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Agenda Item 5: ATM Automation System Implementation Experience by States
5.4 Life cycle management

LIFE CYCLE MANAGEMENT OF ATM AUTOMATION SYSTEM

（Presented by China）

SUMMARY

Holistic lifecycle management of ATM Automation System is a comprehensive and systematic methodology that spans all phases from system inception to decommissioning, ensuring optimal performance and maximum value realization throughout the entire lifespan. This paper elaborates on lifecycle management practices for ATM Automation Systems, especially the management employing Reliability-Centered Maintenance (RCM) methodology during the service phase.

1 INTRODUCTION

1.1 The traditional maintenance of ATM Automation System primarily revolves around periodic maintenance, which is categorized into two tiers based on time intervals: weekly/monthly maintenance and quarterly/semi-annual/annual maintenance. Additionally, scheduled inspections and specialized inspections are implemented. While this conventional approach ensures stable and efficient system operation to a certain extent, it suffers from the following limitations:

(1) The system's large scale and numerous nodes result in fixed and cumbersome periodic maintenance tasks, leading to mental fatigue among maintenance personnel.

(2) Relying solely on operational hours for system lifecycle assessment while rarely evaluating equipment reliability makes it difficult to ascertain the actual working condition of devices.

(3) Implementing "undifferentiated" maintenance for equipment at different lifecycle stages lacks specificity, resulting in both over-maintenance and maintenance blind spots.

1.2 RCM employs logical decision-making methodology to determine the required maintenance tasks, types, intervals, and levels for equipment, thereby achieving maintenance optimization.

1.3 This paper introduces the lifecycle management of ATM Automation System. By applying the RCM methodology, it conducts quantitative analysis of the operational status of hardware and software during service phases, formulates logical decision-making and maintenance programs, optimizes maintenance strategies, reducing maintenance workload by 40%–70% and extending service life by 40%.

2 DISCUSSION

2.1 Full Life Cycle of ATM Automation Systems

Focusing on the deployment modes and operational characteristics of Automation Systems, incorporating operational experience, this study defines the complete lifecycle of the system as the entire process from design review to decommissioning, which is divided into three phases: Initial, Service, and Final. Each phase exhibits distinct characteristics, necessitating phased management strategies. A brief framework is illustrated in Figure 1. The following sections will elaborate on each phase in detail.

