Chapter

# Maintenance Decision Method Based on Risk Level

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## Abstract

Maintenance decision method of the mechanical equipment still has some deficiencies and shortcomings, including unreasonable maintenance methods, surplus or insufficient repair, and unscientific inspection and repair intervals, especially for equipment with different risks. As a consequence, more frequent failures and higher maintenance costs of the mechanical equipment occur along with some major safety accidents and economic losses in the process of production. To overcome these problems, a framework for maintenance decision method based on risk level is presented for mechanical equipment in the petrochemical industry. First, 10 evaluation indexes and a set of scoring criteria quantifying the subjective evaluation are defined to evaluate the risk level of each mechanical equipment. Based on the analytic hierarchy process (AHP), the weight of the evaluation indexes and the evaluation model of the risk levels were established. Then, the subjective effects in the scoring process were removed using the Monte Carlo simulation (MCS) approach. Next, maintenance decision-making trees of the mechanical equipment were formulated by referencing the logic decision tree of reliability-centered maintenance. Finally, the feasibility of the framework was effectively verified by testing a well-control system in the oil field, for which the risk level and maintenance methods were obtained.

**Keywords:** maintenance decision method, mechanical equipment, risk level, petrochemical industry, maintenance decision-making tree

## 1. Introduction

Through extensive research, we found that nearly half of all major accidents and economic losses were caused by failure of the equipments that are inherently high risk in the petrochemical industry. While most equipment failures were attributed to the current maintenance decision method in the petrochemical industry that was backward and unscientific. Moreover, the conventional maintenance methods could not guide the maintenance personnel to carry out timely maintenance for reliability and safety of the mechanical equipment. As we all known, some maintenance decision models and maintenance methods are widely applied in different industries, such as aerospace, electricity generation, and transportation. But there were no effective decision-making methods or scientific theoretical models to satisfy the special mechanical equipment in the petrochemical industry. So that there are some negative outcomes, including surplus repair, insufficient repair, unreasonable repair intervals, higher maintenance costs, and so on, which were brought about in their maintenance work [1]. At present, based on the different attention focuses in each industry and the different model and method choices in the maintenance and management process, many research results are related to the maintenance decision method. Bertolini and Bevilacqua [2] proposed a new maintenance decision method to adopt a modified FEMCA analysis and a type of Monte Carlo simulation (MCS) approach based on different important levels of the power plant equipment. Bertolini and Bevilacqua presented a new maintenance decision technique to determine the better maintenance strategies for the critical centrifugal pumps in an oil refinery [3]. A maintenance decision method of a multi-criteria classification of equipment was proposed by Gómez de León Hijes and Cartagena by the analytic hierarchy process (AHP), and oil pipeline projects were effectively evaluated by Dey with a multiple attribute decision-making technique [4, 5]. Chang et al. applied a new maintenance decision model to estimate the production availability in offshore installations [6]. In the study above, some mathematical models, including AHP and MCS, are often used for making maintenance decisions. However, through research and investigation, very few applications of both AHP and MCS exist for making maintenance decisions of the mechanical equipment based on their different risk levels. Moreover, there are some differences between the mechanical equipment in the petrochemical industry and the ones in other industries, such as types and distribution of the failure, the methods and costs of the maintenance, and requirements for reliability and safety, due to the factors of harsh construction environments, complicated working conditions, and extremely high safety requirements in the production process [7].

Thus, these existing maintenance decision models and the maintenance strategies applied to the equipment in other industries are not directly suitable for the mechanical equipment in the petrochemical industry [8]. Therefore, it is necessary to study the maintenance decision method belonging to the mechanical equipment in the petrochemical production process by focusing on the features of its high risks and hazards [9]. A new framework is put forward for making maintenance decisions based on the different risk levels of the mechanical equipment. Finally, through the framework of maintenance decision making, a more reasonable and more effective maintenance strategy can be devised for the mechanical equipment to guarantee the reliability and security of the production operation.

