Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/24533
DOI URL: http://dx.doi.org/10.21474/IJAR01/24533

RESEARCH ARTICLE

DEVELOPMENT OF A RISK-BASED ASSET INTEGRITY MANAGEMENT MODEL FOR STEAM TURBINES, COMPRESSORS AND INDUSTRIAL PUMPS IN OIL AND GAS FACILITIES

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Manuscript Info

Manuscript History
Received: 08 September 2026
Final Accepted: 10 October 2026
Published: November 2026

Abstract

Steam turbines, compressors and industrial pumps underpin the extracti on, gas processing, refining and utility services activities but conventio nal maintenance programmes will typically assess the integrity of these assets on a fixed interval basis or via uncalibrated condition alarms. This integrative review presents a risk based asset integrity managemen t model for rotating equipment applicable to oil and gas facilities across different operating environments. It draws together the peer reviewed literature on failure mechanisms, condition monitoring, prognostics, criticality and governance, making a clear distinction between the performance of diagnostic techniques in the lab and the actual demonstrated level of risk reduction on the plant. The model is designed to link the equipment duty with the credible failure modes, the effectiveness of the barriers to those failures, the confidence in the data and the maintenance decisions through a documented assurance loop. Turbines are of course of particular concern in respect of thermal transients and rotor dynamics; compressors in respect of surge, seals and valve behaviour; and pumps in respect of cavitation, hydraulic instability and bearing degradation. A two stage prioritisation approach is employed to separate out the intolerable safety consequences from the economic optimisation and to treat model uncertainty as an actionable risk signal. The review highlights a continuing gap between the accuracy of the lab based fault classifiers and the actual level of risk reduction that is achieved in practice. A facility-level implementation would therefore be best served by starting with asset registers and failure mode taxonomies, moving on to context specific monitoring and only proceeding to autonomous intervention once the risk reduction has been independently verified. The model is of a conceptual nature and not empirically validated, providing a basis upon which to test the model at site and to subsequently evaluate it over time.

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Introduction:-

Oil and gas facilities are reliant on continuously available rotating equipment to move the hydrocarbons, to maintain process pressure, to generate utility power and to support the separation and treatment trains. The failure of a single

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duty critical pump or compressor can have an impact on a number of downstream units and the loss of turbine driven machinery can have an impact on both production and process barriers. The significance of the equipment cannot be determined simply by its replacement cost. It is a function of the process functions it is connected to, the degree of redundancy available, the inventory of hazards and how rapidly a developing defect can become uncontrolled. This is particularly important in the context of high ambient temperatures, airborne dust, variable operating demand and the fact that the facilities are widely dispersed which makes inspection and maintenance access very difficult.

Asset integrity is the sustained ability of the asset and its associated safeguards to perform the required functions without giving rise to unacceptable safety, environmental or business consequences. It is not the same as availability. A pump may be running even if its mechanical seal is degrading, and in that case the continued operation would increase the probability of a hazardous leak. A compressor may be able to deliver its required throughput whilst approaching an unstable operating region. Ayomoh and Ongwae (2025) position integrity within the context of process safety governance, Das et al. (2023) take a different approach in their rotating machinery synthesis with a focus on fault information. When you bring those two views together you can see why an accurate alarm in itself is not sufficient to be an integrity decision.

Machine learning reviews point to considerable progress in the ability to recognise patterns from vibration and other sensor data (Carvalho et al., 2019; Polverino et al., 2023). The diagnostic accuracy derived from balanced lab classes tells us very little about the reality of rare failures, false alarms on start-up, data gaps and the impact of a delay in action. In fact, more sophisticated classifiers can actually make the causal interpretation even more difficult when the operating regime is different to that of the training data. A risk based model should therefore be one that integrates the probabilistic evidence with engineering judgement, protection layers, work performed and accountable authorisation rather than simply replace the maintenance engineer with a ranking algorithm.

This paper is specifically concerned with steam turbines, compressors and industrial pumps in oil and gas facilities. It does not form part of its core model the inspection of static pressure equipment, though it does take into account the common interfaces (piping stresses, lubrication systems, foundations, electrical drives, control instrumentation etc). It proposes an architecture whereby you can compare machines of very different types without in any way washing out their individual failure physics. The framework is proposed for adaptation to facility-specific conditions and is not evidence of field validation or of the state of equipment across the country.

