

A Risk-based Method for Selecting Ship Machinery Maintenance Strategies

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ABSTRACT: Ship machinery maintenance must balance safety, reliability, availability, regulatory compliance and cost under operational constraints and frequently incomplete data. Conventional approaches based on fixed maintenance intervals, corrective intervention or isolated condition monitoring remain necessary, but they do not provide a consistent basis for selecting among alternative maintenance strategies when failure likelihood, consequence severity, equipment condition, uncertainty, feasibility and cost interact. This paper proposes an integrated risk-based method for selecting maintenance strategies at machinery, component and failure-mode level. Failure-mode analysis, reliability and conditional probability assessment, condition evidence, consequence assessment, risk classification and uncertainty treatment provide structured inputs to a Maintenance Decision Engine. Candidate strategies - including corrective, time-based preventive, condition-based, predictive, risk-based, opportunity and deferred maintenance - are first screened against statutory, classification, manufacturer, safety and technical constraints. Only admissible alternatives proceed to multi-criteria ranking using the Technique for Order Preference by Similarity to Ideal Solution. The ranking considers expected risk reduction, technical suitability, reliability and availability contribution, implementation feasibility, expected total cost, and evidence confidence. Ranking margins and sensitivity analysis are used to assess robustness, while post-ranking engineering review confirms, modifies or overrides the numerical recommendation according to condition, risk urgency, redundancy and operational feasibility. The selected strategy is then converted into a traceable maintenance action and recorded through the planned or computerised maintenance management system. The principal contribution is the integration of established engineering methods within a constrained, transparent and auditable maintenance decision process.

1 INTRODUCTION

Ship machinery maintenance directly affects safety, environmental protection, reliability, availability, regulatory compliance and the commercial performance of a vessel. Marine machinery operates under variable loads, environmental exposure, limited repair opportunities and demanding voyage schedules. Maintenance decisions must therefore account not only for equipment age or scheduled intervals, but also for the consequences of failure,

current technical condition, available redundancy, operational requirements and the feasibility of intervention. Maintenance practice has consequently developed from predominantly corrective and time-based approaches towards reliability-centred, condition-based, predictive and risk-based strategies intended to improve deterioration detection, intervention timing and the allocation of maintenance resources [18, 19, 21].

Condition monitoring provides important evidence of actual machinery state through methods such as vibration analysis, lubricating-oil analysis, thermography, ultrasonic testing, performance monitoring and process-parameter trending. These techniques can identify developing degradation before functional failure and can support more appropriate maintenance timing than fixed intervals alone [13]. Planned maintenance systems and computerised maintenance management systems, referred to collectively in this paper as PMS/CMMS, also improve the recording of running hours, work orders, defects, spare-parts consumption, inspection findings and completed maintenance. Their value, however, depends on data quality, consistent reporting and the extent to which recorded information is subsequently used in technical decision-making [22, 23].

The availability of additional data does not in itself determine which maintenance strategy should be selected. Possession of condition-monitoring equipment, machinery-performance records and a functioning PMS/CMMS does not guarantee a transparent procedure for choosing between corrective, preventive, condition-based, predictive or risk-based intervention. Condition information must be interpreted in relation to a defined failure mode, decision interval, deterioration mechanism and consequence of failure. Similarly, a calculated probability of failure has limited decision value unless it is considered together with redundancy, operational context, cost, compliance requirements and the practical opportunity to perform the work. Data-driven maintenance therefore depends not only on analytical capability, but also on reliable data, competent interpretation, organisational processes and clear action rules [5, 20].

Several established engineering methods can support individual parts of this problem. Failure Mode and Effects Analysis and Failure Mode, Effects and Criticality Analysis provide a structured basis for defining functions, failure modes, causes, effects and existing controls. Fault-tree analysis can represent causal pathways, while reliability analysis and the Weibull distribution can estimate survival and failure probability where suitable operating and failure records are available. Condition-monitoring evidence can modify the assessment of current failure likelihood, and consequence analysis can determine the potential effects on safety, environment, asset condition, availability, cost and compliance. Risk matrices, Monte Carlo simulation, Bayesian methods and other probabilistic approaches can further assist where uncertainty or conditional dependence must be considered [6, 17].

These methods nevertheless tend to address separate stages of the maintenance problem. Failure analysis identifies potential failure modes, reliability analysis estimates how failure behaviour changes with time, and condition monitoring indicates whether degradation is developing. Risk assessment establishes priority, while cost and feasibility analysis determine whether a proposed intervention can be implemented. None of these outputs independently establishes which maintenance strategy is both technically admissible and preferable under the complete set of safety, operational, economic and regulatory constraints. A further decision layer is therefore

required to convert the outputs of established analyses into a defensible strategy and a practical maintenance action.

A significant issue is the treatment of mandatory constraints. A strategy that conflicts with a statutory requirement, classification condition, manufacturer instruction, company procedure or immediate safety requirement cannot be considered acceptable merely because it has lower cost or greater operational convenience. Such constraints should be applied before alternatives are compared numerically. Otherwise, an inadmissible strategy could remain within the decision matrix and compensate for poor technical or regulatory performance through favourable scores against less important criteria. Maintenance-strategy selection should therefore distinguish between the admissibility of an alternative and its relative performance after admissibility has been established.

Multi-criteria decision-making provides a suitable basis for comparing the remaining alternatives because maintenance strategies must be evaluated against several competing criteria. The Technique for Order Preference by Similarity to Ideal Solution, or TOPSIS, enables alternatives to be ranked according to their proximity to an ideal performance profile and their distance from a least-desirable profile. It can accommodate benefit and cost criteria expressed in different units and produces a transparent preference index for each alternative [4, 8]. TOPSIS has also been used in marine and offshore maintenance-strategy selection, supporting its relevance to decisions involving technical, operational and economic criteria [3, 16]. However, a numerical ranking alone should not be treated as a final engineering decision. The result remains sensitive to criterion definitions, scores, weights, evidence quality and the operating assumptions used in the assessment.

This paper therefore proposes an integrated risk-based method for selecting ship-machinery maintenance strategies. The method is applied at component or failure-mode level and is centred on a Maintenance Decision Engine. Engineering analyses provide structured inputs describing the failure mode, current condition, likelihood, consequence, risk, uncertainty, cost and feasibility. The engine first removes strategies that are legally, technically or operationally inadmissible. It then ranks the admissible alternatives using TOPSIS and evaluates the stability of the ranking through ranking-margin and sensitivity analysis. A post-ranking engineering review subsequently considers mandatory requirements, condition development, risk urgency, redundancy, operational continuity and implementation feasibility before the preferred strategy is converted into a specific maintenance action.

The contribution of the proposed method is not the isolated use of FMEA/FMECA, Weibull analysis, risk matrices, condition monitoring or TOPSIS, all of which are established techniques. Its contribution lies in combining these methods within a controlled and traceable decision process. Engineering evidence and risk assessment first establish the technical basis of the decision. Candidate maintenance strategies are then screened against mandatory requirements before the admissible alternatives are compared using multi-

criteria ranking. The robustness of the ranking is subsequently examined, after which engineering review and, where necessary, override determine the final maintenance action. The selected action and its outcome are then recorded through PMS/CMMS feedback.

This structure distinguishes the reasons for excluding a strategy from the assessment of how admissible strategies perform and from the subsequent decision on implementation. It also ensures that a numerical ranking cannot supersede statutory, classification, manufacturer or safety requirements.