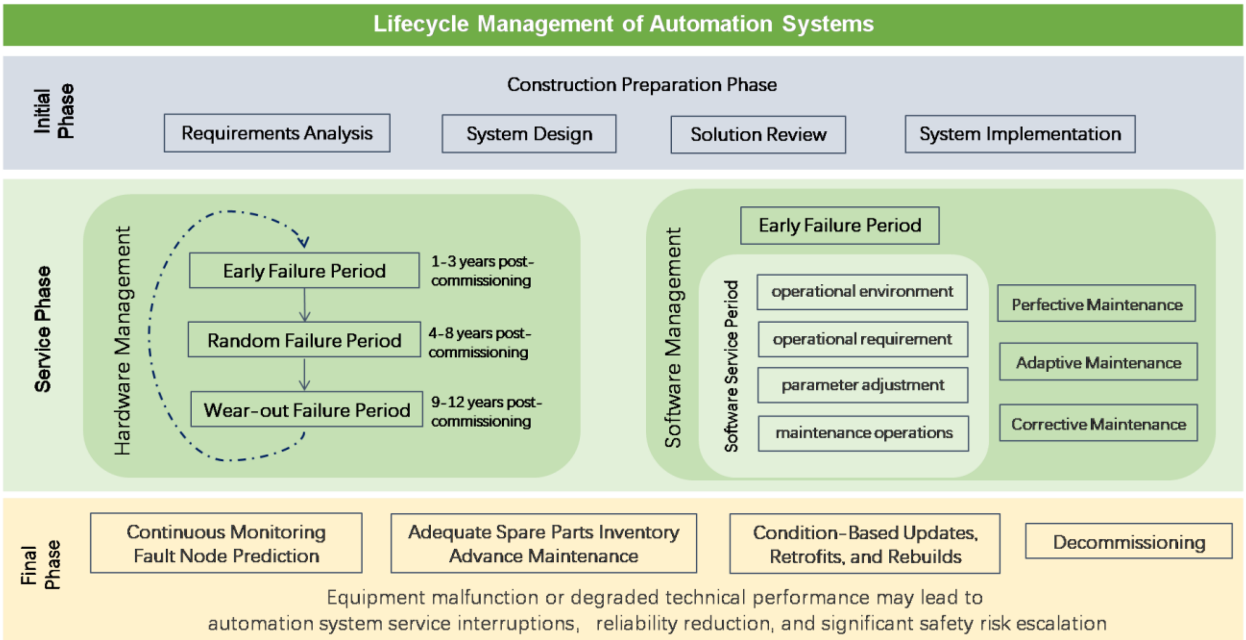

Figure 1. Lifecycle Management Framework for Automation Systems

2.2 Initial Phase Management of ATM Automation Systems

The initial phase refers to the preparatory stage of automation system construction, comprising four stages: System Requirements Analysis, System Design, Solution Review, and System Implementation.

(1) During the System Requirements Analysis and System Design phases, thorough planning and preparation should be conducted with a focus on system performance, to propose comprehensive, rational, and clear functional requirements, thereby minimizing defects and vulnerabilities to the greatest extent;

(2) During the Solution Review phase, technical standards must be rigorously enforced to ensure a well-structured system design, rational resource allocation, and scientifically sound implementation plans;

(3) During the System Implementation phase, maintenance personnel shall fully participate in equipment installation and debugging, promptly identify and resolve issues, ensuring the system performance complies with operational requirements.

The preparatory work during the initial phase determines the inherent reliability level of the automation system. Enhancing system reliability through proactive phase management will significantly reduce operational workload post-deployment and Minimize impact on end-users.

2.3 Service Phase Management of ATM Automation Systems

The service phase refers to the period from system's commissioning to its gradual aging and significant reliability degradation. It is categorized into hardware service lifecycle management and software service lifecycle management. Key metrics for assessing system reliability include Mean Time Between Failures (MTBF), failure rate (λ), and Mean Time To Repair (MTTR). The calculation methods are specified in Appendix 1.

2.3.1 Hardware Service Phase

Hardware service phase can be categorized into three distinct phases based on parameters such as failure frequency, operational duration, and key performance indicators: early failure period, random failure period, and wear-out failure period. The failure rate trend across these phases conforms to the bathtub curve pattern.

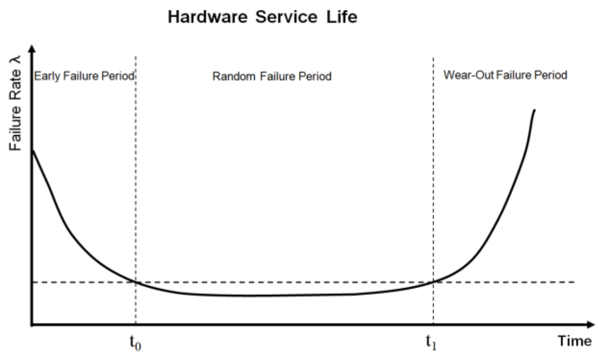

Figure 2. Bathtub Curve of Hardware Failure Rate

(1) Early Failure Period: The Pre-project phase following the commissioning of the ATM automation systems, typically spanning the first 1 to 3 years of operation. During this stage, the equipment generally exhibits a higher failure rate due to factors such as system design flaws, improper assembly, or operational errors by field personnel;

(2) Random Failure Period: Refers to the phase when the performance of the ATM automation system stabilizes after adaptation and adjustment during the early failure period, typically spanning from Year 4 to Year 8 post-commissioning. During this stage, the system demonstrates consistent and reliable performance, exhibiting the lowest failure rates in its lifecycle;

(3) Wear-out Failure Period: This phase refers to the operational stage where prolonged service leads to excessive component wear, material fatigue, and rapid degradation of mechanical

strength and fit quality. Typically occurring between 9 to 12 years post-commissioning. During this phase, the equipment progressively deviates from its original design specifications and stable operational performance, exhibiting exponentially increasing failure rates.

2.3.2 Application of RCM in Hardware Service Phase

2.3.2.1 Historical Hardware Failure Data Analysis

The failure data and annualized failure rates of 156 workstations in an automation system from 2013 to 2024 are presented in Table 1.

