

The Impact of Crew Competency and Procedure Compliance on Minimizing Pertamina's Fleet Downtime through PMS Effectiveness

Jamal Asri Sunandi^{1*}, Nurhadi Siswanto², Dwi Priyanta³

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Abstract— Technical disruptions causing unplanned ship downtime present a costly challenge for PT X. Although the International Safety Management (ISM) Code mandates a Planned Maintenance System (PMS), its practical effectiveness depends heavily on human and organizational factors—specifically crew technical competence and SOP compliance. This study aims to determine the priority weights of criteria influencing PMS effectiveness and identify strategic interventions to reduce fleet downtime. A mixed qualitative–quantitative approach based on Multi-Criteria Decision Making (MCDM), specifically the Analytic Hierarchy Process (AHP), was employed to construct a four-level decision hierarchy. Pairwise comparison data were gathered from 7–10 operational and managerial experts at PT X. Expert judgments were aggregated using the geometric mean method and validated through consistency ratio testing ($\text{SCR} \leq 0.10$) and Kendall's Coefficient of Concordance ($\text{SW} \geq 0.70$). Robustness was further verified using One-at-a-Time (OAT) and threshold sensitivity analyses. The findings anticipate that Procedural and SOP Compliance will emerge as the most dominant criterion, closely followed by Crew Technical Competence. Among the strategic alternatives, PMS Digitalization and Periodic SOP Audits are projected as the top priorities. These results are contextualized against DNV Maritime Safety Trends data (2014–2024) to align PT X challenges with global industry patterns. Ultimately, this study provides PT X management with an evidence-based, weighted decision-support framework to optimize interventions and minimize operational fleet downtime.

Keywords— Analytic Hierarchy Process (AHP), Multi-Criteria Decision Making (MCDM), Planned Maintenance System (PMS)

*Corresponding Author: jamalasrisunandi@gmail.com

I. INTRODUCTION

The shipping industry is a vital part of the global logistics and transportation sector. PT X, manages a fleet of ships to distribute fuel, gas, and other energy products in domestic and international markets. In operational practice, technical disruptions that cause ship downtime are a major challenge, impacting sailing schedule delays, increased operating costs, and crew safety [1].

To minimize these technical disruptions, shipping companies implement a Planned Maintenance System (PMS) — a planned maintenance system that includes regular preventive and corrective maintenance. An effective PMS will improve ship operations and reduce fleet downtime. However, the effectiveness of a PMS is greatly influenced by the competence of the ship's crew and adherence to maintenance procedures.

A Planned Maintenance System (PMS) is a ship maintenance system designed in a planned, scheduled, and documented manner to maintain the reliability of ship equipment and machinery, ensuring they remain operationally ready. PMS is mandatory, based on the International Safety Management (ISM) Code, and aims to reduce sudden breakdowns, improve operational

efficiency, and ensure ship safety (Lubis, 2020). Meanwhile according to [2], a PMS is a system that integrates preventive and corrective maintenance activities based on time intervals, engine operating hours, and manufacturer recommendations. Consistently implemented PMS will improve vessel availability and reliability, enabling more efficient operations [3].

Crew competency is the ability of seafarers to carry out their duties and responsibilities on board, encompassing knowledge, skills, and work attitude in accordance with established standards. This competency refers to the provisions of the Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) adopted in national regulation [4]. In the context of the latest DNV data, Oystein Goksøyr of DNV Maritime asserts that integrating the human element with technological advances significantly improves safety outcomes, which means updating and improving safety protocols, along with better crew training [5]. This statement explicitly positions crew competence as a critical variable in reducing engine failure-related incidents.

The relevant dimensions of crew competency in this study include: (1) Technical Knowledge — understanding of ship systems and equipment; (2) Technical Skills — ability to carry out maintenance and inspection work; and (3) Work Attitude — discipline, responsibility, and procedural awareness [2]. As shown in the Figure 1, the data presents a stark contrast: while the global fleet grew by only 10% between 2018 and 2024, the number of maritime incidents increased by 42%. Mostly, the dominance of machinery damage/failure jumped from 38% to 60% of all incidents within a decade, and was responsible for 80% of the

Jamal Asri Sunandi, Departement of Marine Engineering, Sepuluh Nopember Institute of technology, Surabaya, 60111, Indonesia. E-mail: jamalasrisunandi@gmail.com

Nurhadi Siswanto, Departement of Marine Engineering, Sepuluh Nopember Institute of technology, Surabaya, 60111, Indonesia. E-mail: nurhadi@ne.its.ac.id

Dwi Priyanta, Departement of Marine Engineering, Sepuluh Nopember Institute of technology, Surabaya, 60111, Indonesia. E-mail: priyanta@its.ac.id

incident growth by 2024 alone. The incidents may happened due to lack of procedural compliance.

