment procedure is established in the system, the risk will be continuously updated with dynamic indicators. However, the quantitative logics for corrosion rate diagnosing are not always available or reliable, especially in complex media environments. For instance, in the tower overhead system, API 581 [17] only provides a prediction method for hydrochloric acid corrosion. But it contains various media, such as HCl , H_2S , CO_2 , and NH_3 , and the pH value is affected by the injection process, making it difficult to be accurately predicted using logical models. To solve this problem, the inspected or monitored wall thickness was used to calculate the dynamic risk and corrosion rate in this study. Although the update frequency is low, it ensures the accuracy of risk assessment when the predicting model deviates from the actual situation. Figure 11 is a sketch map to show a comparison of static risk calculated with predicted r_{dp} according to API 581 and dynamic risk with predicted r_{dp} or measured corrosion rate r_{dt} . The results indicate that a significant deviation exists between the prediction and measured corrosion rate. Although r_{dp} is used, the dynamic risk assessment model proposed in this study can also give a timely correction of the

risk results by updating the process parameter pH or monitoring wall thickness, thus improving the accuracy of the risk calculation. Consequently, the re-assessment risk is necessary to determine whether a prediction model or a measured corrosion rate is selected for a specific corrosion loop. It should be stressed that the actual corrosion rate in plants differs significantly from theoretical models, such as sulfuric acid corrosion, hydrochloric acid corrosion, etc. For the corrosion rate prediction in complex media environments, proposing an essential calculated model is also difficult. Consequently, for a multiple media environment or corrosion without logical diagnostic models, machine learning techniques based on big-data collection from similar plants may shed light on this problem [32,33].

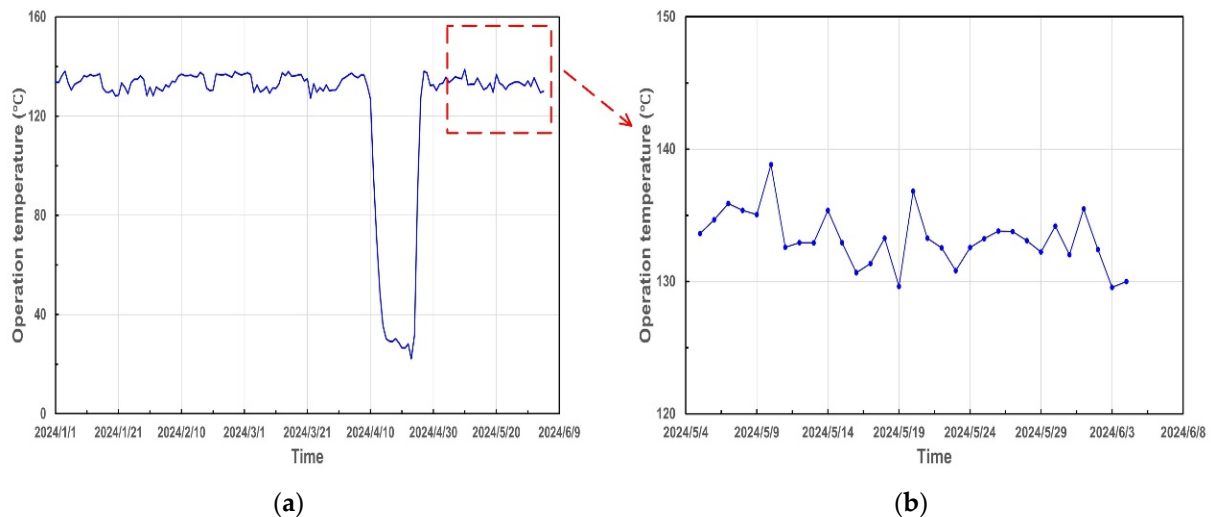


Figure 10. Variation in operation temperature with time for tube-side of heat exchanger E1-2/1-T of (a) and (b) local-enlarged diagram.