The remainder of this chapter is organized as follows. In Section 2, the influence factors of the risk level of the mechanical equipment are defined, and their scoring criteria are formulated. In Section 3, an evaluation model for the risk level of the mechanical equipment is established using AHP, and then, the MCS approach is applied to reduce the subjective influences in the scoring process. Then, three MDMETs for the mechanical equipment are obtained based on their categories of different risk levels in Section 4. Finally, Section 5 provides some discussion and conclusions.

## 2. Maintenance decision method based on risk level

### 2.1 Definition of evaluation indexes and scoring criteria of risk level

Through the FMECA of the mechanical equipment in the petrochemical industry, from the four aspects of reliability, economics, monitorability, and maintainability, 10 influencing factors directly related to its risk level were analyzed, as shown in **Table 1** [10].

In order to ensure that the evaluation of the risk level of machinery and equipment is not too complicated, and that the accuracy of evaluation is balanced, and

| Index | Serial number | Factors of affecting risk Level |
|---|---|---|
| Reliability factor | 1 | Personnel safety (PS) |
| | 2 | Environment and health (EH) |
| | 3 | System functions (SF) |
| | 4 | Failure frequency (FF) |
| Economic factor | 5 | Production loss (PL) |
| | 6 | Maintenance costs (MC) |
| Monitorability factor | 7 | Inspectability (IN) |
| Maintainability factor | 8 | Downtime (DT) |
| | 9 | Maintenance difficulties (MD) |
| Other factor | 10 | Service length (SL) |

**Table 1.**
*Influencing factors of risk level about the mechanical equipment.*

| Serial number | Casualty | Grading |
|---|---|---|
| 1 | No impact at all | 0 |
| 2 | Minor injury | 1–3 |
| 3 | Seriously injured | 4–7 |
| 4 | One death | 8–9 |
| 5 | Mass casualties | 10 |

**Table 2.**
*Scoring criteria of PS.*

the degree of influence of each factor is more effectively quantified. Therefore, by experts, professional maintenance personnel and field operators through the review pointed out that the risk level of influencing factors according to the situation divided into 3–5 levels, using a 10-point system for scoring. The scoring standards for the 10 influencing factors related to the risk level of mechanical equipment are as follows [11].

### *2.1.1 Influence of failure on personnel safety (PS)*

For petroleum and petrochemical companies, ensuring production safety is the most important issue. Among·the petroleum and petrochemical companies' mechanical equipment, some object failures will cause casualties to the platform personnel. The PS indicator is divided into five levels, and the scoring standards are formulated as shown in **Table 2**.

### *2.1.2 Influence of failure on environment and health (EH)*

Whether object failures have an impact on the environment and health is receiving much more attention from enterprises, which will cause social public opinion and bring disaster to enterprises. Therefore, considering the degree of the impact of object failures on the environment, the determination of the EH-scoring standard is mainly based on the country and the enterprise environmental safety system and requirements. The EH index is divided into five levels, and the scoring standards are shown in **Table 3**.

| Serial number | Pollution degree | Grading |
|---|---|---|
| 1 | No pollution | 0 |
| 2 | Slight pollution | 1–3 |
| 3 | Local pollution | 4–7 |
| 4 | Severe pollution | 8–9 |
| 5 | Major pollution | 10 |

**Table 3.**
*Scoring criteria of EH.*

| Serial number | Influence level | Grading | |
|---|---|---|---|
| | | Have spare | No spare |
| 1 | Total loss of system function | 6 | 10 |
| 2 | Basic loss of system function | 5 | 8–9 |
| 3 | Significant decrease in system function | 3–4 | 6–7 |
| 4 | Reduced system functionality | 1–2 | 1–5 |
| 5 | System function has no effect | 0 | 0 |

**Table 4.**
*Scoring criteria of SF.*

### *2.1.3 Influence of failure on system function (SF)*

The SF index mainly considers the impact of object failure on the entire production system or the function of mechanical equipment. In order to ensure continuous production operations, the important mechanical equipment in petrochemical companies generally has certain spare. During the production operation, once such mechanical equipment failure, you can immediately switch the standby equipment and quickly resume operations, which can effectively control downtime and avoid large economic losses. Therefore, the degree of impact of object failures with spare parts on system functions will be reduced accordingly. Therefore, in evaluating the object failures on the system, it needs to be divided into two cases: the object has standby and no standby. Based on the actual production process, the level of the SF index is determined, and its scoring standards are established, as shown in **Table 4**.