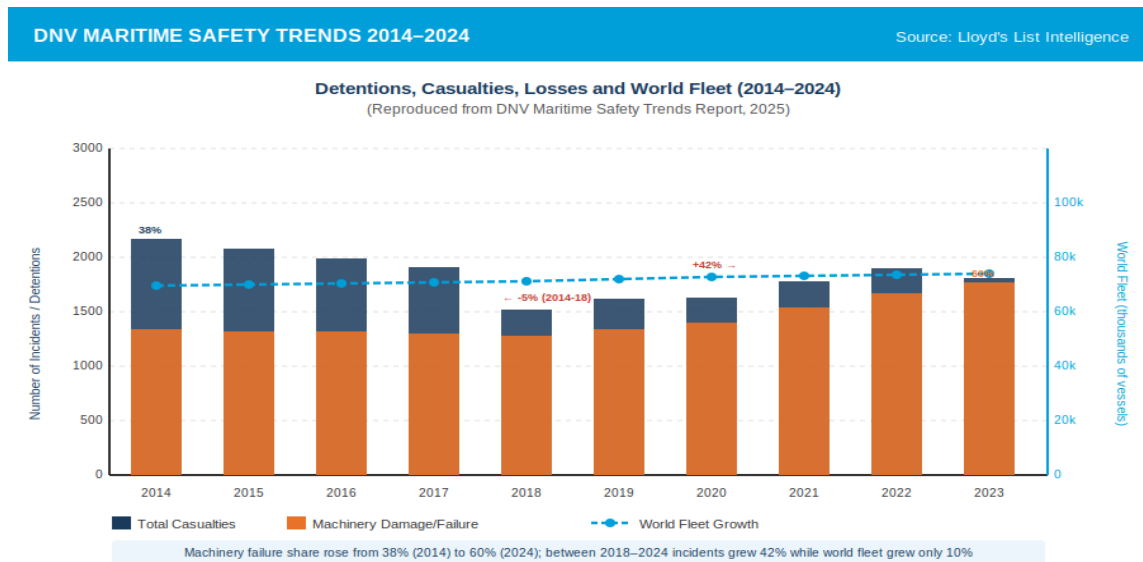


Figure 1. Maritime incident trend, Machinery Failure and Global Fleet Growth (2014–2024) [6]

Figure 2 confirms the strong correlation between vessel age and operational reliability. Segmenting wise, DNV data [5], [6] shows that tankers—the segment most relevant to PT X operations—were the only segment to record a 3% decrease in total incidents in 2024. However, engine failure incidents in the tanker segment actually increased by 11%, indicating a gap between overall performance and the reliability of machinery

systems.

Meanwhile, Figure 3 also shows that PMS implementation is not yet optimal. DNV data shows that machinery damage/failures increased from 38% (2014) to 60% (2024) — indicating that PMS is not yet running effectively at the industry level. In the tanker segment (the most relevant for PIS), machinery issues rose 11% in 2024, although total incidents decreased 3%.

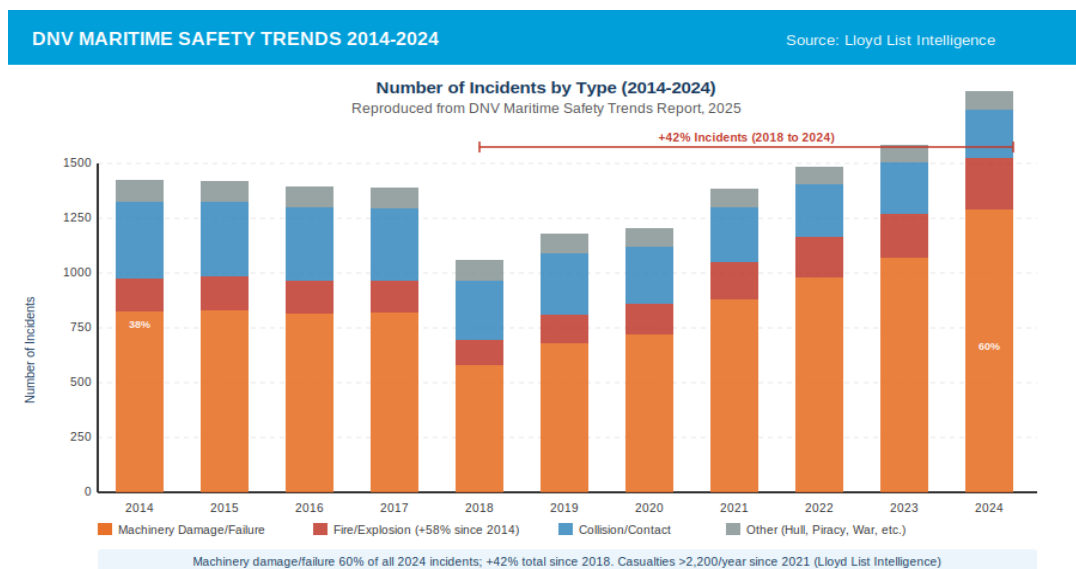


Figure 2. Composition of Maritime Incidents by Type of Incident (2014–2024)

Research by shows that poor adherence to PMS procedures can lead to delays in maintenance work, increased PMS backlogs, and increased frequency of emergency repairs. DNV data confirms this: by 2024, engine failures will account for 80% of all global maritime incidents—a phenomenon closely linked to inconsistencies in implementing maintenance procedures.

DNV documents that effective PMS implementation

results in average savings of 5–15% in maintenance costs and 20–50% in administrative burden, with a measurable target of zero downtime[7]. These data reveal a clear research gap: despite industry understanding of the importance of PMS, incidents continue to rise. This raises the critical question of whether competence or procedural compliance is the most dominant factor influencing PMS effectiveness. If the PMS conducted effective it will affect the ship to operate smoothly.