Table 1. Failure Statistics of Workstations in an Automation System

Equipment Service Year(s)	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Total Failures (unit-events/year)	27	13	6	4	3	3
Annualized Failure Rate λ (%)	0.0020	0.0009	0.0004	0.0003	0.0002	0.0002
Equipment Service Year(s)	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Total Failures (unit-events/year)	3	7	16	23	31	41
Annualized Failure Rate λ (%)	0.0002	0.0005	0.0011	0.0016	0.0022	0.0030

Figure 3 presents the fitted failure rate curve derived from failure rate data, demonstrating close alignment with the classical bathtub curve profile.

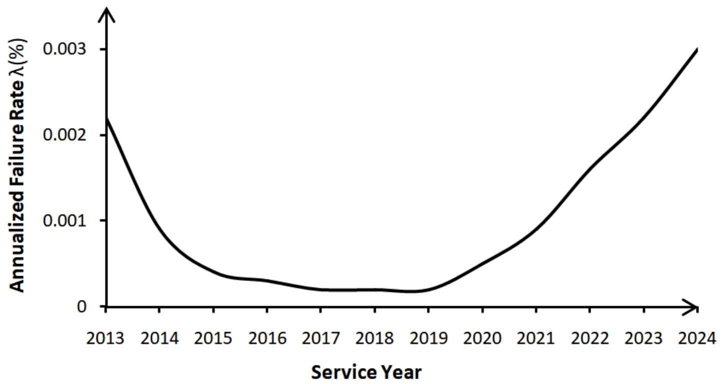

Figure 3. Failure Rate Curve for Workstations in the Automation System

Analysis reveals that between years 8-12 of service, the workstations exhibited a rapid decline in MTBF, with the annualized failure rates increasing sixfold. Combined with the bathtub curve analysis, it can be confirmed that the workstations have transitioned from the random failure period to the wear-out failure period, and it is reasonable to predict that the failure rate will continue to rise in the future.

2.3.2.2 Failure Consequence Classification and Maintenance Decision-Making

According to RCM theory, failure consequences are classified into four categories: safety and environmental consequences(A1), hidden failure consequences(A2), operational consequences(A3), non-operational consequences(A4). Based on the criticality of failure effects, a Logic Decision Diagram has been constructed (refer to Appendix 1). Utilizing this diagram and failure rates, the maintenance program for workstation functional modules is developed as shown in Table 2.

Table 2. Workstation Maintenance Program

Failed Module	**Logical Response (Y/N)**				**Maintenance Approach**	**Failure Description**	**Maintenance and Spare Parts Recommendations**
	A1	**A2**	**A3**	**A4**			
CPU	N	Y	Y	N	**Primary:** Condition-Based Maintenance **Secondary:** Corrective Maintenance	Low failure rate Severe consequences Periodic inspections	Memory expansion
Hard Disk	N	Y	Y	N			
Memory	N	Y	Y	N			
Network Interface Card	N	Y	Y	N	**Primary:** Corrective Maintenance **Secondary:** Condition-Based Maintenance	Low failure rate Minor impact Difficult to detect proactively	Replace spare parts Maintain minimum inventory
Graphics Card	N	Y	Y	N			
Power Supply Unit	N	Y	Y	N			
Cooling Fan	N	Y	N	Y		High failure rate Minor impact Difficult to detect proactively Ensure cleanliness	Replace spare parts Maintain sufficient inventory

2.3.2.3 Maintenance Effectiveness

Practice demonstrated that solely through three measures—memory expansion, spare parts inventory optimization, and operational environment improvement—equipment reliability can be restored to random failure period levels, with stable operation maintained to date (13th year of service). This optimized solution has effectively avoided resource waste, reduced operational costs, and minimized unnecessary/repetitive maintenance tasks for personnel.

Typically, automation system hardware is renewed every six to eight years. The aforementioned analysis and maintenance outcomes demonstrate that implementing precision maintenance strategies can extend the reliable operation duration during the random failure period, defer hardware renewal windows to beyond 10 years, and effectively achieve asset lifespan optimization.

Furthermore, comparative analysis of MTBF data across different models under the same brand and cross-brand workstations under identical operating conditions can provide guidance for equipment selection during the preliminary system design and procurement phases.

2.3.3 Software Service Phase

Software failure distribution characteristics differ from hardware, which can be characterized by a modified bathtub curve as shown in Figure 4.