### *2.1.4 Influence of failure frequency (FF)*

The FF index is related to the trouble-free working time (MTBF) of the object. The MTBF value of the mechanical equipment of petroleum and petrochemical enterprises that has been in operation for a period of time can generally be obtained by analyzing the historical records of the operation of mechanical equipment. Relevant mechanical equipment reliability data are obtained through on-site operation and maintenance personnel's correction. Therefore, the FF index is divided into six levels by the MAXIMO system, the SAP management system, and the historical maintenance records of mechanical equipment during on-site maintenance. The specific scoring criteria are shown in **Table 5**.

| Serial number | MTBF (hours) | Grading |
|---|---|---|
| 1 | >10,000 | 0 |
| 2 | 5000–10,000 | 1–2 |
| 3 | 3000–5000 | 3–4 |
| 4 | 1500–3000 | 5–6 |
| 5 | 500–1500 | 7–8 |
| 6 | <500 | 9–10 |

**Table 5.**
*Scoring criteria of FF.*

| Serial number | Outage loss | Score |
|---|---|---|
| 1 | No loss | 0 |
| 2 | Little loss | 1–2 |
| 3 | Loss | 3–4 |
| 4 | Big loss | 5–7 |
| 5 | Great loss | 8–10 |

**Table 6.**
*Scoring criteria of PL.*

| Serial number | Maintenance cost (Yuan) | Score |
|---|---|---|
| 1 | <10,000 | 0–2 |
| 2 | 10,000–50,000 | 3–5 |
| 3 | 50,000–150,000 | 6–8 |
| 4 | >150,000 | 9–10 |

**Table 7.**
*Scoring criteria of MC.*

### *2.1.5 Influence of failure on production loss (PL)*

The PL indicator is due to the failure of components, subsystems, or systems, which will cause changes in product operation, cause standby products to be put into operation, and cause production problems such as drilling stoppages, which will cause economic losses in the enterprise. In combination with the production of offshore oil and gas, in the case of production loss caused by failure, the PL index is divided into six levels, and the specific scoring standards are shown in **Table 6**.

### *2.1.6 Influence of maintenance cost (MC)*

The MC index needs to consider the complexity of the maintenance object, the labor cost of maintenance, the cost of spare parts, and the inventory cost. Therefore, considering the above aspects of the mechanical equipment of petroleum and petrochemical enterprises, MC is divided into four levels, and the specific scoring standards are shown in **Table 7**.

### 2.1.7 Influence of inspectability (IN)

The IN indicator mainly considers whether the object can be monitored, the number of monitoring parameters, the monitoring cost, and the technical level of the monitoring personnel. The maintenance of the mechanical equipment in petrochemical enterprise cannot be separated from the monitoring of its important subsystems and components. A comprehensive analysis of the existing monitoring technology of mechanical equipment in petroleum and petrochemical enterprises has determined the difficulty of monitoring the object, that is, the IN index is divided into four levels, and the specific scoring standards are shown in **Table 8**.

### 2.1.8 Influence of downtime (DT)

The outage time includes the time required for the outage, maintenance, and start-up of mechanical equipment, so the DT index is related to factors such as the structure type, power, temperature, and pressure of the object. According to the distribution of outage time caused by object failure in offshore oil and gas production, the DT index is divided into four levels according to the working hours. The scoring standards are shown in **Table 9**.