2 INTEGRATED RISK-BASED MAINTENANCE DECISION MODEL

2.1 Framework Architecture, Scope and Inputs

The proposed model converts established engineering analyses into a structured process for selecting ship-machinery maintenance strategies. It is applied at machinery-system, component or failure-mode level, where the assessment boundary, available evidence, operating context and decision interval can be defined. Maintenance decisions are based on the combined influence of failure likelihood, consequence severity, current condition, operational feasibility, cost and mandatory requirements. FMEA/FMECA provides the failure-mode structure, reliability analysis estimates failure likelihood where suitable data are available, condition monitoring describes the current technical state, and consequence assessment establishes criticality and risk. These outputs are supplied to the Maintenance Decision Engine, which screens candidate strategies, compares the admissible alternatives and supports selection of an implementable maintenance action. The method therefore combines the principles of risk-based and reliability-centred maintenance with uncertainty treatment, operational constraints and PMS/CMMS feedback.

The framework comprises four connected layers. The evidence and constraint layer consolidates equipment, maintenance, operating, condition, cost

and mandatory-requirement data and records their quality. The engineering-analysis layer converts these inputs into failure-mode, likelihood, condition, consequence and risk assessments. The Maintenance Decision Engine removes inadmissible strategies and compares the remaining alternatives against risk reduction, technical suitability, reliability and availability, implementation feasibility, expected cost and evidence confidence. The implementation and feedback layer translates the selected strategy into an action, priority, timing and temporary controls, while PMS/CMMS outcomes update subsequent assessments. Figure 1 presents the complete framework.

The central position of the Decision Engine distinguishes the proposed framework from a sequential collection of maintenance tools. The surrounding analytical methods provide evidence and constraints, while the Decision Engine performs the formal comparison and selection.

2.1.1 Scope, boundaries and assumptions of the model

The model supports operational-phase maintenance decisions at machinery-system, component or failure-mode level. The assessment unit comprises a defined function, item, failure mode, operating context and decision interval. This boundary must be detailed enough to connect maintenance history, condition evidence, likelihood, consequence, redundancy and available actions to a specific decision while remaining practical for PMS/CMMS use.

The method is suitable where deterioration, failure history or condition evidence can be observed and technically feasible maintenance responses identified. It operates within the PMS/CMMS, Safety Management System, statutory obligations, classification requirements, manufacturer instructions and company procedures, which remain mandatory constraints. Any deferral or modification of a prescribed task remains subject to the applicable technical and organisational approval process.

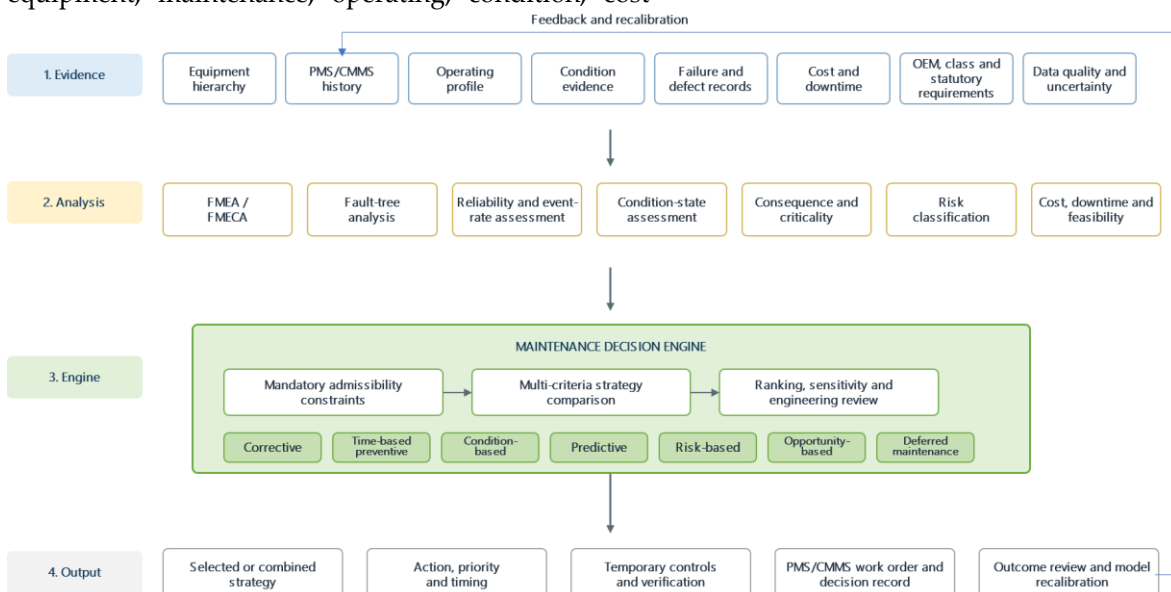


Figure 1 Architecture of the Integrated Risk-Based Maintenance Decision-Support Framework. Source: author, informed by [10, 13–15, 18, 21].

The method assumes that the assessment boundary and failure mode can be defined, that relevant engineering evidence is available, and that the possible consequences can be assessed in relation to safety, environment, asset damage, operational availability, cost, compliance or commercial effect. Evidence can be quantitative or qualitative and includes running hours, maintenance and defect history, inspection findings, condition-monitoring results, failure records and documented engineering judgement. A practical decision interval must also be specified, such as the period until the next port call, inspection, running-hour threshold, maintenance opportunity or dry-docking. Likelihood, risk and the resulting maintenance response are interpreted in relation to this interval.

The method concerns operational maintenance decision-making and does not address ship design, construction, major conversion, disposal or recycling. It is not a complete accident-causation model, although risk and consequence reasoning are used to identify maintenance priorities and required controls.

2.1.2 Model inputs, data requirements and equipment selection

The model uses quantitative and qualitative maintenance, operational and condition evidence. Quantitative inputs include running hours, failure dates, maintenance intervals, repair duration, cost, downtime and condition-monitoring measurements. Qualitative inputs include inspection comments, defect descriptions, crew observations, survey findings, manufacturer recommendations and engineering judgement. These inputs support definition of the assessment boundary and failure mode, estimation of likelihood and consequence, risk classification, maintenance-strategy comparison, feasibility assessment and subsequent PMS/CMMS feedback. The selected equipment item or failure mode should have a clearly defined function, a technically meaningful failure mechanism and potential safety, environmental, operational, compliance, asset or commercial consequences. Sufficient maintenance, failure or condition evidence should be available to support the assessment, and a practical decision interval and feasible maintenance responses must be identifiable. The result should also be capable of being recorded, implemented and reviewed through the PMS/CMMS.

Table 1 summarises the required data, their typical sources and their role in the model.

Before assessment, records are screened for completeness, consistency and relevance. Where the available data do not support quantitative reliability analysis, likelihood classes, manufacturer or fleet evidence, conservative assumptions and documented engineering judgement are used. Isolated condition measurements are interpreted qualitatively unless supported by a reliable trend, while incomplete cost data are used for relative rather than falsely precise comparison.