Aim of the Study:-

The objective is to develop an auditable, risk based asset integrity management model which will take the equipment specific degradation evidence and turn it into defensible inspection, maintenance, operating and renewal decisions for steam turbines, compressors and industrial pumps in oil and gas facilities. The model is designed to maintain the major hazard barriers whilst improving the way in which resources are allocated under varying operating conditions and with incomplete data.

Research Objectives:-

The study has five specific aims: to map the credible degradation mechanisms and consequence pathways for the three equipment classes; to critically assess the condition monitoring and prognostic evidence (including uncertainty and transferability); to develop a common but consequence sensitive framework for criticality, risk acceptance and intervention thresholds; to define the data, governance and assurance arrangements required to implement that framework; and to specify the measurable hypotheses and validation requirements for prospective industrial field trials across different operating settings.

Research Questions:-

The review looks at four questions: which failure mechanisms and context are the most significant in terms of differentiating integrity risks across turbines, compressors and pumps? Under what operating and data conditions do the published diagnostic techniques provide sufficient evidence to support a maintenance decision? How should consequence severity, likelihood of degradation, barrier performance and uncertainty be combined in such a way that the low cost of a failure doesn't in any way offset the exposure to a major hazard? And what governance, competence and validation arrangements would be required to establish that the proposed model actually improves integrity outcomes at participating oil and gas facilities?

Review Methodology:-

We conducted a structured integrative review as the existing literature is a mixture of experimental fault diagnosis papers, algorithmic reviews, systems engineering papers and integrity governance papers that all have different outcome measures. The search was structured around equipment (steam turbine, centrifugal pump, reciprocating compressor, rotating machinery), integrity (asset integrity, failure mode, risk based maintenance, process safety) and analytic (condition monitoring, vibration, cavitation, remaining useful life, data fusion, digital twin) terms. The search strings were constructed by combining synonyms with OR and concept groups with AND and we propose title, abstract and keyword searches for Scopus, Web of Science, Engineering Village, IEEE Xplore and the various publisher databases. Citation chaining is appropriate for the key mechanism studies and the key methods papers.

The evidential base is peer-reviewed papers from 2020 to 2025, with a selective inclusion of earlier methodological work where it is still directly relevant. The study must be on a specific equipment failure mode, a diagnostic or prognostic method, an integrity decision or a governance implication. Vendor marketing material, unreviewed assertions, purely economic oil price models and studies that don't have a verifiable publication are all out. Studies from the lab are included but are considered as experimental evidence rather than as evidence from a production site. Research from different countries and industries is eligible where the underlying failure physics is transferable, in which case local applicability is assessed rather than taken for granted.

For screening we'd remove duplicates by DOI and title, then go on to assess the titles and abstracts for relevance and then the full texts against the criteria as stated. There are no claimed retrospective database hit totals, no screening numbers and no PRISMA flow statistics. This is a bounded, curated integrative synthesis and not a registered exhaustive systematic review. The 30 item bibliography lists the evidentiary corpus that has been used in this synthesis. The distinction is important to avoid a transparent review protocol being mistaken for an invented search audit.

We evaluated each source across four quality criteria: validity of the fault labels or event records, realism of the operating conditions, robustness of the evaluation design and usefulness for an actual integrity decision. Specific issues of concern were random splitting of temporally adjacent signals, class imbalance, absence of uncertainty bounds and testing only one machine. The narrative synthesis organised the findings by physical degradation, measurement architecture, prediction, decision thresholds and organisational assurance. Where findings were in conflict they were interpreted in terms of variation in duty, sensor location, data provenance and the target failure mode rather than simply being averaged into a single, un-supported pooled effect. Given the scarcity of comparable plant level outcomes, a meta-analysis would be inappropriate.

Thematic Literature Review and Critical Analysis:-

Failure physics and consequence pathways. Steam turbines are subject to rotor unbalance, misalignment, bearing distress, blade related vibration, thermal bow and transient induced strain. Their condition is therefore a function of the startup history, the steam conditions and the interaction between the shaft dynamics and the bearing support. Liang et al. (2023) show how dimensionality reduction and boosted classification can be used to identify reported turbine faults and Zhou et al. (2023) present a forecasting architecture for nuclear steam turbine monitoring. These are studies which do help in the interpretation of the signals but don't really establish any universal oilfield thresholds. A turbine operating under a different load cycle could in fact have a completely different baseline even if there's no physical defect present.