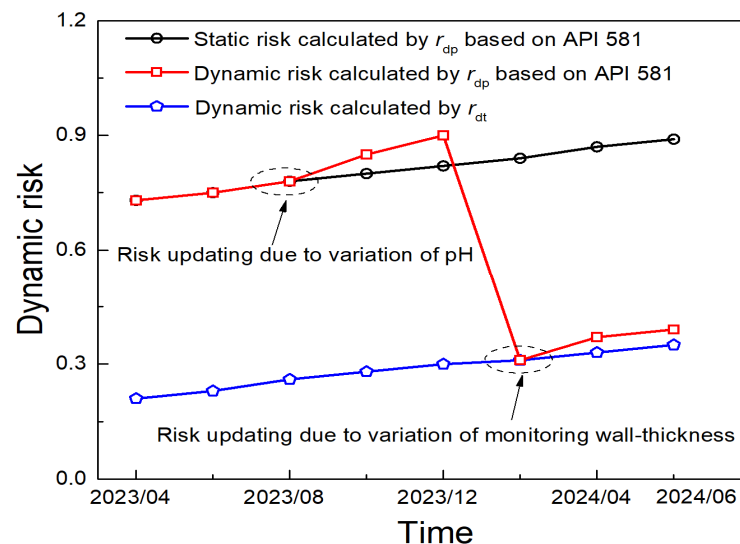


Figure 11. Comparison of static risk and dynamic risk with the predicted or measured corrosion rate.

For a specific definition of IOW limits, API 584 [20] provides a principled setting method, and several articles [4,8,21] studied the detailed IOW boundaries for different process plants and corrosion loops. Generally, the process operation manual will provide the boundary values for some critical parameters. For example, the limits of S, TAN, and Cl^- have been well established in typical loops of a CDU process operation manual. The IOWs for specific parameters are recommended to be determined by inspectors, equipment

managers, and process experts or scenario-based research. The purpose of this study is not to provide detailed IOW boundaries for certain parameters, but to provide a framework and software tool for implementing IOWs in collaboration with dynamic risk assessment.

Taking prefractionator bottom C-1 as an example, Figure 12 shows the dynamic interaction process between risk variation and IOW boundary control. It can be seen that the S content and TAN exceed the set upper limits of IOWs (Figure 12b,c), which accounts for a risk value beyond the acceptable level (Figure 12a). With the early warning system for a risk exceeding the acceptable level, the equipment operators take measures to control S content and TAN, and thus the equipment risk is significantly reduced and effectively controlled. This process forms a closed loop in dynamic risk assessment to facilitate stable operation and ensure the integrity of the equipment.