Table 1 Data requirements for the proposed maintenance strategy model

Data category	Main data required	Typical source	Use in the model
Equipment identification	System, component, tag number, maker, model, function, installation details	PMS/CMMS, manuals, drawings, equipment register	Defines the assessment boundary
Maintenance history	Planned jobs, completed jobs, overdue jobs, maintenance interval, task content, previous repairs	PMS/CMMS, work orders, maintenance reports	Supports maintenance history review and interval assessment
Running data	Running hours, calendar age, starts/stops, duty cycle, load profile, standby/continuous use	PMS/CMMS, engine logs, automation system, logbooks	Supports likelihood and Weibull assessment
Failure and defect data	Failure date, failure mode, defect description, corrective action, recurrence, downtime	Defect reports, corrective work orders, incident reports, chief engineer reports	Supports failure-mode definition and probability assessment
Condition evidence	Vibration, oil analysis, thermography, pressure, temperature, flow, visual inspection, class/manufacturer findings	Condition-monitoring systems, inspection reports, survey reports, laboratory reports	Supports condition interpretation and likelihood adjustment
Consequence information	Safety effect, environmental effect, operational effect, asset damage, compliance effect, commercial effect	Risk assessment, incident records, class/SMS requirements, technical judgement	Supports consequence and criticality assessment
Cost and feasibility data	Spare parts, repair cost, service attendance, repair duration, off-hire, port opportunity, dry-docking opportunity	Purchasing records, superintendent reports, quotation records, voyage plan, dock plan	Supports cost, downtime and feasibility assessment
Compliance requirements	Class requirements, statutory requirements, manufacturer instructions, company procedures, critical-equipment status	SMS, class rules, manuals, circulars, company procedures	Defines mandatory constraints and escalation requirements
Feedback data	Selected action, decision rationale, implemented work, outcome, revised interval, next review date	PMS/CMMS, close-out reports, superintendent review	Supports model updating and organisational learning

Source: author.

2.1.3 Equipment breakdown and failure-mode definition

Before likelihood and consequence are assessed, machinery is decomposed to the lowest level that supports a specific and traceable maintenance decision. The hierarchy can include system, subsystem, component, itemised part and failure mode and should follow the existing PMS/CMMS structure where practical.

Each item is defined by its required function and operating conditions. A failure mode describes the

specific manner in which the function is lost or degraded and must be distinguished from both symptoms and causes. For example, high temperature is a symptom, reduced cooling capacity is a failure mode, and fouling or pump degradation are possible causes.

Failure modes are identified from vessel records, manuals, condition reports, survey findings, crew observations and comparable engineering evidence. For each mode, the assessment records its causes, local, system and vessel-level effects, and existing preventive, detective or mitigating controls.

The resulting failure-mode register contains equipment identification, function, failure mode, causes, effects, controls, evidence source and confidence, decision interval and feasible responses. It follows FMEA/FMECA logic to structure the evidence, while criticality is determined subsequently through consequence and risk assessment.

2.2 Reliability, Uncertainty and Risk Assessment

The model uses a tiered approach to likelihood assessment. Where sufficient failure and survival data are available, reliability analysis is applied, with the Weibull distribution used to estimate reliability and failure probability. Where the available records do not support quantitative estimation, condition evidence, maintenance history and engineering judgement are used to assign a semi-quantitative likelihood class.

Likelihood is assessed over a defined decision interval expressed in running hours, calendar time, voyage duration or the period until the next port, inspection or maintenance opportunity. The selected time basis should reflect the relevant failure mechanism: running hours are generally appropriate for use-dependent deterioration, while calendar time is more suitable for age-dependent processes. Where both are relevant, both should be considered and the more conservative interpretation applied.

Reliability is the probability that an item will perform its required function for a specified period under stated conditions. For a non-repaired item or a component considered between maintenance interventions, reliability at time t can be expressed as:

$$R(t) = P(T > t) \quad (1)$$

where $R(t)$ is the reliability at time t , and T is the time to failure.

Reliability estimates are conditional on the operating profile, maintenance history, component age, environmental conditions, data quality and similarity of the supporting dataset. The calculated value should therefore be recorded together with its evidence source and confidence level.

The probability of failure by time t is the complement of reliability. It is expressed as:

$$F(t) = 1 - R(t) \quad (2)$$

where $F(t)$ is the cumulative probability of failure by time t .

For maintenance planning, the most useful probability is often the probability that the item will fail during the next interval, given that it has survived until the present time. This is expressed as:

$$P_f(t, \Delta t) = 1 - \frac{R(t + \Delta t)}{R(t)} \quad (3)$$

where $P_f(t, \Delta t)$ is the probability of failure during the interval from t to $t + \Delta t$, $R(t)$ is the reliability at the current running time or age, and $R(t + \Delta t)$ is the reliability at the end of the decision interval.

This formulation connects reliability analysis with practical maintenance timing because the relevant question is whether the component can continue operating through the selected interval rather than whether it will eventually fail. The interval should therefore correspond directly to the maintenance decision being considered.

The Weibull distribution is selected as the main quantitative reliability model because it is widely used in lifetime reliability and maintenance engineering. It is flexible and can represent different failure behaviours, including early failures, random failures and wear-out failures.

For the proposed model, the two-parameter Weibull reliability function is expressed as:

$$R(t) = \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (4)$$

where β is the shape parameter, and η is the scale parameter or characteristic life.

The corresponding cumulative probability of failure is:

$$F(t) = 1 - \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (5)$$

The conditional probability of failure during the next decision interval can therefore be written as:

$$P_f(t, \Delta t) = 1 - \exp \left[- \left(\left(\frac{t + \Delta t}{\eta} \right)^\beta - \left(\frac{t}{\eta} \right)^\beta \right) \right] \quad (6)$$

The Weibull hazard rate provides an additional indication of the failure tendency over time:

$$h(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \quad (7)$$

where $h(t)$ is the instantaneous failure rate at time t .

The mean time to failure for the two-parameter Weibull distribution is:

$$MTTF = \eta \Gamma \left(1 + \frac{1}{\beta} \right) \quad (8)$$

where Γ is the gamma function.

The shape parameter β describes the failure tendency. Values below 1 indicate a decreasing failure rate associated with early-life or installation-related failures; values close to 1 indicate an approximately constant failure rate; and values above 1 indicate increasing failure tendency associated with ageing, wear, fatigue, corrosion, fouling or similar deterioration. The scale parameter η represents the characteristic life, at which the cumulative failure probability of the two-parameter Weibull distribution is approximately 63.2%.

Weibull parameters are application-specific and should be interpreted in relation to load, operating profile, environmental exposure, maintenance quality and other relevant conditions. Where vessel-specific records are insufficient, fleet data, manufacturer information, published evidence or documented engineering judgement can provide provisional inputs, provided that the source and uncertainty are recorded.

Quantitative estimation requires operating time, failure or replacement dates, component age, repair history and censored observations representing items that have survived for a known period without failure. Where sufficient failure and survival data exist, Weibull parameters can be estimated through maximum likelihood estimation, probability plotting or suitable reliability software. Estimates based on small samples should be treated as provisional, supported by sensitivity analysis and reported together with the underlying data basis and confidence level.

Condition evidence—including vibration, lubricating-oil analysis, thermography, process parameters, inspection findings and manufacturer recommendations—can indicate that actual equipment condition is better or worse than expected from age or running hours alone. This evidence is therefore used to support or modify the reliability-based estimate. A worsening and well-supported trend can justify a higher likelihood class, while stable repeated measurements can support retaining or, where technically justified, reducing the assigned class. Every modification should be supported by a recorded engineering justification.

Where failure history is insufficient for defensible quantitative analysis, likelihood is assigned using the semi-quantitative scale in Table 2. The classification should consider running hours, maintenance and defect history, condition evidence, manufacturer guidance, fleet experience and documented engineering judgement. The probability bands are indicative thresholds for the selected decision interval and can be mapped to an existing company-approved likelihood scale.