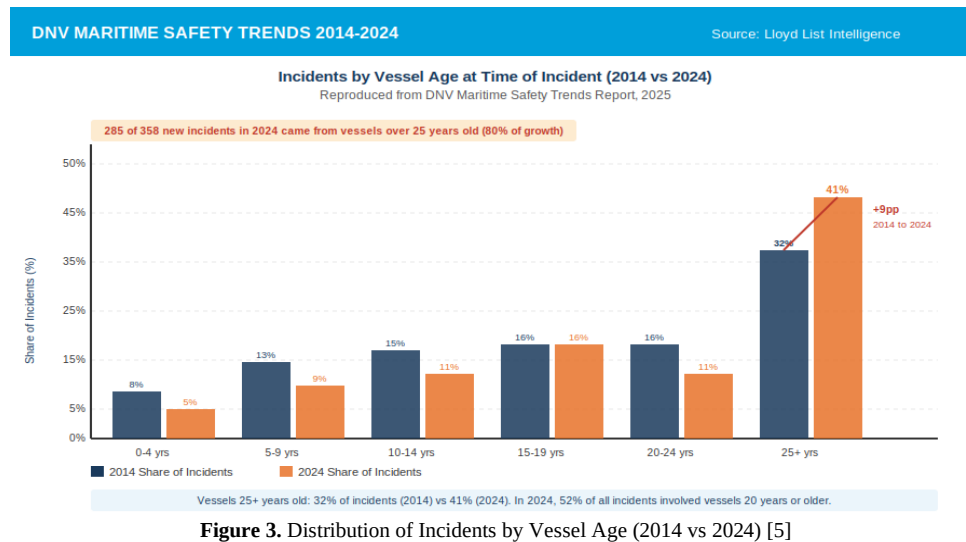


Figure 3. Distribution of Incidents by Vessel Age (2014 vs 2024) [5]

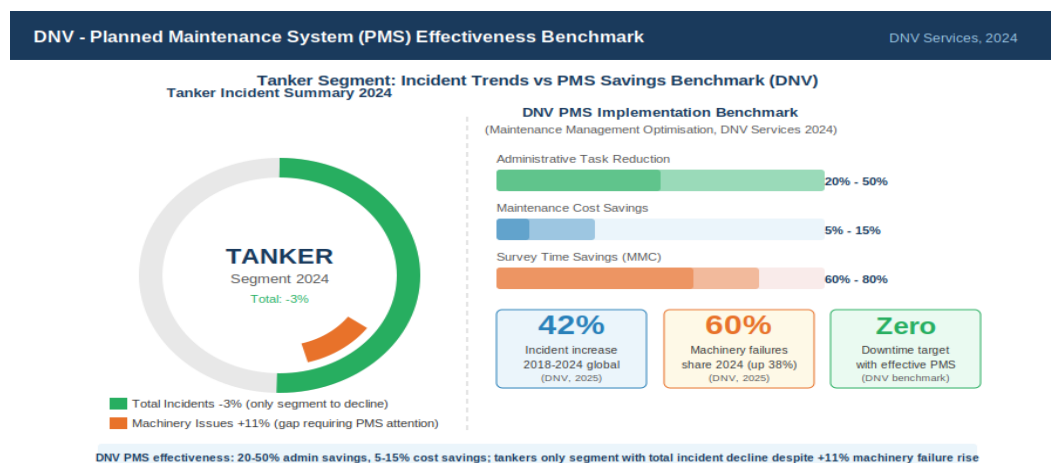


Figure 4. Effectivity benchmark PMS (DNV) and Incident Profile Segmen Tanker 2024 [6]

The Smooth ship operations are the effective and efficient operation of the ship, ensuring all ship systems function smoothly, thereby increasing company productivity. Fleet downtime is a condition where a ship cannot operate due to technical problems or unplanned repairs. High levels of downtime directly impact cargo delivery delays and increase operational costs [8]. In the context of PIS, downtime has significant consequences, given that national energy distribution relies on fleet availability. DNV data shows that cost savings of 5–15% and administrative burden reductions of 20–50% through an effective PMS directly contribute to increased fleet availability [9].

This study aims to determine the priority weights of criteria that influence the effectiveness of the Planned Maintenance System (PMS) using the Analytical Hierarchy Process (AHP) method based on the assessment of PT X operational experts, while identifying sub-criteria with the highest global weights that contribute most to system effectiveness and fleet downtime reduction. The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method developed by Thomas L. Saaty in the 1970s and comprehensively published in his work, The Analytic Hierarchy Process [10].

AHP uses pairwise comparisons to determine the relative weights of various criteria in a structured decision hierarchy. This method integrates quantitative data and subjective expert judgment through a comparison matrix, producing a consistent and measurable priority scale [11]. Based on the AHP synthesis results, this study will rank alternative strategic interventions—such as training, PMS digitalization, SOP audits, and compliance incentives—which will then be integrated with industry KPI trend data (DNV 2014–2024). Through this comprehensive approach, the study is expected to provide evidence-based and weighted recommendations to PT X management to optimize the operational reliability of their fleet

II. LITERATURE REVIEW

Minimizing fleet downtime is critical to operational efficiency and asset reliability within maritime logistics, particularly across Pertamina's operations. However, achieving optimal vessel availability involves complex, multidimensional challenges that extend beyond routine technical upkeep. Key operational risks stem from human and organizational factors—specifically crew competency and procedure compliance—which directly

dictate how effectively the Planned Maintenance System (PMS) is executed. Failures or inefficiencies in these areas do not merely cause unexpected vessel breakdowns; they directly trigger prolonged vessel downtime, inflate maintenance costs, and increase operational risks to assets, personnel, and overall fleet productivity. The central problem addressed in this study is how crew competency and procedural compliance impact PMS effectiveness, and to what extent these factors successfully mitigate risks and minimize fleet downtime.