### 2.1.9 Influence of maintenance difficulties (MDs)

From the perspective of object maintenance, MD is an important indicator that affects the level of object risk, which is related to the difficulty of the object (including height and surrounding environment), the complexity of the object, and the supply of spare parts. Based on a comprehensive consideration of on-site maintenance of mechanical equipment in petroleum and petrochemical enterprises, the MD index is divided into four levels, and its scoring standards are shown in **Table 10**.

| Serial number | Ease of monitoring | Score |
|---|---|---|
| 1 | Low | 0–2 |
| 2 | Medium | 3–5 |
| 3 | High | 6–8 |
| 4 | Very high | 9–10 |

**Table 8.**
*Scoring criteria of IN.*

| Serial number | Working hours (h) | Score |
|---|---|---|
| 1 | <2 | 0–2 |
| 2 | 2–8 | 3–5 |
| 3 | 8–12 | 6–8 |
| 4 | >12 | 9–10 |

**Table 9.**
*Scoring criteria of DT.*

| Serial number | Ease of maintenance | Score |
|---|---|---|
| 1 | Easily | 0–2 |
| 2 | General | 3–5 |
| 3 | More difficult | 6–8 |
| 4 | Difficult | 9–10 |

**Table 10.**
*Scoring criteria of MD.*

| Serial number | Length of service (year) | Score |
|---|---|---|
| 1 | <3 | 0–2 |
| 2 | 3–8 | 3–5 |
| 3 | 8–12 | 6–8 |
| 4 | >12 | 9–10 |

**Table 11.**
*Scoring criteria of SL.*

#### *2.1.10 Influence of service length (SL)*

From the perspective of mechanical equipment maintenance management, object service age (or operating time) and frequency of use are also indicators that affect its risk level. The SL index is related to the service life of the mechanical equipment, the operating environment and working conditions, the frequency of use (continuous operation, interval operation, and temporary use), the past failures, and the maintenance of the mechanical equipment. Therefore, through discussions with field operations and maintenance personnel, it was determined that the SL index of mechanical equipment in petroleum and petrochemical enterprises is divided into four levels, and its scoring standards are shown in **Table 11**.

### 2.2 Research on risk assessment methods of mechanical equipment

#### *2.2.1 Establishment of risk assessment model for mechanical equipment*

After completing the scoring according to each evaluation index, it is necessary to comprehensively evaluate the risk level of the object. Therefore, it is necessary to comprehensively consider the rating vector $V$ of its evaluation index and its corresponding weight value vector $W$ [12]. The object's risk level evaluation index can be expressed as

$$Index(V, W) = F[v_1 w_1, v_2 w_2, \dots, v_n w_n]. \tag{1}$$

Among them, $F[\cdot]$ is a comprehensive evaluation function that reflects the degree of influence of each evaluation index on the object risk level and can be a function of various forms. Using a simpler linear weighted model, the formula for calculating the object risk level evaluation index, namely, $Index$, is as follows:

$$Index = \sum_{i=1}^{n} v_i w_i \tag{2}$$

where $n$ is the number of evaluation indicators; $v_i$ is the rating value of the $i$th evaluation index of the evaluated object; and $w_i$ is the weight value of the $i$th evaluation index of the evaluated object.

Therefore, the magnitude of evaluation value *Index* indicates the risk level, so that the objects can be sorted and screened based on their different risk levels.

From Eq. (2), we can know that the weight $w_i$ of the influencing factors will have a great influence on the final value of the risk level evaluation index *Index*. Therefore, the AHP method is used for this calculation above. The specific calculation steps are as follows:

**Step 1:** Constructing a judgment matrix $D$ through pairwise comparisons among the evaluation indexes,

$$D = \begin{bmatrix} u_{11} & u_{12} & \ldots\ldots & u_{1n} \\ u_{21} & u_{22} & \ldots\ldots & u_{2n} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots \\ u_{n1} & u_{n2} & \ldots\ldots & u_{nn} \end{bmatrix} \tag{3}$$

where $u_{ij}$ is a relative risk level value that of the $i$th evaluation index compared with the$j$th evaluation index and $u_{ji}u_{ji}$ is the relative risk level value that of the $j$th evaluation index compared with the $i$th evaluation index.