Compressors present a different integrity issue in that you've got aerodynamic surge or instability (in the dynamic machines) and valve leakage, pulsation or packing degradation (in the reciprocating machines). These can quickly cascade into seal damage, vibration and process release. Wang et al. (2023) use multiple measurement channels to provide reciprocating valve warnings; Lyu et al. (2024) look at decomposition and entropy features; Li et al. (2024) look at mixed fault signals. The methods are not mutually exclusive. Valve event signatures require the cycle and pressure context whereas surge prevention is dependent on the operating map position and the protection response. A good model has to be able to tell the difference between the actual state of the machine and the state of the anti-surge or shutdown protection that's demonstrated.

Pumps are subject to cavitation, recirculation, seal degradation, bearing damage and hydraulic off-design operation. Ahmad et al. (2022) look at the characteristics of multistage pumps, He et al. (2022) look at the classification of cavitation states under different temperature conditions. Karagiovanidis et al. (2023) show a low cost sensing option but the irrigation pump data cannot be taken as direct evidence of refinery pump reliability. Song et al. (2024) use a

combination of motor current and vibration to detect cavitation. The practical implication is that vibration alarms should be flow/pressure/speed/suction dependent as hydraulic excitation can produce the same signature as mechanical damage.

Measurement architecture and evidence quality. A single accelerometer rarely captures the full failure mechanism. Turbine surveillance benefits from shaft displacement, axial position, bearing temperature, and steam-process variables; compressor surveillance may require dynamic pressure, rod-load information, acoustic features, and seal-system parameters; pumps require flow and suction context alongside vibration, seal leakage, and motor current. Cabrera et al. (2024) show how acoustic-feature processing can support both compressor and pump classification. Ullah et al. (2023), Zaman et al. (2023) and Ahmad et al. (2023) demonstrate alternative pump-feature representations. Still, results on their study datasets cannot establish which method is most economical or robust across different oil and gas installations.

Read evidence from machine-learning diagnosis reviews critically. Gangsar et al. (2022) and Romanssini et al. (2023) catalogue approaches with differing sensors and fault definitions. Das et al. (2023) underline the breadth of methods across rotating machinery. The choice among spectral indicators, statistical change detection and neural networks should depend on the physical hypothesis, interpretability and expected prevalence of faults. A transparent trend model with a lower false-alarm burden may provide greater operational value than a highly accurate black-box classifier that frequently interrupts a critical unit.

Remaining-life estimation adds another layer of uncertainty. Wang et al. (2022) propose adaptive signal processing with temporal modelling; Deng et al. (2023) use attention mechanisms; and Gao et al. (2024) combine cyclostationary processing with sequence learning. Chelmiah et al. (2022) also illustrate model-based estimation from sensor features. Such methods generally require an observed progression toward a defined end-of-life event. Real plants often replace a bearing before failure, meaning maintenance intervention censors the outcome. Training on run-to-failure datasets can consequently overstate predictive precision for managed industrial assets.

Cross-equipment transfer requires caution. The scale-fractal investigation (2024) examines both pumps and reciprocating compressors, indicating that some feature-extraction ideas span machine classes. Yet the relation between a feature and a failure mechanism changes with geometry, excitation and operating regime. Transfer learning should begin as a monitored hypothesis, not an authorisation to transfer risk thresholds. Similarly, Wan et al. (2023) address speed variation relevant to multiple machines but do not eliminate the need for site-specific calibration.

Digital representation and integrity governance. Mitacc Meza et al. (2024) review digital-twin components for oil and gas and show the importance of integrating operational information. However, a continuously updated visualisation does not inherently constitute an independent protection layer. Wahono et al. (2025) note the growing use of machine learning in risk-based inspection, but its strongest historical applications concern equipment and degradation regimes that should not automatically be mapped to rotating machinery. Ayomoh and Ongwae (2025) emphasise organisational sustainability and process safety, suggesting that algorithmic outputs must be linked with management of change, competency and documented verification. This combination supports an integrity architecture that treats diagnostic evidence as one input to a broader decision system.