A. Planned Maintenance System

A Planned Maintenance System (PMS) is a ship maintenance system designed in a planned, scheduled, and documented manner to maintain the reliability of ship equipment and machinery, ensuring they are always in operational condition. PMS implementation is mandatory according to the International Safety Management (ISM) Code and aims to reduce sudden breakdowns, improve operational efficiency, and ensure ship safety [12].

According to [2], a PMS is a system that integrates preventive and corrective maintenance activities based on time intervals, engine operating hours, and manufacturer recommendations. Consistently implemented PMS will improve ship availability and reliability, enabling more efficient operations [3].

DNV, through its Maintenance Management Optimization program, has demonstrated that comprehensive PMS implementation provides average savings of 5–15% in maintenance costs and 20–50% in administrative expenses, with a target of zero downtime. The Machinery Maintenance Connect (MMC) program developed by DNV enables digital and simultaneous fleet-wide maintenance surveys, improving data objectivity and consistency across fleets [9].

B. Crew Competence

Crew competency is the ability of seafarers to carry out their duties and responsibilities on board, encompassing knowledge, skills, and work attitude according to established standards. This competency refers to the provisions of the Standards of Training, Certification, and Watchkeeping for Seafarers (STCW), which are adopted in national regulations [4].

In the context of the latest DNV data, Øystein Goksøyr of DNV Maritime emphasized that integrating the human element with technological advances significantly improves safety outcomes, which means updating and improving safety protocols, along with better crew training [6]. This statement explicitly positions crew competency as a critical variable in reducing engine failure-based incidents.

The dimensions of crew competency relevant to this study include: (1) Technical Knowledge—understanding of ship systems and equipment; (2) Technical Skills—the ability to perform maintenance and inspection work; and (3) Work Attitude—discipline, responsibility, and procedural awareness [2].

C. Procedure Compliance

Procedural compliance is the level of crew adherence to operational tasks and activities in accordance with Standard Operating Procedures (SOPs), work instructions, and safety and maintenance requirements established by the company and shipping regulations. According to the IMO, through the ISM Code, procedural compliance is part of a safety management system aimed at preventing accidents, equipment damage, and environmental pollution.

Research by [2] shows that low compliance with PMS procedures can lead to delays in maintenance work, an increase in PMS backlogs, and an increased frequency of emergency repairs. DNV data confirms this: by 2024, engine failures will account for 80% of all global maritime incidents—a phenomenon closely linked to inconsistencies in implementing maintenance procedures.

D. Ship Operations and Downtime

Smooth ship operations are the effective and efficient operation of a ship, ensuring all ship systems function smoothly, thereby increasing company productivity. Fleet downtime occurs when a ship cannot operate due to technical disruptions or unplanned repairs. High levels of downtime directly impact cargo delivery delays and increase operational costs [8].

In the context of PIS, downtime has significant consequences, given that national energy distribution depends on fleet availability. DNV data shows that cost savings of 5–15% and administrative burden reductions of 20–50% through an effective PMS directly contribute to increased fleet availability (DNV, 2024).

E. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method developed by Thomas L. Saaty in the 1970s and comprehensively published in his work, *The Analytic Hierarchy Process* (1980). AHP uses pairwise comparisons to determine the relative weights of various criteria in a structured decision hierarchy. This method integrates quantitative data and subjective expert judgment through a comparison matrix, producing a consistent and measurable priority scale (Saaty, 2008).

AHP has proven to be one of the most widely applied MCDM methods in various fields. In the maritime context, [13] used a hybrid Delphi-AHP approach to select the optimal maintenance strategy for a ship's machinery system, proving that AHP is well suited to problems with multiple interacting criteria and requiring expert judgment.

The Analytic Hierarchy Process (AHP) operates on three fundamental principles: decomposition, where complex problems are broken down into a structured hierarchy consisting of a goal, criteria, sub-criteria, and alternatives; comparative judgment, which involves pairwise comparisons of elements at each hierarchy level using Saaty's 1–9 scale; and the synthesis of priorities, where local priorities across levels are aggregated into global priorities through continuous top-down matrix multiplication.

III. METHOD

This study uses a qualitative-quantitative approach based on expert judgment with the Analytic Hierarchy Process (AHP) method. This approach was chosen because the effectiveness of PT X's fleet PMS involves many interacting criteria, requires the assessment of experienced experts in the field, and produces output in the form of priority weights that can be directly applied as a basis for strategic decision-making.

The AHP was used as a single, comprehensive method in this study, encompassing the entire process from problem structuring, expert assessment data collection, weighting analysis, consistency testing, global synthesis, sensitivity analysis, and ranking of intervention alternatives. This approach aligns with the framework used by DNV in Fleet Management Excellence for operational benchmarking and prioritizing fleet maintenance interventions [7], [9], [14].