The scale does not replace an approved SMS or company risk-assessment procedure. Where an existing likelihood classification is already used, it can be mapped to the proposed model. The assigned class must correspond to the defined decision interval because the same component can have different likelihood levels over the period to the next port call, scheduled maintenance or dry-docking.

Table 2 Proposed likelihood classes for the model

Likelihood class	Description	Indicative probability within the decision interval	Typical evidence
1 – Very Low	Failure is credible but unlikely within the decision interval	< 1%	No defects, stable condition trend, recent maintenance, low running hours
2 – Low	Failure is possible but not expected within the decision interval	1-5%	Minor concerns, stable or slowly changing condition, adequate controls
3 – Moderate	Failure may occur within the decision interval	5-15%	Moderate running hours, recurring minor defects, uncertain condition evidence
4 – High	Failure is a realistic concern within the decision interval	15-30%	Deteriorating trend, repeated defects, overdue maintenance, reduced confidence
5 – Very high	Failure is expected unless action is taken	> 30%	Severe degradation, alarms, repeated failure, clear defect, ineffective controls

Source: author.

2.2.1 Uncertainty treatment

Maintenance decisions frequently rely on incomplete records, limited failure histories, uncertain condition evidence and changing operating circumstances. Relevant uncertainty concerns data quality, reliability parameters, condition measurements, consequence judgement, cost, feasibility, operating context and model assumptions. These uncertainties are addressed through screening, confidence classification, ranges or probability distributions, scenario analysis, sensitivity testing and conservative engineering judgement.

Evidence is classified as having high, medium or low confidence. High-confidence records support quantitative reliability analysis; medium-confidence evidence requires interpretation and sensitivity testing; and low-confidence evidence supports semi-quantitative likelihood classes, conservative assumptions or scenario analysis rather than unsupported statistical precision.

Where uncertain inputs can be represented by defensible ranges or probability distributions, Monte Carlo simulation produces distributions of failure probability, risk or expected cost rather than a single point estimate [24, 25]. Where distributions cannot be justified, normal, adverse and conservative scenarios are used.

Sensitivity analysis identifies the assumptions that most strongly influence the recommendation. A result that remains stable under plausible variations is regarded as robust, whereas a materially changing result requires additional evidence, revised assumptions or a more conservative decision. The essential requirement is that uncertainty is explicitly recorded and treated in proportion to the available evidence.

2.2.2 Consequence and criticality assessment

Consequence is assessed separately from likelihood to avoid double counting and preserve the transparency of the risk calculation. The likelihood module estimates whether the failure mode can occur within the selected decision interval, while the consequence assessment determines the severity of the resulting effects. A low-probability failure can therefore require urgent attention where its credible consequences are severe, while a more frequent failure can remain manageable where effects are limited and effective controls are available.

Consequence is assessed across seven categories: safety, environmental impact, asset damage, operational availability, financial cost, class or statutory compliance, and commercial or reputational effect. The assessment considers both local component effects and wider system- or vessel-level effects, including loss of function, reduced redundancy, delay, off-hire, pollution exposure and compliance consequences.

Redundancy and existing barriers can reduce consequence only where their availability, independence and suitability for the relevant operating condition are verified. Standby equipment should not be assumed effective where it is unavailable, defective, overloaded or exposed to the same common-cause failure. Consequence should also reflect the operating context, including manoeuvring, restricted waters, cargo operations, high load, reduced redundancy, remote operation and the time until external support or repair is available. The assessment therefore uses the same decision interval and operational assumptions as the likelihood module.

Table 3 defines a five-level consequence scale in which 1 represents very low consequence and 5 represents very high consequence. The scale supports consistent classification and subsequent combination with the likelihood result.

For each failure mode, the analyst should assign a score to each consequence category. The model then uses the maximum credible consequence score as the primary consequence score:

$$C_i = \max(C_{i,1}, C_{i,2}, \dots, C_{i,m}) \quad (9)$$

where C_i is the consequence score for failure mode i , $C_{i,k}$ is the score assigned to consequence category k , and m is the number of consequence categories considered.

The maximum credible consequence is used because it prevents severe safety, environmental or compliance effects from being diluted by lower scores in other categories. A failure mode is therefore not treated as having low criticality merely because its direct repair cost or local equipment damage is limited.

Where a company already uses an approved weighted consequence method, the weighted score is calculated as:

$$C_i^w = \sum_{k=1}^m w_k C_{i,k}, \quad \sum_{k=1}^m w_k = 1 \quad (10)$$

where C_i^w is the weighted consequence score and w_k is the weighting assigned to consequence category k .

Table 3 Consequence categories and scoring criteria for the proposed model

Consequence category	1 - Very low	2 - Low	3 - Moderate	4 - High	5 - Very high
Safety	No injury or material exposure	First aid or minor unsafe condition	Medical treatment or lost-time injury potential	Serious injury or multiple-person exposure	Fatality or multiple serious-injury potential
Environmental	No release	Small contained leak	Reportable minor release requiring shipboard response	Significant pollution requiring external response	Major pollution or severe environmental damage
Asset damage	No damage	Minor repair by or minor ship staff adjustment	Planned repair or service attendance	Major system or consequential damage	Catastrophic machinery or major-system loss
Operational availability	No operational effect	Minor manageable delay	Reduced redundancy or restricted operation	Off-hire, or repair at next port	Vessel unfit to proceed or loss of essential function
Financial cost	Negligible routine cost	Low normal-budget repair cost	Moderate repair, service or downtime cost	High emergency, logistics or off-hire cost	Major claim, salvage or extended off-hire exposure
Class, statutory and compliance	No effect	Minor documentation issue	Deficiency requiring planned correction	Condition of class, PSC deficiency or critical-equipment non-conformity	Detention, loss of class or major statutory non-compliance
Commercial and reputational	No effect	Minor administrative or customer inconvenience	Voyage delay or service disruption	Significant charter, cargo, customer reputation effect	Major contractual, reputational or market-access consequence

Source: author.

The model therefore applies the maximum credible consequence unless an approved weighted method is already established within the company's risk-management system. A failure mode is classified as critical where any category receives a high or very high score, where the affected equipment is designated as critical under the SMS, where class or statutory compliance is involved, or where failure can lead to loss of an essential ship function.

2.2.3 Risk estimation and classification

Risk is estimated by combining the likelihood of failure within the decision interval with the corresponding consequence assessment. This preserves the distinction between how likely a failure is and how severe its effects would be. A frequent but low-consequence failure is generally addressed through monitoring or planned intervention, whereas a low-probability failure with severe safety,

environmental, compliance or essential-function consequences is subject to escalation or immediate control.

When a numerical probability of failure is available, the risk value for failure mode i can be expressed as:

$$R_i = P_i \times C_i \quad (11)$$

where R_i is the numerical risk value for failure mode i , P_i is the probability of failure within the selected decision interval, and C_i is the consequence value or consequence score.

Where consequence is expressed monetarily, the result represents an expected failure consequence. Where a consequence score is used, the result is a relative risk value intended for transparent comparison rather than a precise monetary estimate.

Where likelihood is expressed as a class rather than as a numerical probability, the semi-quantitative risk score is calculated as:

$$RS_i = L_i \times C_i \quad (12)$$

where RS_i is the semi-quantitative risk score for failure mode i , L_i is the likelihood class, and C_i is the consequence score.

This formulation supports applications where available failure and operating records do not justify a numerical probability estimate. The likelihood and consequence scores must follow the defined scales and remain supported by recorded evidence and engineering judgement.