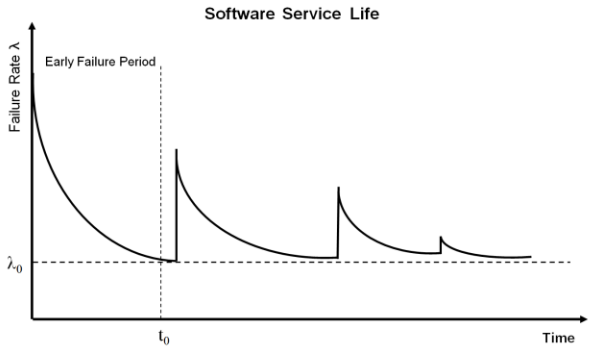

Figure 4. Modified Bathtub Curve of Software Failure Rate

(1) During the initial post-deployment phase, software typically exhibits a concentrated emergence of vulnerabilities and peak failure rates, attributable to factors including: ambiguous initial requirements, design deficiencies, coding errors, and insufficient testing;
(2) As maintenance activities progress, vulnerabilities are systematically addressed, leading to a gradual decline in failure rates that eventually stabilize at a low level;
(3) Changes in the operating environment, parameter adjustments, or human operations may introduce new vulnerabilities with latent periods that are difficult to detect. Failure modes manifest as abrupt mutations without warning, posing direct and cascading risks to software operation;
(4) The turning point timing depends on update frequency, system conditions, maintenance capacity, and can be forecasted via MTBF.

2.3.4 Application of RCM in Software Service phase

2.3.4.1 Historical Software Failure Data Analysis

Based on the severity of failure consequences, the author classifies software failures into four categories: S1-Catastrophic, S2-Critical, S3-Moderate, and S4-Minor, with classified statistics and analysis conducted for software failures occurring between 2018 and 2024, as detailed in Table 3.

Table 3. Statistical Table of Automation Software Failure Classification

Failure Level	**Definition**	**Failure Statistics**						
		2018	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**

S1 Catastrophic Failure	Complete loss of core system functionality.	0	0	0	0	0	0	0
S2 Critical Failure	Severe degradation of a major operational function.	0	0	0	0	0	1	0
S3 Moderate Failure	Partial impairment of a non-critical function; resolvable without affecting primary operations.	2	3	8	3	2	2	0
S4 Minor Failure	No functional impact, but causes slight operational inconvenience.	2	8	4	5	4	2	4
MTBF（h）		2190	796	730	1095	1460	1752	2190
Annualized Failure Rate λ（%）		0.05	0.13	0.14	0.09	0.07	0.06	0.05
7-year MTBF（h）		1459						

The above statistics indicate that the automation software system maintained stable operation throughout the 7-year period, with no S1-catastrophic failures attributable to software causes. The system achieved a high-reliability MTBF of 1,459 hours (≈60.8 days). S3-moderate failures exhibited an MTBF of 3,066 hours (≈127.8 days), with failure points concentrated in functional modules. S4-minor failures showed an MTBF of 2,108 hours (≈87.8 days), primarily occurring in non-functional module exceptions.

2.3.4.2 Classification of Software Maintenance Activities and Maintenance Strategies

Based on operational maintenance data of an automation system software from 2018 to 2024 (see Table 4), corrective maintenance accounted for merely 19% of the total maintenance workload, while perfective maintenance and adaptive maintenance constituted 55% and 26% respectively.

Table 4. Maintenance Workload Statistics for Automation System Software

	2018	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Technical Modifications	16	22	29	17	14	12	17
Software Patch Installation	0	3	5	2	3	0	4
New Software Deployment	0	3	3	2	1	1	1
Platform Reboot	2	4	7	6	4	0	2

Software Failure	4	11	12	8	6	5	4

The maintenance content and methodologies are illustrated in Figure 5.