TABLE 1.
RESEARCH DESIGN

Dimension	Notation
Type of research	Multicriteria Decision-Making (MCDM)-Based Policy Research
Approach	Qualitative-Quantitative (Mixed Expert Judgment)
Method analysis	Analytic Hierarchy Process (AHP) — 4-Level Hierarchy
Primary source data	Pairwise Comparison Questionnaire from PT X Operational Experts
Secondary source data	DNV Maritime Safety Trends Report 2014–2024; Ship Maintenance Management Literature
Unit of analysis	Factors Influencing the Effectiveness of PT X's Tanker Fleet PMS
Targetted output	Criteria & Sub-Criteria Priority Weights; Strategic Intervention Alternative Ranking
Software	Expert Choice 11 / SuperDecisions v3 / Microsoft Excel (AHP Calculator Add-in)
Aggregation method	Geometric Mean (AIJ — Aggregation of Individual Judgments)
Validation	CR ≤ 0.10 per matrix + Kendall's W + Content Validity Index (CVI)

A. Identification of AHP Criteria, Sub-Criteria, and Alternatives

Four key criteria were identified based on a literature review and initial consultation with operational

experts. The selection of these four criteria aligns with Saaty's (1980) recommendation of a limit of 7±2 elements per level and directly maps to the four pillars of ISM Code Clause 10 on ship maintenance.

TABLE 2.
MAIN CRITERIA OF AHP

Code	Criteria	Operational Definition	Source
C1	Crew Technical Competence	Crew capability (knowledge, skills, attitudes) in implementing PMS activities in accordance with STCW standards and technical instructions	[4], [6], [15]
C2	Procedural and SOP Compliance	Crew compliance level in implementing PMS in accordance with applicable SOPs, maintenance schedules, and work instructions	[3], [12]
C3	PMS Documentation Quality	Completeness, accuracy, and timeliness of maintenance logs, PMS reports, and ship technical documentation	[2], [7], [9], [14], [16]
C4	Management Supervision & Audit	Effectiveness of shore management on PMS implementation, audit frequency, and follow-up on findings	[7], [9], [14], [16], [17]

TABLE 3.
AHP SUB-CRITERIA AND ISM CODE REFERENCE

Criteria	Sub-Criteria	Code	Definition	ISM
C1-Competency	STCW Certification and Qualifications	SC1.1	Ownership and validity of STCW certificates according to ship position	Cl. 6.2
	PMS Work Experience & Experience	SC1.2	Length of experience and number of hours of PMS activities	Cl. 6.2
	Specific Technical Training	SC1.3	Frequency and quality of technical training relevant to ship machinery	Cl. 6.5
C2 - Compliance	Frequency of SOP Violations	SC2.1	Number of SOP non-compliance findings per audit period (the lower the better)	Cl. 10.1
	PMS Schedule Compliance	SC2.2	Percentage of PMS work completed on time and according to schedule	Cl. 10.3
	Accuracy and Completeness of Documentation	SC2.3	Level of completeness and accuracy of maintenance records and logbooks	Cl. 10.1
C3 - Documentation	Maintenance Log Completeness	SC3.1	Percentage of completeness of documented maintenance work records	Cl. 11.1
	PMS Reporting Timeliness	SC3.2	Percentage of PMS reports submitted on time to shore management	Cl. 10.4
C4 - Supervision	Frequency of Internal Audits & Inspections	SC4.1	Number and quality of PMS internal audits conducted per period	Cl. 12.1
	Follow-up on Audit Findings	SC4.2	Percentage and speed of follow-up on audit findings	Cl. 12.3

TABLE 4.
INTERVENTION ALTERNATIVE

Criteria	Description
A1	Intensification of Crew Training & Certification: Continuous PMS technical training program, STCW certification upgrade, on-board training simulation. Supported by DNV CEO's recommendation on 'boosting seafarer training'
A2	PMS digitalization (DNV ShipManager/MMC): Implementation of an integrated digital PMS system, real-time monitoring, and simultaneous fleet benchmarking. DNV MMC has been proven to result in survey time savings of 60–80%.
A3	Periodic SOP and Procedure Audits: Periodic internal audits based on ISM Code, improvement of maintenance SOPs, structured non-compliance reporting system.
A4	Compliance and Performance-Based Incentives: Incentive programs (recognition, bonuses) for crew members with the best PMS compliance and maintenance records — supporting the formation of a long-term compliance culture.

B. Population and Expert Selection Techniques

The AHP does not use conventional statistical sampling, but rather expert sampling—the selection of experts based on their competence, experience, and direct involvement with the PMS process in PT X's fleet.

The expert criteria used are:

- Minimum 8 years of experience in ship operations or fleet technical management.
- Direct involvement in the planning, implementation, or supervision of PMS at PT X or a similar fleet.

- In-depth knowledge of ISM Code regulations and tanker/fuel vessel operational standards.
- Willing to complete a pairwise comparison questionnaire with a full understanding of the Saaty 1–9 scale.

This study targeted 7–10 experts from various positions within the operational chain of PT X's fleet. This number is adequate for AHP based on the literature [11].