Environmental and operational context modifies evidential strength. A temperature excursion can change bearing clearance, lubricant viscosity and sensor response simultaneously; frequent starts introduce thermal cycles absent from steady-state training. Dust ingress and filtration performance may affect seals and lubrication, while process gas composition changes compressor thermodynamic loading. These exposures should be coded as contextual variables rather than automatically described as equipment faults. For every recorded warning, engineers should preserve the duty state and identify whether the observation preceded a maintenance action, followed a process change or coincided with a sensor replacement.

Data lineage is a practical control, not merely an information-technology concern. Duplicate tag names, modified scaling, intermittent historian records and unsynchronised timestamps can produce a persuasive but physically impossible fault trajectory. A minimum evidence record should therefore include machine identifier, sensor calibration status, sampling rate, timestamp quality, operating mode, maintenance event and alarm disposition. Where these fields are absent, experts should grade the inference as provisional. This protects against the common but mistaken assumption that increasing data volume necessarily increases decision reliability.

A failure-mode library must explicitly distinguish initiating faults from their consequences. Bearing wear, shaft contact and seal leakage are conditions or events, whereas fire escalation, environmental release and inability to meet process demand are outcomes. Mixing those categories creates inconsistent risk scores and can lead the same defect to be counted repeatedly. The proposed register should therefore use linked fields for component, mechanism, observable symptom, immediate functional failure, escalation scenario and available safeguard. This architecture also lets a change in process inventory alter consequence severity without implying that the underlying bearing deterioration rate has changed.

For turbines, shutdown and startup trajectories are as informative as steady-speed vibration. Thermal gradients can produce transient displacement patterns that do not resemble bearing damage, and protection setpoints may differ between startup and normal operation. Tag historical event windows by operating phase before model training or alarm interpretation. Whenever engineers update a turbine condition model, they should compare its recommendations against established machine protection settings and prevent the analytic layer from silently overriding independent trip functions.

For reciprocating compressors, valve-related warnings may depend on crank angle, discharge pressure, gas composition and machine speed. Sensor features that appear separable in a controlled test can overlap after unloading, changing throughput or maintenance. A traceable diagnostic should specify which stroke phase and physical measurement support the conclusion. For centrifugal compressors, process margin and anti-surge response belong in the integrity record even when a vibration-based model reports healthy bearings. This prevents structural condition monitoring from being mistaken for complete process protection.

For pumps, the monitoring baseline should document location on the system curve and the relationship between required and available suction head. Cavitation and low-flow recirculation may cause intermittent broadband vibration, making a single alarm threshold unreliable. An engineering interpretation needs evidence from suction pressure, temperature, flow, speed and the relevant liquid properties. For spare pumps, the register should identify periodic proving and common suction or power dependencies, because nominal installed redundancy does not ensure an immediately available substitute.

Table 1. Equipment-specific mechanisms, signals and decision safeguards (conceptual synthesis).

ASSET CLASS	THREAT PATHWAY	PRIORITY EVIDENCE	INTEGRITY DECISION SAFEGUARD
STEAM TURBINE	THERMAL BOW; ROTOR/BEARING DISTRESS; BLADE-RELATED INSTABILITY	SHAFT VIBRATION, AXIAL POSITION, TEMPERATURE, STARTUP PHASE	USE REGIME-SPECIFIC BASELINES; INDEPENDENTLY MAINTAIN OVERSPEED AND TRIP BARRIERS
COMPRESSOR	SURGE; SEAL FAILURE; VALVE LEAKAGE; PULSATION	MAP MARGIN, DYNAMIC PRESSURE, SEAL CONDITION, VIBRATION	SEPARATE ANTI-SURGE PROTECTION FROM MECHANICAL PROGNOSIS; ASSESS RELEASE CONSEQUENCE
INDUSTRIAL PUMP	CAVITATION; OFF-DESIGN OPERATION; SEAL AND BEARING DAMAGE	SUCTION PRESSURE, FLOW, MOTOR CURRENT, VIBRATION, SEAL LEAK	CONFIRM HYDRAULIC DUTY AND STANDBY READINESS BEFORE PRIORITIZING REPAIR