The risk category is assigned from the likelihood-consequence matrix:

$$RC_i = f(L_i, C_i) \quad (13)$$

where RC_i is the risk category for failure mode i and $f(L_i, C_i)$ represents the mapping defined in the risk matrix.

The proposed model uses a 5x5 likelihood-consequence matrix presented in Table 4. The likelihood scale follows Table 2, while the consequence scale follows Table 3. The product of the two values gives a risk score between 1 and 25.

Table 4 Proposed likelihood-consequence risk matrix

Likelihood class / Consequence score	1 - Very low	2 - Low	3 - Moderate	4 - High	5 - Very high
5 - Very high	5 Moderate	10 High	15 Very high	20 Very high	25 Very high
4 - High	4 Low	8 Moderate	12 High	16 Very high	20 Very high
3 - Moderate	3 Low	6 Moderate	9 Moderate	12 High	15 Very high
2 - Low	2 Low	4 Low	6 Moderate	8 Moderate	10 High
1 - Very low	1 Low	2 Low	3 Low	4 Low	5 Moderate

Source: author.

The matrix provides a consistent classification for the proposed model but does not replace an approved SMS, class or statutory risk-assessment procedure. Where an established company matrix exists, the

likelihood and consequence outputs can be mapped to that matrix before maintenance-strategy selection.

The resulting score is grouped into low, moderate, high and very high risk categories, as shown in Table 5. These categories identify the required attention, urgency and escalation level but do not independently select the final maintenance strategy or action. That selection is performed by the Maintenance Decision Engine.

Table 5. Risk bands and indicative maintenance response levels

Risk score band	Risk category	Meaning in the proposed model	Indicative maintenance response
1-4	Low	Risk is controlled by existing maintenance and monitoring arrangements.	Continue normal PMS/CMMS task, maintain routine monitoring and review at next planned interval.
5-9	Moderate	Risk is acceptable only with active monitoring or planned follow-up.	Increase monitoring, inspect at next suitable opportunity, review PMS interval or prepare spare parts.
10-14	High	Risk requires planned corrective action or management review within the decision interval.	Plan repair, replacement or overhaul; escalate to superintendent where operational or compliance effect is material.
15-25	Very high	Risk is not acceptable without prompt action, additional control or formal escalation.	Take urgent action, restrict operation, repair at earliest opportunity, stop or isolate equipment where required, and escalate to shore management, class or manufacturer where relevant.

Source: author.

A numerical likelihood-consequence product is insufficient where failure can affect safety, environmental protection, statutory or class compliance, or an essential ship function. A low likelihood must not suppress a severe credible consequence. The model therefore applies the following high-consequence review trigger:

$$C_i \geq 4 \Rightarrow \text{criticality review required} \quad (14)$$

The trigger is model-specific and corresponds to consequence scores of 4 and 5, representing high and very high consequence. It ensures that severe safety, environmental, compliance or essential-function effects receive explicit engineering review even where their calculated likelihood is low. Where an approved company or class-related procedure defines an equivalent threshold, that procedure can be mapped to the model.

High-consequence, low-probability failure modes are therefore assessed conservatively. The reviewer should consider the maximum credible consequence, verified redundancy, existing barriers, common-cause exposure and the operating context before accepting continued operation or deferral.

Uncertainty results should also inform the assigned risk category. Where Monte Carlo simulation or sensitivity analysis is used, the assessment should consider the range of outcomes and the probability of exceeding a risk threshold rather than relying only on a mean value. A risk category that changes materially under plausible assumptions indicates a sensitive

result and should prompt additional evidence, inspection or conservative treatment. Where quantitative analysis is not justified, the failure mode should be assessed under normal, adverse and conservative scenarios, and the selected response should remain acceptable under the plausible higher-risk condition.

2.3 Maintenance Decision Engine

The preceding modules convert reliability, condition, consequence, uncertainty and operational evidence into a classified risk position. This establishes the significance and urgency of the assessed failure mode but does not independently determine which maintenance strategy is most appropriate.

The Maintenance Decision Engine provides the formal strategy-selection stage of the framework. It first removes alternatives that are legally, technically or operationally inadmissible, then compares the remaining strategies through multi-criteria ranking. The preliminary recommendation is subsequently subjected to engineering review and converted into a specific action, priority, timing and control arrangement. The method therefore distinguishes strategy admissibility, comparative performance and practical implementation, preserving the reason for each exclusion, ranking and final decision.

2.3.1 Candidate maintenance strategies

The Decision Engine evaluates alternative maintenance strategies at failure-mode level. For each assessed failure mode i , the initial set of candidate strategies is defined as:

$$A_i = \{A_{i1}, A_{i2}, A_{i3}, A_{i4}, A_{i5}, A_{i6}, A_{i7}\} \quad (15)$$

where A_{i1} to A_{i7} represent corrective maintenance, time-based preventive maintenance, condition-based maintenance, predictive maintenance, risk-based maintenance, opportunity maintenance and deferred maintenance, respectively.

The initial set includes corrective, time-based preventive, condition-based, predictive, risk-based, opportunity and deferred maintenance. Corrective maintenance permits continued operation until a recognised defect or functional failure requires action and is principally suitable for low-criticality, adequately redundant items. Time-based preventive maintenance applies a predetermined calendar or running-hour interval, while condition-based maintenance initiates action from observed deterioration. Predictive maintenance estimates future condition, remaining useful life or failure probability from historical and current evidence. Risk-based maintenance determines priority from the combined likelihood and consequence of failure. Opportunity maintenance schedules technically appropriate work during a suitable operational, port, shutdown or dry-docking window. Deferred maintenance postpones action to a defined point subject to temporary controls, acceptance criteria and a review date.

Inclusion in the initial set does not establish technical suitability or permission to use the strategy. Alternatives that conflict with mandatory

requirements or lack the conditions necessary for effective implementation are removed during admissibility screening. Strategies can also be combined; for example, risk assessment establishes priority, condition monitoring determines the intervention point, and opportunity maintenance defines the execution window.

2.3.2 Strategy admissibility and mandatory engineering constraints

Before the candidate strategies are compared mathematically, the Decision Engine determines whether each strategy is admissible for the assessed failure mode. Admissibility is treated as a mandatory engineering constraint rather than as an ordinary weighted criterion. A strategy that is legally non-compliant, technically ineffective or operationally unsafe cannot compensate for that deficiency through lower cost or greater convenience.

$$g_{ij} = \begin{cases} 1, & \text{if strategy } j \text{ is admissible for failure mode } i, \\ 0, & \text{if strategy } j \text{ is inadmissible for failure mode } i. \end{cases} \quad (16)$$

Only strategies for which $g_{ij}=1$ proceed to the multi-criteria comparison. Every exclusion must be supported by a recorded technical, regulatory or operational justification.

The admissible strategy set for failure mode i is defined as:

$$A_i^{\text{adm}} = \{A_j \in A_i \mid g_{ij} = 1\} \quad (17)$$

Mandatory statutory, class, SMS, manufacturer and company requirements are assessed before numerical ranking. Where a requirement prescribes or necessitates a specific response, that response takes precedence regardless of cost, convenience or calculated likelihood. This applies particularly to critical equipment, protection systems, statutory deficiencies, class conditions, manufacturer limits and immediate safety concerns.

A mandatory response therefore bypasses the ranking procedure rather than being retained as an alternative with a low score. The Decision Engine records the applicable requirement, the resulting override and the authority responsible for the decision.