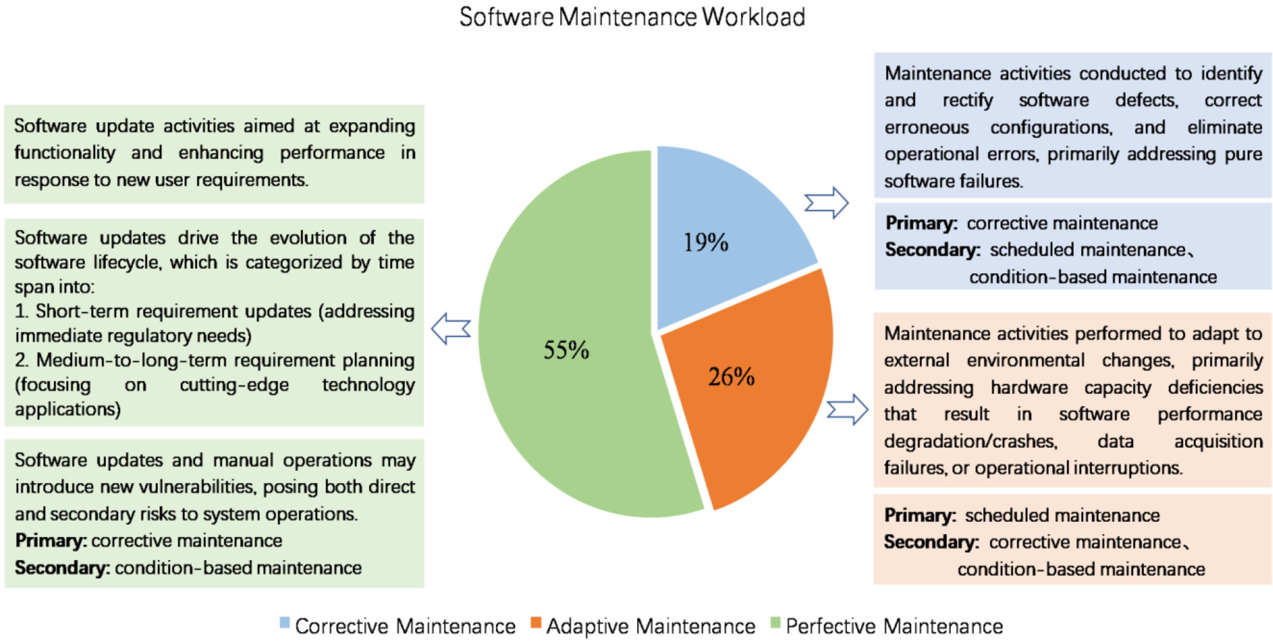

Figure 5. Pie Chart of Software Maintenance Workload Distribution

2.3.4.3 Maintenance Effectiveness

(1) Predicting the occurrence time of failures at each severity level based on MTBF metrics can enhance operators' risk awareness and proactive judgment capabilities.

(2) Through RCM-based quantitative analysis of high-frequency, high-impact issues across different software failure grades, maintenance personnel can accurately identify critical software vulnerabilities and develop targeted optimization strategies.

(3) Aggregated analysis and big data mining of regional RCM results can provide data support and decision-making basis for modular upgrades of automation system software.

2.4 Final Phase Management of ATM Automation Systems

The final phase refers to the stage when an automation system continues to operate and provide services despite approaching or exceeding its designed or normal service life, during which system reliability declines while safety risks increase significantly.

During this phase, continuous system performance monitoring shall be implemented, with the following management actions recommended:

(1) Based on RCM analysis results during the service period, predict degradation trends and anticipate failure timepoints, locations, and impacts. For components with high failure rates and critical parts, ensure adequate spare parts inventory and perform advance maintenance.

(2) Implement appropriate updates, retrofits, or rebuilds as needed to maintain system reliability levels.

(3) If equipment performance can no longer meet operational requirements, decommissioning measures shall be implemented.

2.5 **Summary and Outlook**

2.5.1 By adopting the RCM methodology to guide operational maintenance during the service period in lifecycle, quantitative analysis of system hardware and software reliability metrics is conducted to optimize maintenance strategies. This approach significantly enhances system reliability, ensures efficient resource utilization, improves operational efficiency, and reduces costs, thereby providing practical references for lifecycle management.

2.5.2 Further research on this management model will effectively elevate the operational maintenance capabilities of ATM automation systems across the Asia-Pacific region, offering scientific recommendations and guidance for the periodic inspection and preventive maintenance of ATM automation systems, as well as for the formulation of relevant standards and specifications.

3 ACTION BY THE MEETING

3.1 The meeting is invited to:

a) note the information contained in this paper; and

b) discuss any relevant matter as appropriate

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Introduction to RCM Theory

Reliability-Centered Maintenance (RCM) is a maintenance strategy that determines optimal maintenance plans based on system functionality, failure modes, and failure consequences, following the principle of cost-effectiveness. Using logical decision-making methodologies, it defines the required maintenance tasks, types, intervals, and levels for equipment, thereby optimizing maintenance operations.