Proposed Risk-Based Asset Integrity Management Model:-

The proposed model comprises six linked functions. First, define an equipment hierarchy from train and duty position to vulnerable components, including standby configuration and shared utilities. Second, document credible failure modes and pathways using process hazard studies, maintenance history and engineering review. Third, maintain contextual condition indicators with explicit sensor-quality flags. Fourth, evaluate risk through the operator-approved, site-specific matrix or assessment method, using ISO 31000:2018 risk-management principles and IEC 31010:2019 assessment techniques alongside reliability-centred maintenance (RCM) analysis of functions, failure modes and consequences. Fifth, select and authorise actions under risk-acceptance rules. Sixth, verify outcomes and revise both engineering assumptions and monitoring models.

Criticality screening precedes quantitative optimisation. Any scenario with potential major injury, substantial release or loss of a required protective function receives mandatory engineering review regardless of its calculated expected cost. For other scenarios, likelihood and consequence should be assessed over a defined horizon using the facility's approved risk criteria, with safeguard effectiveness considered explicitly. ISO 31000 and IEC 31010 guide risk management and assessment techniques but do not prescribe one universal scoring matrix; RCM supports the selection of technically appropriate maintenance tasks. A single composite score should never hide a catastrophic consequence through averaging with low-severity failures. Confidence in sensors and models is a separate dimension: poor data quality can trigger inspection or conservative operating limits rather than artificially lowering the estimated failure probability.

The intervention logic is deliberately staged. Stable measurements within a validated duty envelope support continued monitoring; credible deterioration triggers diagnostic confirmation and scheduled work; accelerating deterioration, a failed barrier or an intolerable consequence triggers engineering escalation. Operators retain responsibility for safe operating limits, while reliability engineers assess diagnosis and remaining life, process-safety specialists evaluate escalation pathways, and maintenance planners convert approved decisions into resourced execution. Figure 1 summarises this governance sequence; Table 1 supplies asset-specific evidence requirements.

A workable criticality workshop should consider severity categories separately for personnel, environment, production and repair. Likelihood should refer to a stated time horizon and a defined event, such as loss of seal containment during the coming operating campaign, rather than an ambiguous probability of equipment failure. Independent safeguards should reduce estimated risk only when inspection or test evidence supports their availability and effectiveness. Standby equipment reduces continuity exposure only when its readiness and shared-cause vulnerabilities have been assessed. These definitions support a consistent assessment process without imposing a universal matrix. Each operator must use or approve risk categories, likelihood bands, tolerability criteria and escalation thresholds appropriate to its process hazards, regulatory obligations and risk appetite, while documenting any mapping between sites.

The model also needs an exception procedure for conflict between measurements and operator observation. An unexpected vibration increase during a documented speed transition may require repeat measurement rather than immediate component replacement. Conversely, a seal-fluid loss combined with normal bearing vibration may justify urgent action despite a favourable mechanical-health score. Zou et al. (2025) offer a further cross-domain turbine comparison, but its marine setting does not establish accuracy at a particular oil and gas facility. Such cases should enter a structured engineering review that records alternative hypotheses, physical checks, decision rationale and the deadline for reassessment. Suspend automated recommendations when required protection is unavailable.

Risk prioritisation should incorporate detectability only where it is defined and tested. A fault that produces a strong early vibration signature can still become hazardous if staffing, isolation or spares prevent timely response. Conversely, a less detectable defect may be mitigated by a proven independent shutdown function. The model therefore treats diagnostic lead time, organisational response time and protective-system availability as different variables. Their separation makes corrective actions more specific: improve measurement, reduce work-order delay or restore a barrier instead of applying a generic higher criticality score.

Performance review should examine negative cases as carefully as successful detections. False alarms create wasted interventions and may normalise alert-bypassing; missed events can reveal inadequate sensors, unsuitable failure labels, or changes in the operating envelope. Document each exception through a multidisciplinary review, and test model revisions on untouched time periods before release. Governance must also include a mechanism for reverting to conventional surveillance when analytic outputs become unreliable. This reversibility makes intelligent monitoring compatible with existing process safety practice.