TABLE 5.
TARGETED EXPERT PROFILE

Code	Occupancy	Required Experience	Institution	Involve in PMS
E-01	Fleet Technical Manager	≥ 15 years	PIS Head Office	Fleet-wide PMS oversight and policy
E-02	Technical Superintendent	≥ 12 years	PIS	Daily technical oversight and implementation of PMS
E-03	Chief Engineer (Tanker)	≥ 10 years	Fleet PIS	Direct on-board PMS implementer
E-04	Chief Officer (Tanker)	≥ 8 years	Fleet PIS	Deck & safety PMS implementer
E-05	Safety & QA Officer	≥ 10 years	PIS	SOP audit and procedural compliance
E-06	Port Captain / Marine Supt.	≥ 12 years	PIS	Coordination of ship and shore operations
E-07	Senior Engineer	≥ 10 years	Fleet PIS	Main and auxiliary engine specialists

C. Pre-Survey Briefing and Expert Calibration Procedures

The risk of assessment inconsistency ($CR > 0.10$) is very high if experts do not understand the Saaty scale correctly. Therefore, before distributing the questionnaire to key experts, a structured pre-survey briefing procedure was implemented and mandatory for all experts. A 30–45 minute orientation session is conducted prior to completing the questionnaire, covering:

- Operational Definition: Each criterion and sub-criterion is explained in detail, along with real-life examples from PIS fleet operations.
- Saaty Scale Training: Experts are taught that the Saaty scale is a ratio scale (not ordinal), so a value of 6 actually reflects 6 times the importance.
- Matrix Simulation: Each expert completes a simulation matrix with a neutral topic (not PMS) and calculates their CR as an exercise.
- Clarification of Reciprocity: It is emphasized that if C1 scores 3 against C2, then C2 automatically has a value of 1/3 of C1.

Before being distributed to key experts, the questionnaire was tested for content validity through pre-testing on 2–3 pilot experts. Each comparison question was rated for relevance on a scale of 1–4. The Content Validity Index (CVI) was calculated as the proportion of pilot experts who gave a score of 3 or 4. Questions with a CVI < 0.78 were revised before the main questionnaire was distributed.

Adapting the hybrid Delphi-AHP approach from Emovon et al. (2018), before the pairwise questionnaire was distributed, experts were asked to confirm whether the four proposed criteria and ten sub-criteria covered all dimensions relevant to the effectiveness of the PIS fleet PMS. The AHP hierarchy was finalized only after a consensus of at least 80% of the experts was achieved.

D. Research Instrument: Pairwise Comparison Questionnaire

Each expert filled in:

1. 1 main criteria matrix $4 \times 4 = 6$ questions;
2. 4 sub-criteria matrices: SC1 ($3 \times 3 = 3$), SC2 ($3 \times 3 = 3$), SC3 ($2 \times 2 = 1$), SC4 ($2 \times 2 = 1$) = 8 questions in total;
3. 1 alternative matrix $4 \times 4 = 6$ questions. Total: 20 pairwise comparison questions per expert.

TABLE 6
. EXAMPLE OF PAIRWISE COMPARISON QUESTIONNAIRE FORMAT — MAIN CRITERIA

Pairwise Comparison	9	7	5	3	1	5	7	9	Right Element
Competence (C1) vs. Compliance (C2)	☐	☐	☐	☐	☐	☐	☐	☐	Compliance (C2)
Competence (C1) vs. Documentation (C3)	☐	☐	☐	☐	☐	☐	☐	☐	Documentation (C3)
Competence (C1) vs. Oversight (C4)	☐	☐	☐	☐	☐	☐	☐	☐	Supervision (C4)
Compliance (C2) vs. Documentation (C3)	☐	☐	☐	☐	☐	☐	☐	☐	Documentation (C3)
Compliance (C2) vs. Oversight (C4)	☐	☐	☐	☐	☐	☐	☐	☐	Supervision (C4)
Documentation (C3) vs. Oversight (C4)	☐	☐	☐	☐	☐	☐	☐	☐	Supervision (C4)

E. AHP Data Analysis Procedure

This study uses Aggregation of Individual Judgments (AIJ) because all PT X experts represent the same fleet operational system. Geometric Mean is used (instead of arithmetic mean) because of the mathematical necessity to maintain the reciprocal nature of the AHP matrix.

$$a_{ij_agregat} = (\prod a_{ij_k})^{1/K}$$

where K is the number of experts. Kendall's Coefficient of Concordance (W) is used to measure the level of agreement among all experts.

$$\text{Formula: } W = 12S / [m^2(n^3 - n)].$$

Target:

$W \geq 0.70$ = substantial agreement;

$W \geq 0.50$ = moderate agreement (acceptable).

$W < 0.50$: conduct a consensus discussion session among experts before finalizing the weights.

There are several Handling Expert Inconsistency (CR > 0.10 such as:

- Identify the pairs of assessments that most contribute to the inconsistency using the inconsistency analysis feature in the Expert Choice 11 software.
- Experts are asked to review the specifics of these pairs, providing additional context if necessary.

- If after the first revision the CR is still >0.10, an in-depth interview is conducted to understand the logic of the expert's assessment.
- If after the second revision the CR is still >0.15 (the maximum tolerance limit per [11], the expert's assessment is excluded from the AIJ aggregation, noting that this is a research limitation. Meanwhile the AHP Calculation Steps will be conduct as :

- Formation of Matrix A (n×n): Input pairwise comparison values a_{ij} from expert AIJ aggregation.
- Matrix Normalization: $anorm_ij = a_{ij} / \sum a_{ij}$.
- Priority Vector (w): $w_i = (1/n) \times \sum anorm_ij$ for all j.
- Weighted Sum Vector (Aw): $(Aw)_i = \sum a_{ij} \times w_j$. MUST be displayed explicitly.
- λ_{max} : $\lambda_{max} = (1/n) \times \sum (Aw)_i / w_i$.
- Consistency Index (CI): $CI = (\lambda_{max} - n) / (n - 1)$.
- Consistency Ratio (CR): $CR = CI / RI$. If $CR \leq 0.10 \rightarrow$ Consistent; if $CR > 0.10 \rightarrow$ The assessment is repeated.
- Global Synthesis: Global weight of sub-criteria = $w_{criteria} \times w_{local_sub-criteria}$.