Thus, the value of $u_{ji}$ is the reciprocal value of $u_{ij}$, namely $u_{ji} \times u_{ij} = 1$ . The definition and fundamental scale of the relative risk level are shown in **Table 12**.

**Step 2:** Calculating the maximum eigenvalue $\lambda_{max}$ of the judgment matrix $D$ using the system of homogeneous linear equations as follows:

$$\begin{cases} (u_{11} - \lambda)\omega_1 + u_{12}\omega_2 + \cdots + u_{1n}\omega_n = 0 \\ u_{21}\omega_1 + (u_{22} - \lambda)\omega_2 + \cdots + u_{2n}\omega_n = 0 \\ \qquad\qquad \cdots\cdots\cdots\cdots \\ u_{n1}\omega_1 + u_{n2}\omega_2 + \cdots + (u_{nn} - \lambda)\omega_n = 0 \end{cases} \tag{4}$$

**Step 3:** Determining the eigenvector relative to the maximum eigenvalue $\lambda_{max}$, which is given by

$$W = (\omega_1, \omega_2, \cdots, \omega_n) \tag{5}$$

**Step 4:** Checking the consistency of the judgment matrix $D$,

$$CR = CI/RI \tag{6}$$

| Important scale | Definition |
|---|---|
| 1 | Equally important |
| 3 | Moderately important |
| 5 | Strongly more important |
| 7 | Very strongly important |
| 9 | Extremely more important |
| 2, 4, 6, 8 | Situation between the above levels |

**Table 12.**
*The definition and fundamental scale of the relative risk level.*

$$CI = (\lambda_{\max} - n)/(\text{n-1}) \tag{7}$$

where CR is the random consistency ratio of the judgment matrix; CI is the general consistency index of the judgment matrix; and RI is the mean random consistency index of the judgment matrix.

For 2 to 9th-order judgment matrix, the value of RI is shown in **Table 13**.

**Step 5:** Performing consistency adjustment and weight ordering.

If CR < 0.01, the consistency of the judgment matrix $D$ is satisfactory, which means that the weight apportionment of each evaluation index is reasonable; if not, the judgment matrix $D$ should be adjusted until the consistency meets the above requirement. At this time, the maximum eigenvector of the judgment matrix $D$ corresponds to the weight value of each factor. The priority of mechanical equipment can be determined according to the weight of each factor.

### *2.2.2 Analysis of eliminating the subjective factors based on the MCS*

Because the scoring process of the influencing factors of the risk level of mechanical equipment has subjective factors and differences among individual experts, based on the AHP analysis method to determine the ranking of the influencing factors of each level of risk, the Monte Carlo simulation method is used for calculation [13]. In the calculation process of the Monte Carlo method, the weight of each evaluation factor can be changed by generating random numbers, so that the robustness of the risk level ranking of mechanical equipment is enhanced, and the ranking results are less affected by subjective factors. The logic block diagram of the Monte Carlo simulation is shown in **Figure 1** [12].

As shown in **Figure 1**, a certain random numbers in [0, 1] are generated in the calculation process. The random numbers are regarded as the weight value of certain evaluation indexes and assigned with the priority order obtained in the previous calculation process [14]. In other words, for any group of random numbers, the largest random number will be assigned to the top priority, the smallest one will be assigned to the lowest priority, and the rest of random numbers will be assigned to the other evaluation indexes in order of priority from large to small. Then, in an MCS computation, the total score of all evaluation indexes can be calculated using Eq. (1), and the risk level of the mechanical equipment will be obtained and ranked according to the calculated *Index* . Through $N$ times simulation calculations in the MCS, a number of ranking values are obtained based on different risk levels of the same mechanical equipment. Then, the risk level of a single equipment can be displayed from their sequence of cumulative frequency reaching 1, namely, the faster cumulative frequency of one mechanical equipment reaches "1," so that it will be a higher risk level.