1. Basic Principles of RCM:

（1） The reliability and safety of equipment are inherent characteristics determined by design and manufacturing. Maintenance can only preserve but cannot improve this intrinsic level.

（2） Different failure modes have varying impacts or consequences, necessitating tailored maintenance strategies.

（3） Failures follow distinct occurrence and progression patterns, requiring differentiated maintenance approaches.

（4） Equipment varies in resource consumption, cost, complexity, and maintenance depth. Maintenance strategies should be adapted to conserve resources and reduce costs while ensuring reliability and safety.

2. Reliability-Centered Maintenance Analysis (RCMA) Methodology

RCMA is a systematic methodology used to determine optimal maintenance strategies for equipment or systems, guiding preventive maintenance activities. It consists of the following four steps:

（1） Identify Critical Functional Equipment (CFE)：Classify equipment based on failure impacts and consequences. Equipment is designated as CFE if its failure could affect safety, system functionality, or result in significant economic losses.

（2） Failure Modes and Effects Analysis (FMEA)：Identify potential failure modes of CFE, analyze root causes, and evaluate impacts on performance, safety, production, and cost.

（3） Determine Maintenance Task Types：Apply a logic decision diagram to select targeted, cost-effective, and feasible preventive maintenance strategies.

（4） Establish Maintenance Intervals：Define appropriate maintenance intervals through statistical analysis of failure data, balancing equipment reliability and maintenance costs.

3. Key Metrics and Calculation Methods for RCM

Key metrics for evaluating system reliability in RCM include: Mean Time Between Failures (MTBF)、Failure Rate (λ)、Mean Time To Repair (MTTR).

（1） MTBF：

MTBF describes the average time between two consecutive failures of a repairable device, measured in hours. This metric reflects the device's ability to maintain stable performance and functionality over a specified period, with higher values indicating better reliability. It is typically calculated by dividing the total operational time of the device by the number of failures observed during that period.

$$\mathrm{MTBF} = \frac{1}{N}\sum_{i=1}^{n} t_i$$

Where:

t_i: Cumulative operating time of the *i*-th test unit (in hours)；

N: Total count of failures occurring across all test units during the experimental period.

According to 《*Civil Aviation Air Traffic Control Automation System — Part 2: Technical Requirements*》, the MTBF values for surveillance data processing systems shall meet the following minimum hardware reliability requirements:

- ≥100,000 hours for both large-scale and medium/small-scale systems
- ≥10,000 hours for individual workstations

（2） Failure Rate：

Failure rate (λ) indicates the probability of a device failing within a unit time period, typically expressed in failures per hour (f/h) or failures per year (f/yr). It is calculated by dividing the number of failures by the total operational time. A lower failure rate corresponds to higher device reliability. This metric is applicable only to repairable equipment.

For equipment demonstrating exponential failure distribution characteristics, the MTBF is mathematically derived as the reciprocal of the failure rate.

$$\mathrm{MTBF} = \frac{1}{\lambda}$$

（3）MTTR：

MTTR quantifies the average time required to restore a system or equipment to normal operation following a failure, with smaller values indicating better performance. This metric serves as a critical indicator of maintenance efficiency and responsiveness. Expedited and effective repair operations can substantially reduce downtime, thereby playing a pivotal role in ensuring business continuity and minimizing operational costs. The standard computational methodology involves dividing the aggregate repair time of all failures by the total number of failure incidents.

$$\mathrm{MTTR} = \frac{1}{N}\sum_{i=1}^{m} t_i$$

Where:

t_i: Cumulative repairing time of the i-th device (in hours);

N: Total count of failures occurring across all test units during the experimental period.

The cumulative repair time for each equipment unit shall be computed based on a complete repair cycle, encompassing the following temporal components:

（1） Maintenance team response time (t_response)

（2） Preparation time (t_prep)

（3） Fault diagnosis time (t_diag)

（4） Spare parts acquisition time (t_parts)

（5） Disassembly time (t_disass)

（6） Component replacement time (t_replace)

（7） Reassembly time (t_reass)

（8） Alignment/calibration time (t_align)

（9） Verification testing time (t_test)

（10） System restart time (t_restart)

（11） Documentation time (t_doc)

Where:

t_repair = Σ(t_response → t_doc) represents the total elapsed time for a single repair event.