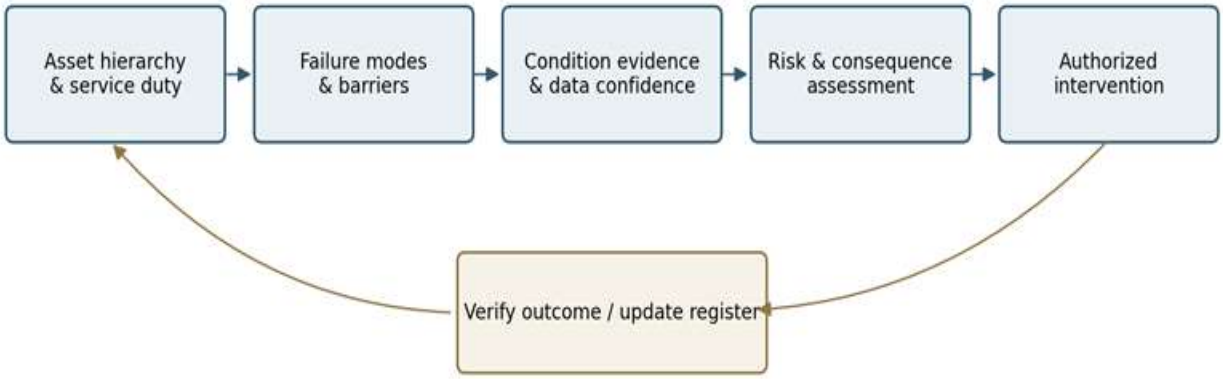


Figure 1. Six-function asset-integrity decision architecture with evidence feedback.

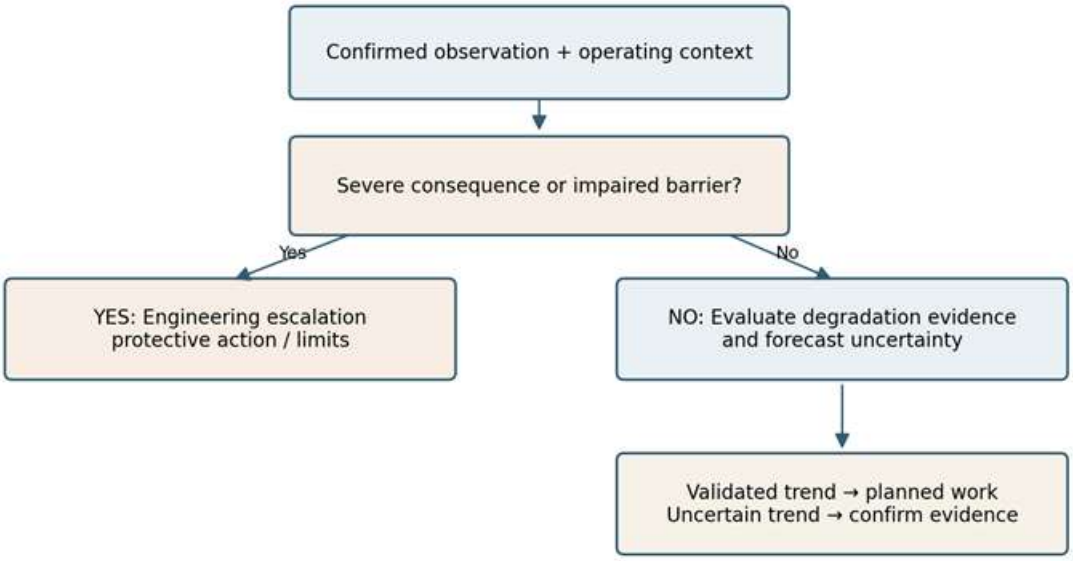


Figure 2. Consequence-sensitive screening and escalation pathway.

Discussion:-

The principal synthesis is that risk-based integrity management should not be reduced to predictive maintenance. Prediction asks what condition may occur; integrity management asks whether the existing asset, barriers and organisation can safely sustain a specified duty until an authorised intervention. This distinction matters when a steam turbine's rising vibration is tolerable only at reduced load, when a compressor's developing seal problem carries a release consequence, or when a pump is mechanically healthy. Still, its hydraulic operating point invites imminent cavitation. Similar alarm scores may demand materially different actions.