After the admissibility stage, the Decision Engine compares the remaining maintenance strategies against a common set of decision criteria. For failure mode i , the comparison is represented by a decision matrix:

$$X_i = [x_{jk}]_{m \times n} \quad (18)$$

where:

m is the number of admissible maintenance strategies;
 n is the number of decision criteria;
 x_{jk} is the performance score of maintenance strategy j against criterion k .

The decision matrix contains only admissible strategies. An excluded alternative is removed entirely rather than retained with a low score, preventing legal, safety or technical inadmissibility from being offset by favourable cost or convenience. The remaining

strategies are assessed against six criteria: expected risk reduction, technical suitability, reliability and availability contribution, implementation feasibility, expected total cost, and evidence confidence and traceability. These criteria translate the preceding reliability, condition, risk and feasibility outputs into the common comparison structure defined in Table 6.

Table 6. Decision criteria for maintenance-strategy comparison

Criterion	Definition	Direction
Expected risk reduction	Degree to which the strategy reduces failure likelihood, consequence exposure or both during the decision interval.	Benefit
Technical suitability	Compatibility of the strategy with the failure mechanism, degradation behaviour, detectability and available maintenance method.	Benefit
Reliability and availability contribution	Expected effect on functional reliability, equipment availability, redundancy and continuity of essential operations.	Benefit
Implementation feasibility	Practical ability to apply the strategy considering access, competence, spares, service support, operating condition and maintenance opportunity.	Benefit
Expected total cost	Direct maintenance cost together with expected downtime, off-hire, service, spare-parts and residual failure-cost exposure.	Cost
Evidence confidence and traceability	Extent to which the strategy is supported by reliable condition data, failure history, technical documentation and auditable decision evidence.	Benefit

Source: author, developed from the integrated risk, reliability, condition, cost and feasibility modules of the proposed framework and informed by marine maintenance-strategy selection research [7, 18].

Risk reduction, technical suitability, reliability and availability, implementation feasibility, and evidence confidence are benefit criteria, for which higher values are preferable. Expected total cost is a cost criterion, for which lower values are preferable. Quantitative values should be used where defensible; otherwise, the ordinal scale in Table 7 can be applied.

Table 7. Ordinal scoring scale for Decision Engine criteria

Score	Benefit-criterion interpretation	Expected-total-cost interpretation
1	Very poor or unsupported performance	Very low expected total cost
2	Poor performance	Low expected total cost
3	Moderate performance	Moderate expected total cost
4	Good performance	High expected total cost
5	Very good or strongly supported performance	Very high expected total cost

Source: author.

Ordinal scores must be supported by identifiable reliability results, condition evidence, risk classifications, technical requirements, maintenance history, feasibility constraints or cost estimates. Where the evidence does not justify a distinction between adjacent scores, the more conservative value should be selected and the uncertainty recorded.

Because the decision criteria can contain monetary values, operating hours and ordinal assessments, they are normalised before weighting.

For each criterion k , the normalised value is calculated as:

$$r_{jk} = \frac{x_{jk}}{\sqrt{\sum_{j=1}^m x_{jk}^2}} \quad (19)$$

where r_{jk} is the normalised performance of strategy j against criterion k .

Vector normalisation converts the criteria into dimensionless values while preserving their relative differences. Benefit and cost directions are subsequently reflected in the ideal-solution calculation.

Criterion weights represent the relative importance of each factor in the strategy comparison. The weighted normalised value is:

$$v_{jk} = w_k r_{jk} \quad (20)$$

where:

v_{jk} is the weighted normalised value;

w_k is the weight assigned to criterion k ;

r_{jk} is the normalised criterion value.

The weights are subject to:

$$\sum_{k=1}^n w_k = 1, \quad w_k \geq 0 \quad (21)$$

The criterion-weight vector is written as:

$$w = (w_1, w_2, \dots, w_n) \quad (22)$$

The weights w_k are established through documented expert elicitation, company policy or another structured weighting procedure. Their influence on the ranking is examined through sensitivity analysis.

Risk reduction and technical suitability should normally receive the greatest emphasis because the method seeks a technically defensible response rather than the lowest-cost alternative. The selected weights must be documented and tested through sensitivity analysis, and no weighting arrangement can compensate for unacceptable risk or technical incompatibility.

2.3.3 TOPSIS strategy-ranking procedure

TOPSIS is used because it can compare a limited set of admissible strategies against benefit and cost criteria expressed through different units or ordinal scales. The method ranks alternatives according to their proximity to a positive ideal solution and distance from a negative ideal solution, producing a transparent preference index [4, 8]. Its computational simplicity and suitability for sensitivity analysis are appropriate for the proposed Decision Engine, and previous marine and offshore studies have applied TOPSIS to maintenance-strategy selection [3, 16]. The ranking is performed only after admissibility screening and remains subject to engineering review.

After the criterion values have been normalised and weighted, the Decision Engine applies TOPSIS [8] to determine the ideal and least-desirable performance

profiles. The ideal profile represents the most desirable observed performance for each criterion among the admissible strategies, while the least-desirable profile represents the least favourable observed performance.

The positive ideal solution is defined as:

$$A^P = \{v_k^P\}, \quad v_k^P = \begin{cases} \max_j v_{jk}, & k \in B \\ \min_j v_{jk}, & k \in C \end{cases} \quad (23)$$

The negative ideal solution is defined as:

$$A^N = \{v_k^N\}, \quad v_k^N = \begin{cases} \min_j v_{jk}, & k \in B \\ \max_j v_{jk}, & k \in C \end{cases} \quad (24)$$

The criterion sets used in the ideal-solution definitions are:

$$\begin{aligned} B &= \{k | k \text{ is a benefit criterion}\}, \\ C &= \{k | k \text{ is a cost criterion}\} \end{aligned} \quad (25)$$

For benefit criteria, the positive ideal is the highest weighted normalised value and the negative ideal is the lowest; this relationship is reversed for expected total cost. A strategy is therefore favoured only where it performs satisfactorily against the technical and risk-related criteria as well as cost.

The separation of each strategy from the positive ideal solution is calculated as:

$$S_j^P = \sqrt{\sum_{k=1}^n (v_{jk} - v_k^P)^2} \quad (26)$$

The separation from the negative ideal solution is calculated as:

$$S_j^N = \sqrt{\sum_{k=1}^n (v_{jk} - v_k^N)^2} \quad (27)$$

The preferred strategy should be close to the positive ideal profile and distant from the least-desirable profile.

The relative preference index for strategy j is calculated as:

$$C_j = \frac{S_j^N}{S_j^P + S_j^N}, \quad 0 \leq C_j \leq 1 \quad (28)$$

The preference index ranges from zero to one, with larger values indicating stronger relative performance. The admissible strategies are ranked in descending order of the preference index:

$$A_i^{\text{pref}} = \arg \max_{A_{ij} \in A_i^{\text{adm}}} C_j \quad (29)$$

The highest-ranked admissible strategy becomes the preliminary recommendation. It is not the final maintenance decision until ranking robustness, engineering compatibility and implementation conditions have been reviewed.

2.3.4 Ranking robustness, confidence and engineering review

The TOPSIS ranking is treated as a decision aid because criterion scores and weights often reflect incomplete data, uncertain condition trends, estimated costs and professional judgement. Its robustness must therefore be examined before implementation.

The first robustness indicator is the ranking margin between the first- and second-ranked strategies:

$$\Delta C_i = C_{(1),i} - C_{(2),i} \quad (30)$$

where $C_{(1)}$ and $C_{(2)}$ are the highest and second-highest preference indices, respectively.