| *n* | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| RI | 0.00 | 0.58 | 0.9 | 1.12 |
| *n* | 6 | 7 | 8 | 9 |
| RI | 1.24 | 1.32 | 1.41 | 1.45 |

**Table 13.**
*RI values of the 2 to 9th-order judgment matrix.*

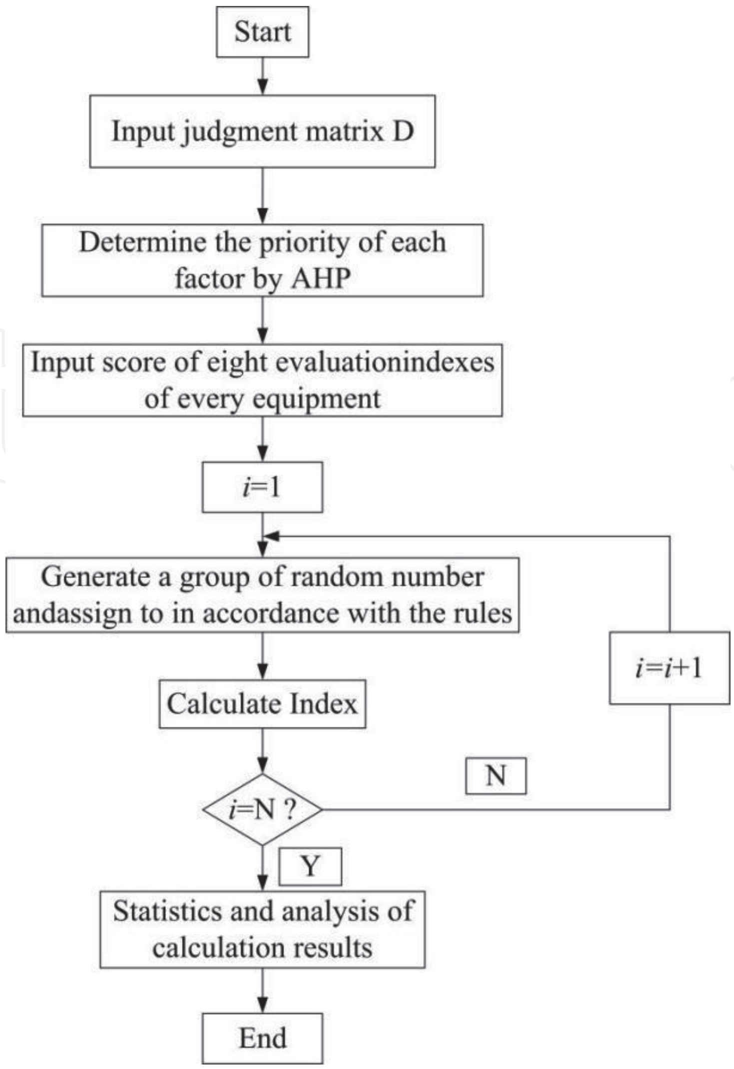


**Figure 1.**
*Logic block diagram of the Monte Carlo simulation.*

### 2.3 Research on maintenance decision-making methods based on the risk level of mechanical equipment

According to statistical data about the priority orders of the mechanical equipment from their evaluation risk levels in the previous step, their cumulative frequency can be plotted with a curve chart. Based on the principle of establishing a cumulative frequency curve chart, the percentage of the area on the right side of the curve from the total area can be taken as another representation evaluating the risk level of the mechanical equipment [15]. A larger area percentage is indicating that one mechanical equipment has a higher risk level. According to their different area percentages, namely, the different risk levels among them, the mechanical equipment can be divided into three categories, including Classes A, B, and C. Class A is an area percentage of 0–30% of mechanical equipment. Class B is an area percentage of 30–80% of mechanical equipment. Class C is an area percentage of 80–100% of mechanical equipment [16, 17].