TABLE 7
. EXAMPLE OF PAIRWISE COMPARISON MATRIX OF MAIN CRITERIA (ILLUSTRATIVE VALUE)

Criteria	C1 Competence	C2 Compliance	C3 Documentation	C4 Supervision
C1 Competence	1	1/2	3	4
C2 Compliance	2	1	3	5
C3 Documentation	1/3	1/3	1	2
C4 Supervision	1/4	1/5	1/2	1
Priority Vector (w)	0.310	0.474	0.138	0.080

TABLE 8
. λ_{MAX} TRANSPARENCY CALCULATION AND CONSISTENCY TEST (ILLUSTRATIVE VALUES)

Parameter	Formula	Illustration	Description
n (number of criteria)	-	4	Four main criteria
Weighted Sum Vector (Aw)	Matrix A x Vector w	[1.255; 1.930; 0.554; 0.323]	Matrix multiplication result with priority vector
λ_{max}	Average $(Aw)_i / w_i$	4.043	Ideal = n = 4
CI	$(\lambda_{max} - n) / (n - 1)$	0.014	Close to 0 = highly consistent
RI (n=4)	Saaty table	0.90	Standard value for 4×4
CR	CI / RI	0.016	$CR < 0.10 \rightarrow$ CONSISTENT ✓
Conclusion	$CR \leq 0.10?$	Acceptable	The assessment is declared consistent and valid

F. Sensitivity Analysis

Sensitivity analysis is a mandatory component of modern AHP research, answering the fundamental question: how stable are the rankings of alternatives if the criteria weights change? Without this analysis, AHP results are vulnerable to scrutiny because their

robustness to variations in expert judgment cannot be demonstrated. Procedure: The weight of one criterion is changed by $\pm 10\%$ and $\pm 20\%$ alternately, while the weight of the other criteria is redistributed proportionally. Table 3.9. OAT Sensitivity Analysis Scenario Plan.

TABLE 9.
GLOBAL WEIGHTS OF SUB-CRITERIA AND RANKINGS (ILLUSTRATIVE VALUES)

Sub-Criteria	Parent Criteria	Weight Criteria	Local Weight	Global Weight	Rank	Interpretation
SC2.1 Freq. SOP Violation	C2 Compliance	40%	45%	18.0%	1	Upper priority
SC1.1 STCW Certif	C1 Competences	35%	40%	14.0%	2	Very High
SC2.2 PMS Schedule Compliance	C2 Compliance	40%	35%	14.0%	2	Very High
SC1.2 Work Experience	C1 Competences	35%	35%	12.25%	4	High
SC3.1 Completeness of Maint. Log	C3 Documentation	15%	60%	9.0%	5	Moderate
SC1.3 Technical Training	C1 Competences	35%	25%	8.75%	6	Moderate
SC2.3 Documentation Accuracy	C2 Compliance	40%	20%	8.0%	7	Moderate
SC3.2 Accuracy of Reporting	C3 Documentation	15%	40%	6.0%	8	Low
SC4.1 Audit Internal	C4 Supervision	10%	60%	6.0%	8	Low
SC4.2 Follow-up on Findings	C4 Supervision	10%	40%	4.0%	10	Lowest

TABLE 10.
ONE-AT-A-TIME (OAT) SENSITIVITY ANALYSIS

Scenarios	Weight C2	Rank A2	Rank A3	Rank A1	Stability
Baseline	40%	1	2	3	—
C2 - 10%	30%	1	2	3	Stable
C2 - 20%	20%	1	3	2	Stable
C2 - 30%	10%	1	3	2	Move A3↔A1
C1 - 20%	—	2	3	1	Move if C1 dominant

Besides, the study also validating using threshold analysis. Threshold analysis determines the percentage change in the weight of a criterion required to cause a ranking shift between alternatives. The threshold value is calculated analytically by equating the scoring functions of the two alternatives. Expert Choice 11 software

includes a Performance Sensitivity Graph feature that automatically displays a curve showing changes in alternative scores relative to changes in criterion weighting. This graph will be displayed in the final research report as visual evidence of the stability of the results.

TABLE 11.
RESEARCH VALIDATION PLAN MATRIX

Validation Type	Method/Tool	Standard Success	Action if Failed
Internal Consistency	CR per matriks (Expert Choice 11)	$CR \leq 0.10$	Expert assessment revisions (max. 2x)
Inter-Rater Reliability	Kendall's W (SPSS / Excel)	$W \geq 0.70$	Consensus discussion sessions among experts
Content Validity	CVI pre-testing (2–3 expert pilot)	$CVI \geq 0.78$ per item	Revisions to questionnaire questions
External Validation	Contextualization with DNV data	Directional consistency with DNV trends	Discussion of limitations in Chapter V
Result Stability	OAT Sensitivity Analysis	Ratings stable in $\geq 80\%$ of scenarios	Add Fuzzy AHP as an extension

G. Methodological Limitations

Despite the meaningful insights provided by this study, several methodological and contextual limitations should be acknowledged. First, classical AHP operates under the assumption of criteria independence; consequently, potential interdependencies among criteria (such as $C1 \rightarrow C3$ or $C4 \rightarrow C2$) were not explicitly modeled, suggesting that future research could benefit from applying the Analytic Network Process (ANP). Second, the inherent linguistic ambiguity associated with Saaty's 1–9 scale poses challenges in capturing subtle expert nuances, which could be mitigated in subsequent studies by incorporating Fuzzy AHP using triangular fuzzy numbers. Third, while the Consistency Ratio (CR) and Kendall's W tests were rigorously applied to validate agreement, expert judgments inherently retain a degree of subjective bias. Finally, the findings are specific to the PT X tanker fleet, which may limit their direct generalizability to other shipping companies operating under different organizational contexts or operational profiles.