4. RCM Failure Classification and Logic Decision Diagram

RCM theory classifies failure consequences into four categories: safety and environmental consequences, hidden failure consequences, operational consequences, and non-operational consequences. Based on the severity of failure impacts, the logic decision diagram is constructed as shown below (see Figure 1):

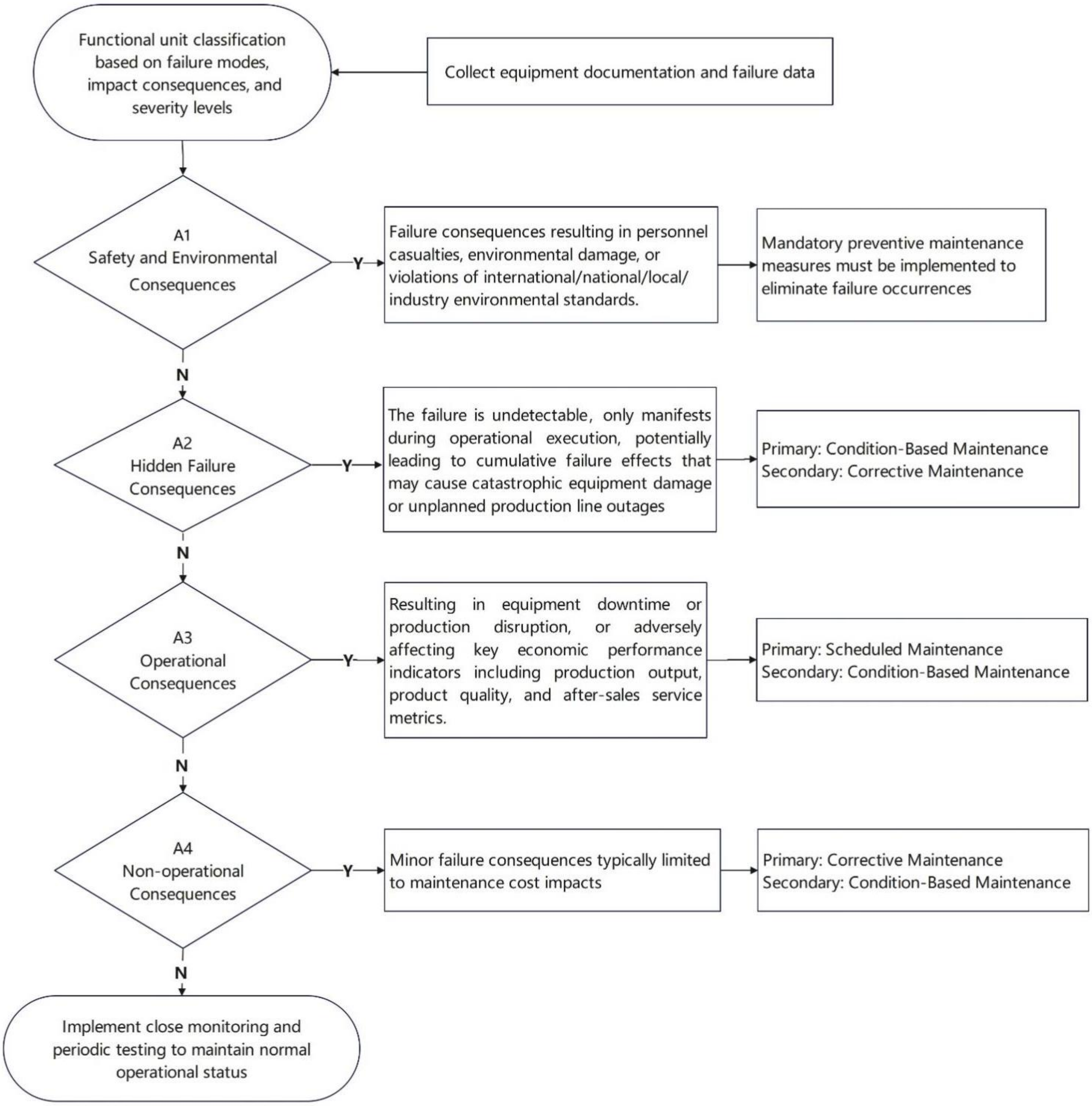

Figure 1. RCM Logic Decision Diagram