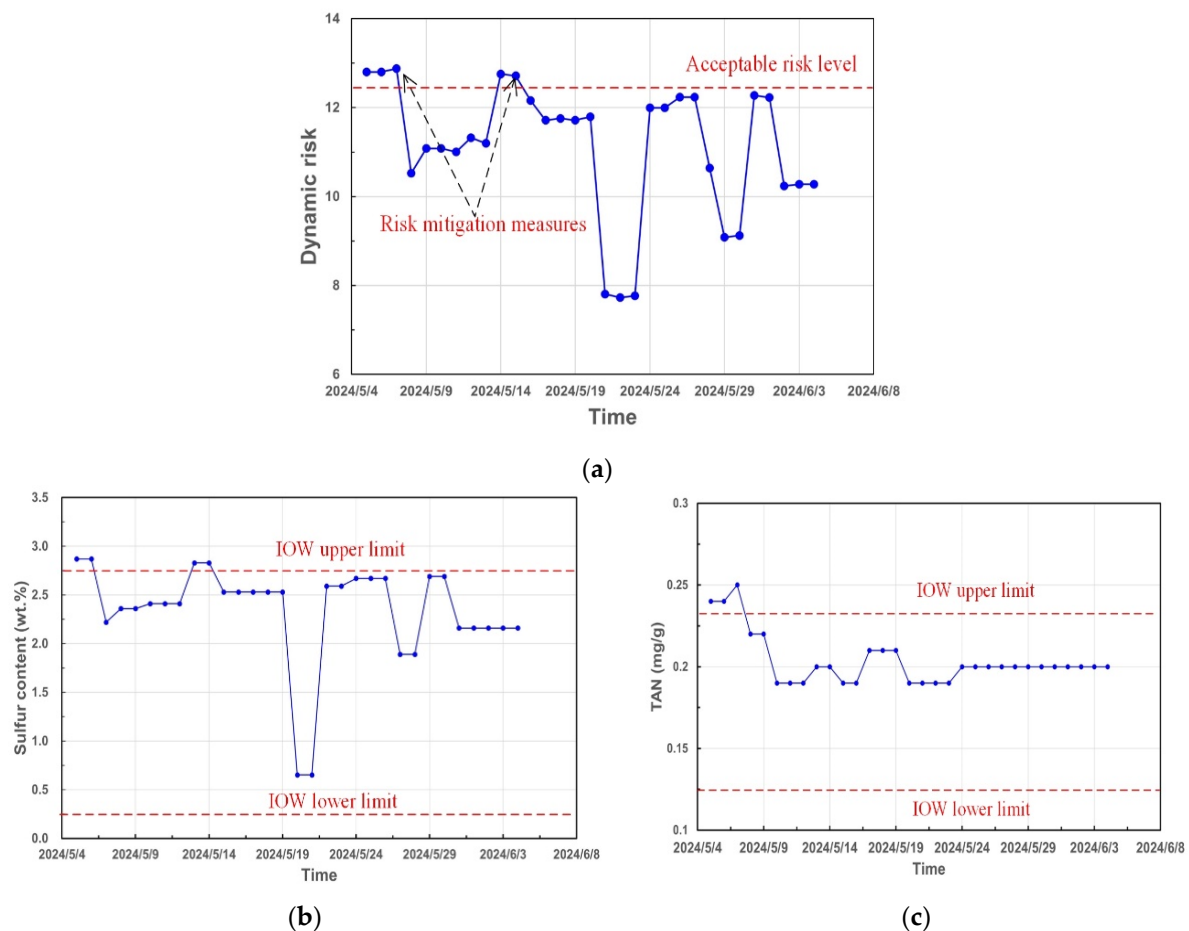


Figure 12. (a) Dynamic risk variation and acceptable level for prefractionator bottom C-1; (b) IOWs boundary control of S content; (c) IOWs boundary control of TAN.

Due to the different damage mechanisms and effect factors, the applications of DRBI-IOW systems in various process plants still need further investigation. In addition, corrosion analysis from a team including equipment operators, inspectors, and corrosion experts is also crucial for the successful application of the system. The accuracy of the input data needs to be carefully checked, and the re-assessment is usually necessary. Finally, the training of equipment operators and managers is important, which directly determines the long-term effectiveness of the system. Continuous improvement and training will enhance the risk management of equipment, ultimately achieving the target including cost savings from reduced inspections, decreased downtime, and improved equipment lifespan. In fact, the applied crude distillation unit has increased the overhaul interval from 4 years to 5 years, where the application of DRBI-IOW technology has played an important

role in dealing with the process fluctuations during long-term operation. The decrease in unplanned shutdowns and cost reduction still needs further verification compared to the previous operation period.

5. Conclusions

The integrated method and corresponding system of DRBI and IOWs are reported in this article to improve the accuracy of risk assessment and maintain the stable operation of stationary equipment in the petrochemical industry. To realize dynamic risk assessment, the improved dynamic risk indexes are re-organized by introducing time variables and dynamic monitoring indicators. While the real-time dynamic parameters are directly utilized in the DRBI model, any unexpected fluctuations deviated for IOW boundaries are captured to realize the integration of DRBI and IOWs. The corresponding software system is carefully developed and further applied in the CDU. It indicated that the dynamic risk profiles provide direct and real-time insights into the actual risk and give an early warning for the process parameter control, while the integration of IOWs with DRBI supplies the effective risk management of unexpected failures and allows for a dynamic plan for the inspection maintenance schedule. This study thus demonstrates a possible route for the development of condition-based proactive maintenance in petrochemical plants.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

CDU	crude distillation unit
DCS	distributed control system
DID	damage identification diagnosis
DRBI	dynamic risk-based inspection
IOWs	integrity operating windows
LIMS	laboratory information management system
PMM	process medium monitoring
PPM	process parameter monitoring
RBI	risk-based inspection
RBM	risk-based maintenance
RLP	residual life prediction
TAN	total acid number
WTM	wall-thickness monitoring
A_{rt}	component wall thickness factor
r_d	diagnosed corrosion rate/sensitivity
r_{dt}	long-term corrosion rate
t	nominal thickness
t_T	monitored minimum wall-thickness
T_T	assessment time point
T_0	latest wall thickness monitoring time point

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