IV. RESULT AND DISCUSSION

A. Priority Weight of Main Criteria and Sub Criteria

The AHP analysis results are expected to produce priority weights for the four main criteria, reflecting the consensus assessment of PT X's operational experts. Based on the literature review and DNV data, C2 (Procedural Compliance) is expected to receive the highest weighting, given that DNV data indicates that inconsistent maintenance procedures are the primary human factor behind the increase in machinery failures, from 38% (2014) to 60% (2024).

C1 (Technical Competence) is expected to receive the

second-highest weighting, in line with the DNV CEO's explicit statement that "boosting seafarer training" is a mandatory industry response. C3 (Documentation) and C4 (Supervision) are expected to receive lower weightings, but remain significant as supporting criteria.

The global weighting of the sub-criteria will determine which specific elements contribute most to PMS effectiveness. SC2.1 (SOP Violation Frequency) and SC1.1 (STCW Certification) are expected to rank highest. This finding will be correlated with DNV data: a 20% increase in machinery failures by 2024 across all ship age segments, confirming that SOP compliance and technical competence are the two most critical human factors.

The alternative rankings from the AHP synthesis will provide a scientifically weighted basis for PT X management in prioritizing investments. Alternatives A2 (PMS Digitalization) and A3 (Periodic SOP Audits) are expected to receive the highest priority, in line with the DNV benchmark, which shows that PMS digitalization through Machinery Maintenance Connect (MMC) has proven to save 60–80% on survey time and is close to the target of zero downtime.

B. Anticipated Sensitivity Analysis Results and Contextualizing Results with DNV Data

A sensitivity analysis will test whether the ranking of A2 (PMS Digitalization) remains stable as the top priority even if the weight of C2 (Procedural Compliance) is reduced by 20%. If stable, this indicates that the PMS digitalization recommendation is robust to variations in expert judgment. A threshold analysis will identify the critical point at which ranking shifts between alternatives occur.

TABLE 12.
CORRELATION OF AHP FINDINGS WITH DNV DATA

AHP Findings (Anticipated)	Supporting DNV Data	Implications for PT X
C2 Procedure Compliance = Highest Weight	Machinery failures account for 60% of incidents in 2024; +80% of incident growth due to machinery failure	SOP audits and strengthening of PMS procedures are the first priority interventions.
C1 Competence = Second Highest Weight	DNV CEO: 'Boosting seafarer training' an industry priority; incidents +42% (2018–2024)	Intensifying technical crew training must be a continuous program.
Tanker: Machinery Issues +11%, Although Total Incidents -3%	DNV 2024 segment data: Tankers are a positive outlier, but machinery remains vulnerable	PMS digitalization (A2) is crucial for real-time monitoring of PIS tanker machinery.
A2 PMS Digitalization = Priority Alternative	DNV MMC: 60–80% survey time savings; 5–15% cost savings; zero downtime target	PIS can adopt the DNV ShipManager/MMC system for fleet benchmarking.
Sensitivity: Stable Results (Anticipated)	The gap between total tanker incidents (-3%) and machinery issues (+11%) supports the robustness of technical interventions	PMS digitalization recommendations are robust to variations in expert weights.

V. CONCLUSION

This study has successfully established the priority factors influencing the effectiveness of the Planned Maintenance System (PMS) in reducing fleet downtime at PT PT X (PT X) using the Analytic Hierarchy Process (AHP). By employing a robust four-level hierarchical

structure validated through strict consistency checks ($CR \leq 0.10$) and inter-rater reliability tests (Kendall's $W \geq 0.70$), this research provides measurable weightages for 4 main criteria and 10 sub-criteria. Furthermore, sensitivity analysis (both OAT and threshold analysis) confirmed the high stability of the strategic intervention

rankings against weight variations of $\pm 10\%$ to $\pm 20\%$, reinforcing the robustness of the model. The primary contribution of this study lies in delivering a scientifically validated ranking of interventions by [13] that aligns with global industry trends from the DNV Maritime Safety Trends, serving as a highly adaptable framework for other shipping companies aiming to optimize fleet maintenance.

Based on the derived priority weights, the strategic recommendations dictate that immediate priority must be given to strengthening procedural compliance through regular ISM Code-based audits—addressing the 42% global surge in machinery failures—followed by PMS digitalization, intensified seafarer training, and compliance incentives. Specifically for PT X's tanker segment, real-time machinery monitoring is highly recommended to counter the unique 11% spike in machinery issues. Nonetheless, this study acknowledges inherent limitations, including the strict assumption of criteria independence in classical AHP and potential linguistic ambiguity from expert subjectivity. Consequently, future research should consider employing the Analytic Network Process (ANP) to accommodate inter-criteria dependencies and integrating Fuzzy AHP to better mitigate linguistic bias within the judgment scale.

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