According to different own characteristics and failure modes of the mechanical equipment in the petrochemical industry, the existing maintenance methods include Lubrication, Service, Corrective Maintenance, Time-based Maintenance, Hidden Failure Detection, and Condition-based Maintenance. In order to reasonably establish maintenance decisions of mechanical equipment tree (MDMET) and effectively implement the existing maintenance methods above, the failure mode, failure effect, and failure cause of the three categories of mechanical equipment are determined based on the FMEA method. Then, the MDMETs on the mechanical equipment of the petrochemical industry are established by referencing the logic decision diagram in the reliability centered maintenance (RCM) theory. The MDMETs are shown in detail as follows [18–20]:

1. The failure consequence of Class A of mechanical equipment has little or no influence on the function of the whole system or causes lower maintenance costs. Increasing the spare part inventory or decreasing the failure frequency for Class A of mechanical equipment cannot affect the production process. A MDMET of Class A of mechanical equipment is shown in **Figure 2**.

2. When Class B of mechanical equipment has been failed, it might result in severe failure consequences, but it usually does not influence personnel safety and environment. The failure frequency of Class B of mechanical equipment could be reduced through reasonable maintenance strategies, so that failure consequences could be decreased as well. But these maintenance strategies might cause higher maintenance costs. A MDMET of Class B of mechanical equipment is shown in **Figure 3**, which includes corrective maintenance, time-based maintenance, and hidden failure detection.

3. The failure of Class C of mechanical equipment might endanger the personnel safety, pollute the environment, and cause the significant economic consequences. In order to ensure the operation reliability and maintenance economy of Class C of mechanical equipment, some special maintenance