A large margin indicates clear separation between the leading strategies, while a small margin indicates similar overall performance and greater sensitivity. The margin is interpreted together with data confidence and weight sensitivity rather than against a universal acceptance threshold.

Sensitivity analysis varies the criterion weights under plausible scenarios, including greater emphasis on risk and technical suitability, reliability and availability, cost and feasibility, or evidence confidence. A recommendation is considered robust where the same strategy remains preferred or where changes in ranking do not materially alter the required maintenance response. Repeated changes under small weight variations indicate a sensitive result.

A sensitive ranking does not invalidate the method but indicates that the available evidence does not clearly distinguish between the leading alternatives. The available engineering responses include requesting additional condition evidence, refining cost or feasibility assumptions, verifying redundancy, revising the scores or weights, selecting a combined strategy, or retaining the more conservative admissible option.

The final engineering review should confirm that the recommended strategy is compatible with the identified failure mechanism, risk category, condition trend, redundancy arrangement, statutory and class requirements, operational circumstances and available implementation opportunity. The review should also identify whether the preferred strategy represents the principal maintenance orientation or whether it should be combined with a supporting strategy.

The Decision Engine record should identify the admissible and excluded strategies, exclusion reasons, supporting evidence, scores, weights, preference indices, sensitivity results, ranking confidence, selected strategy, engineering-review conclusion and required implementation conditions. This record links the analytical evidence to the subsequent implementation assessment.

Following TOPSIS ranking, the preliminary strategy is reviewed against five implementation conditions. Mandatory statutory, class, SMS or manufacturer requirements can override the ranking. Condition evidence must support the proposed intervention or prompt further inspection and increased urgency. The selected action must provide sufficient control of the classified risk, and continued operation or deferral requires verified and

independent redundancy. Where immediate implementation is not feasible, temporary controls and the earliest safe execution opportunity must be defined. The decision, controls and subsequent outcome are recorded in the PMS/CMMS. Figure 2 summarises this post-ranking engineering logic.

Escalation is required where the assessed failure mode affects safety, pollution prevention, class or statutory compliance, essential functions, redundancy, repeated failure or an uncertain technical diagnosis. The appropriate shipboard, shore-management, class, flag, manufacturer or specialist authority should be involved according to the required competence and approval level. A mandatory or engineering override supersedes the TOPSIS result where a prescribed response applies or where the leading strategy does not provide adequate risk control. The reason, authority, supporting evidence and approved action must be recorded so that any difference between the calculated recommendation and the final decision remains traceable.

2.3.5 Cost, downtime and operational feasibility assessment

The multi-criteria comparison incorporates expected total cost and implementation feasibility, but its criterion scores do not constitute a complete work-planning estimate. A subsequent implementation check therefore considers direct and residual failure costs, downtime, required resources, operating restrictions and the earliest safe maintenance opportunity. This assessment applies only to technically admissible actions; safety, environmental, class, statutory, SMS and manufacturer requirements remain controlling constraints.

Where sufficient information is available, alternative maintenance actions are compared using expected cost. For a maintenance action (a), expected cost can be expressed as:

$$EC(a) = C_a + P_f(a) \times C_f + C_d(a) \quad (31)$$

where $EC(a)$ is the expected cost of action a , C_a is the direct action cost, $P_f(a)$ is the probability of failure under or after action a , C_f is the consequence cost of failure, and $C_d(a)$ is the downtime, off-hire or operational cost associated with the action.

Equation (31) combines the direct action cost, residual failure exposure and downtime or operational cost associated with each alternative. It allows monitoring, inspection, planned intervention and urgent repair to be compared without assuming that the option with the lowest immediate cost is preferable. Where monetary inputs are uncertain, ranges or scenarios should be used and the underlying assumptions recorded.

A technically preferred action is not always immediately feasible because of unavailable spare parts, specialist or class attendance, unsafe access, the vessel's operating status or an insufficient port window. In such cases, the model identifies the earliest safe execution opportunity and defines time-limited temporary controls, such as increased monitoring, reduced load, operating restrictions, use of verified standby capacity or preparatory inspection. The PMS/CMMS record should state why immediate implementation is not possible, who approved the interim arrangement and when the permanent action will be completed. Operational feasibility must not be used to normalise unacceptable risk.

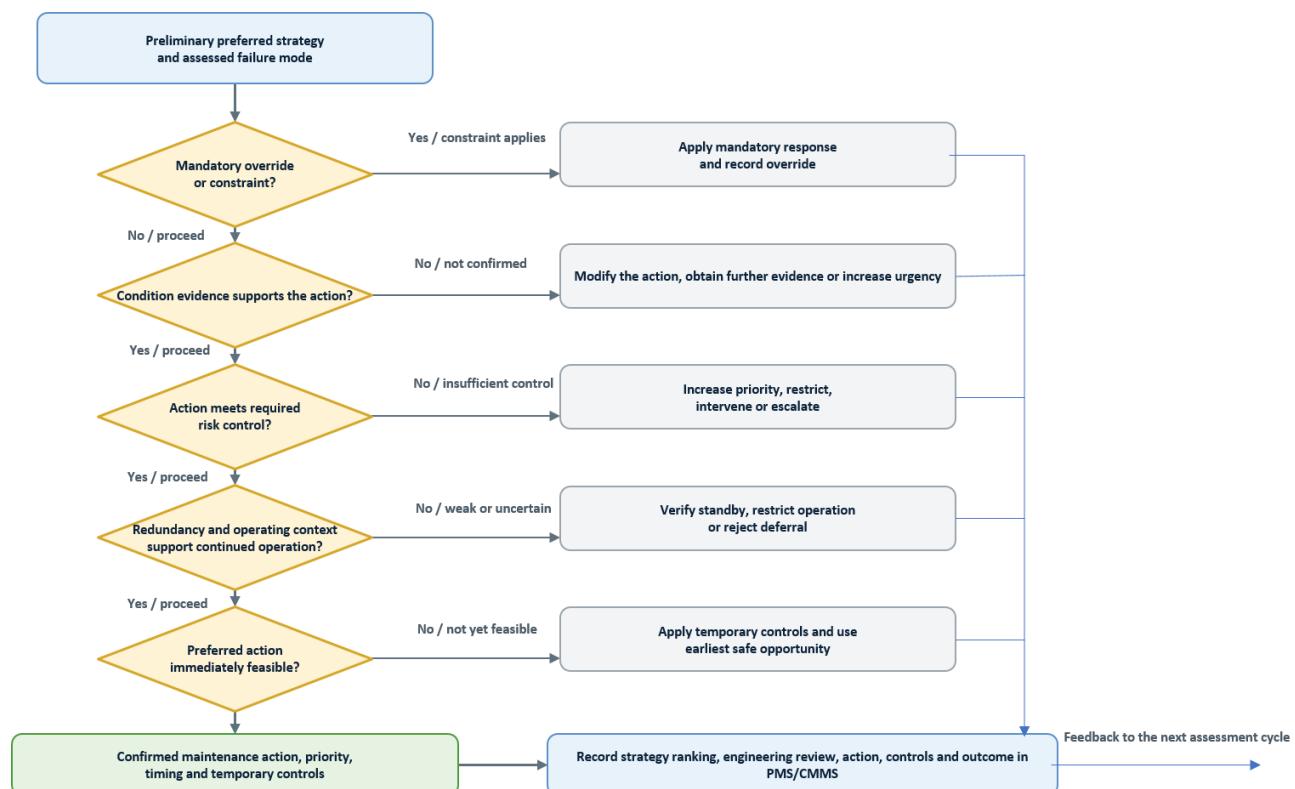


Figure 2 Maintenance-action selection logic following maintenance-strategy ranking. Source: author, adapted from [1, 2, 9–11, 21].