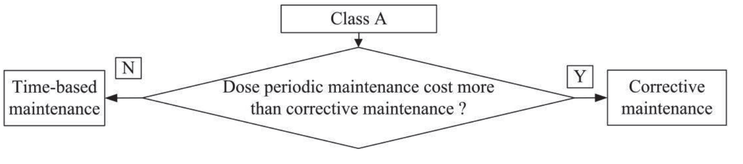


**Figure 2.**
*MDMET of Class A of mechanical equipment*

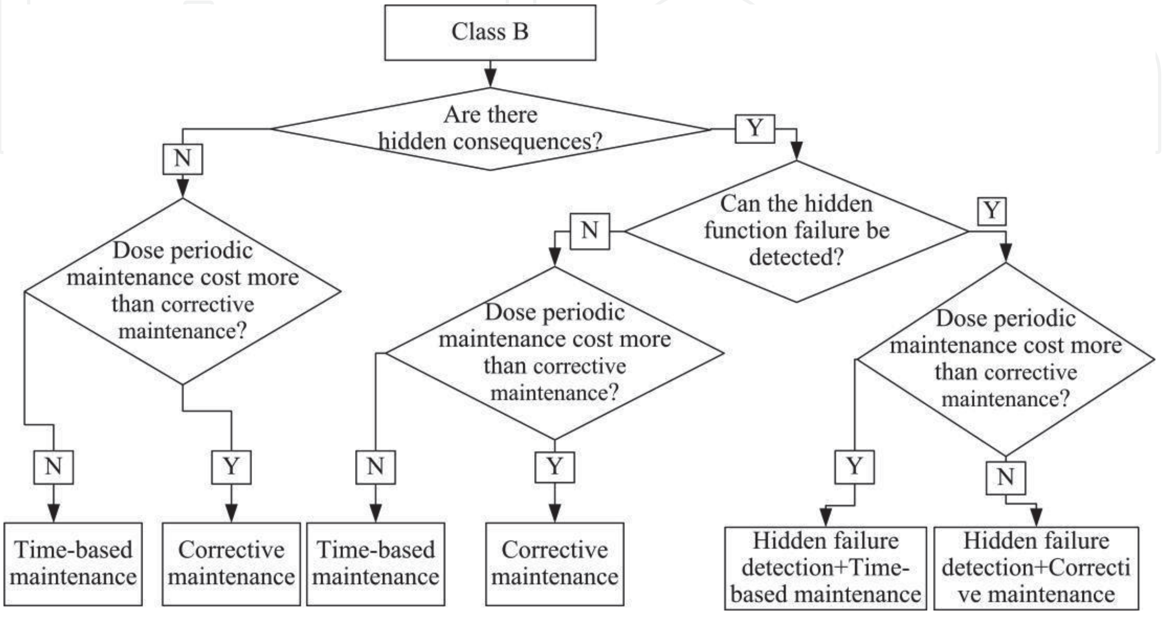


**Figure 3.**
*MDMET of Class B of mechanical equipment.*

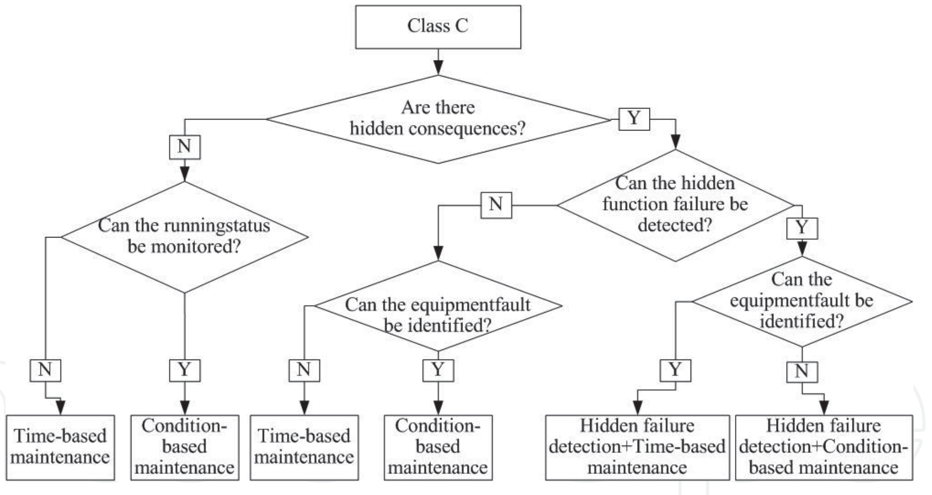


**Figure 4.**
*MDMET of Class C of mechanical equipment.*

strategies should be applied, and the failure frequency should be reduced by increasing the maintenance costs with advanced maintenance methods. A MDMET of Class C of mechanical equipment is shown in **Figure 4**, which includes corrective maintenance, time-based maintenance, hidden failure detection, and condition-based maintenance.

## 3. Conclusions

The aim of this study was to present the framework for making maintenance decisions for mechanical equipment to improve their reliability and security and to decrease safety accidents and economic losses. The framework adopts the idea of different equipment classifications based on their own risk level with different MDMETs. We summarized 10 evaluation indexes for evaluating the risk level of the mechanical equipment and defined a set of scoring criteria to quantify the subjective evaluation in the petrochemical industry. The evaluation model of the risk level was established based on the AHP and the MCS, which calculate the weight of the evaluation indexes and remove the subjective effects in the scoring process. Moreover, we divided the mechanical equipment into three categories based on their risk level and established their MDMETs.

From the discussion above, we can conclude that the framework for making maintenance decisions, combining the quantitative and qualitative methods with the mathematical model and decision-making theory, can be effectively applied to mechanical equipment and provides them with reasonable and scientific maintenance strategies. The framework is suitable not only for mechanical equipment but also for other similar equipment on the premise that the evaluation index and scoring criteria are revised based on their respective features. This framework also includes three analysis methods for the risk level of the mechanical equipment, which can be put into use for other equipment or systems to filter out the unimportant parts. Moreover, the analyzed methods and results in this study will help the study of asset integrity management (AIM) in oil companies.

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