The implementation check confirms whether the selected action should be executed immediately, performed at the earliest safe opportunity, supported by temporary controls or formally escalated. Among the technically feasible and compliant implementation alternatives associated with the confirmed maintenance strategy, the preferred action is the option with the lowest expected cost that reduces residual risk to the accepted level:

$$a^* = \arg \min_{a \in A_f} EC(a) \quad (32)$$

where a^* is the preferred feasible action and A_f is the set of actions that are technically feasible and compliant with mandatory safety, class, statutory, SMS and operational constraints.

The feasible action set is defined as:

$$A_f = \left\{ a \in A \mid \begin{array}{l} a \text{ is technically feasible,} \\ R(a) \leq R_{acc}, a \text{ complies with mandatory constraints} \end{array} \right\} \quad (33)$$

Here, A is the complete set of candidate maintenance actions, $R(a)$ is the residual risk associated with action a , and R_{acc} is the accepted risk level. Mandatory constraints include applicable safety, class, statutory, Safety Management System, manufacturer and operational requirements.

Neither the cheapest nor the most conservative option is automatically preferred. The selected action must provide adequate risk control, remain technically appropriate and be capable of implementation within the relevant decision interval.

2.3.6 PMS/CMMS feedback and model updating

The PMS/CMMS supplies the equipment hierarchy, running hours, maintenance and defect history, inspection findings and condition evidence used by the model and retains the approved decision [12, 13, 22, 23]. The record identifies the assessed item and failure mode, assumptions, risk and admissibility results, selected strategy, engineering review, temporary controls, responsibility and review date.

After implementation, actual findings, condition improvement, recurrence, delays and modifications are recorded to update failure history, maintenance intervals, condition thresholds, cost assumptions and reliability estimates. Repeated findings also support fleet-level review of maintenance tasks, spare-parts selection, operating practices, monitoring, training and supplier arrangements, subject to applicable safety, class, statutory, manufacturer and company requirements.

3 DISCUSSION

The proposed model is transferable as a decision-support architecture rather than as a fixed numerical template. Its principal elements—the definition of equipment functions and failure modes, assessment of likelihood and consequence, treatment of uncertainty, screening of candidate strategies, multi-criteria ranking, engineering review and PMS/CMMS feedback—can be applied to different vessels, machinery systems and operating contexts. The

numerical inputs, however, must reflect the characteristics of the particular application. Equipment boundaries, failure modes, decision intervals, consequence scores, criterion weights, redundancy assumptions, cost estimates and admissibility constraints therefore require vessel- and system-specific calibration.

This requirement should be regarded as normal engineering adaptation rather than as a fundamental limitation. The same machinery component can have different criticality depending on vessel type, operating profile, available redundancy, trading area, maintenance history and repair opportunity. A failure that is manageable on a vessel with verified standby capacity and frequent port access can require a more conservative response where redundancy is limited or external assistance is not readily available. The method preserves a consistent decision structure while allowing these differences to be represented through application-specific evidence and constraints.

The maturity of the maintenance-management system and the quality of the available data both influence confidence in the resulting recommendation. PMS/CMMS records can contain incomplete running hours, inconsistent equipment names, unclear defect descriptions and insufficient distinction between preventive replacement and functional failure. Such limitations affect failure-mode definition, Weibull estimation, likelihood classification and the confidence assigned to the Decision Engine output. Quantitative reliability analysis should therefore be used only where failure and survival data are sufficiently complete and comparable. Where this condition is not met, semi-quantitative likelihood classes, conservative assumptions and scenario analysis provide a more defensible basis than unsupported numerical precision. Uncertainty should be explicitly recorded and considered in accordance with established risk-management principles [10, 14].

Condition-monitoring evidence also requires careful interpretation. Vibration, oil analysis, thermography and process-parameter trends can identify deterioration, but their significance depends on measurement quality, operating load, baseline definition, alarm thresholds and diagnostic competence. A single abnormal measurement does not necessarily demonstrate an imminent failure, while apparently stable values do not guarantee that all relevant degradation mechanisms are detectable. Condition evidence is therefore used as one input to likelihood assessment and strategy admissibility rather than as an independent maintenance decision.

The risk matrix provides a practical means of combining likelihood and consequence, but it remains semi-quantitative. Broad risk categories can conceal differences between failure modes and are influenced by judgement, company risk tolerance and operating context. The maximum credible consequence rule and the high-consequence review trigger reduce the possibility that severe safety, environmental or compliance effects are obscured by a low likelihood score. Nevertheless, failure modes close to a decision threshold, subject to substantial uncertainty or capable of affecting essential functions require engineering review beyond the numerical matrix.

The TOPSIS ranking is similarly dependent on the selected criteria, scores and weights. Its value lies in making those assumptions explicit and applying them consistently across admissible strategies, not in removing professional judgement. A narrow ranking margin indicates that the leading alternatives are closely matched, while repeated changes under plausible weight variations show that no strategy is clearly dominant. In such circumstances, the method supports additional inspection, revised scoring, a combined maintenance strategy or selection of the more conservative admissible option. Sensitivity analysis and post-ranking engineering review are therefore integral safeguards rather than optional additions.

Finally, the proposed model remains a decision-support method and not an autonomous maintenance authority. Its effectiveness depends on competent personnel, reliable reporting, clear responsibilities and proper execution of the selected action. Operational constraints such as voyage schedule, safe access, spare-parts availability and specialist attendance sometimes delay implementation, but they should not be used to normalise unacceptable risk. Where immediate intervention is not feasible, temporary controls, responsibility, approval, escalation conditions and a defined review date must be recorded. This is consistent with the treatment of maintenance as a continuing shipboard and shore-management responsibility under the ISM framework and associated IACS maintenance guidance [9, 11].

4 CONCLUSIONS

This paper proposes an integrated risk-based method for selecting ship-machinery maintenance strategies at component and failure-mode level. The method combines FMEA/FMECA, reliability and conditional probability analysis, condition evidence, consequence assessment, risk classification, uncertainty treatment and multi-criteria decision-making within a single decision-support framework. Its central feature is the Maintenance Decision Engine, which separates mandatory admissibility from comparative ranking. Statutory, class, manufacturer, Safety Management System and safety requirements are therefore applied as controlling constraints rather than treated as ordinary weighted criteria.

The admissible alternatives are evaluated using TOPSIS against expected risk reduction, technical suitability, contribution to reliability and availability, implementation feasibility, expected total cost and evidence confidence. Ranking margins and sensitivity analysis indicate whether the numerical preference is robust. The ranking remains preliminary until engineering review confirms compatibility with the failure mechanism, condition trend, risk urgency, redundancy arrangement and operational circumstances. This prevents a mathematically favourable option from overriding mandatory requirements or providing insufficient risk control.

The selected strategy is converted into an implementable maintenance action that defines timing, responsibility, temporary controls and escalation where required. Recording the decision and its

outcome through the PMS/CMMS provides traceability and supports later revision of failure history, maintenance intervals, condition thresholds, cost assumptions and reliability estimates. The method is intended for vessel- and system-specific calibration rather than use as a fixed universal template. Its effectiveness depends on the quality of maintenance records, condition evidence, failure data and professional judgement. The paper therefore establishes the formal methodology and its decision safeguards, while practical application and empirical validation remain subjects for vessel-specific studies.

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