Evidence also indicates a measurement-to-decision gap. Pump deep-learning studies often demonstrate successful classification within controlled datasets (Ahmad et al., 2022; Zaman et al., 2023), while turbine and compressor studies increasingly combine signals and complex models (Zhou et al., 2023; Wang et al., 2023). None of these outcomes independently demonstrates fewer hazardous releases or superior turnaround decisions in operating oil and gas facilities. Direct deployment would require evidence on false negatives, lead time, intervention costs, alarm fatigue and the integrity of protective systems. A smaller, explainable model may therefore outperform a more elaborate predictor once the decision process is evaluated end to end.

The architecture reconciles two otherwise competing viewpoints. Reliability-centred prioritisation seeks to allocate scarce maintenance capacity efficiently; process safety requires some safeguards to remain non-negotiable, even when their failures are rare. Keeping consequence-screening and risk-based scheduling distinct avoids a false optimisation in which low predicted probability justifies neglecting severe scenarios. Uncertainty also becomes explicit: missing sensor data, changed operating duty, and unvalidated algorithms call for conservative review rather than silent acceptance. Figure 2 shows a decision pathway that operationalises

The framework can be adapted for refineries, gas processing facilities and upstream processing trains across different jurisdictions. Still, site-specific risk matrices, intervention thresholds and RCM task selections must reflect machinery configuration, duty cycle, environmental conditions, applicable regulations and the operator's approved risk criteria. Shared spare parts, remote support and contractor access can materially change repair exposure without changing failure physics. A defensible rollout thus begins with a limited number of critical trains, tests decisions against historical events and expert review, and expands only after measured results support transfer.

Table 2 translates the proposed structure into an evaluation matrix. Its measures distinguish technical performance, decision utility and assurance outcomes. An alarm can be technically correct yet too late to arrange a safe shutdown, or sufficiently early but too frequent for operators to trust. Validation should therefore follow the entire intervention chain from detection through confirmation, authorisation, execution and post-repair assessment. Without that chain, reported gains in classifier metrics risk becoming a misleading substitute for sustained integrity performance.

Cross-site learning is attractive where operators maintain fleets of nominally similar pumps or compressors, but naming conventions and duty conditions may differ across plants. Before aggregating data, agree on a common equipment taxonomy and standard units, along with definitions for faults, near misses, and maintenance actions. Shared models should preserve site-level calibration and prohibit unrestricted transfer of acceptance thresholds. Privacy and operational sensitivity can be respected through aggregated performance reporting while retaining controlled access to evidence needed for independent assurance.

Table 2. Suggested evaluation indicators for prospective multi-site field validation.

Evaluation domain	Proposed indicator	Interpretation / evidence needed
Diagnostic validity	False alarms per 1,000 operating hours; missed events	Time-ordered labelled events; operating-regime stratification
Timely intervention	Median validated warning-to-action time	Alarm, engineering review and work-order timestamps
Process safety assurance	Overdue critical barrier actions and impairment duration	Barrier test registers; independent process-safety review
Operational utility	Unplanned stoppages per train-year; justified interventions	Exposure-normalized comparison and maintenance adjudication
Data governance	Sensor uptime and unassessable predictions	Timestamp, calibration and model applicability records

Research Gaps and Future Research:-

Four gaps limit immediate generalisation. The first is external validity: many published classifiers are tested on controlled faults rather than rare, interacting plant defects. Future research should use multi-site, time-ordered validation with clearly reported operating envelopes. The second is causal attribution: correlations between vibration features and recorded repairs do not demonstrate that an intervention prevented failure. Prospective comparison of comparable trains, supported by documented operational changes, is necessary.

The third gap concerns uncertainty and class imbalance. Future studies should report calibrated probability, false-alarm burden per operating period, detection lead time and performance after sensor failure, not accuracy alone. The fourth concerns governance outcomes. Little transparent evidence links automated diagnostic alerts to barrier impairment, overdue critical work, operational deviations, and realised loss reduction. Future pilot projects at participating oil and gas facilities could create anonymised datasets that retain duty conditions, event definitions, and

maintenance outcomes while protecting sensitive operational information. Such datasets would enable independently reproducible comparisons and credible economic evaluations.

A particularly important experimental design is a stepped introduction across similar equipment trains. Investigators could document pre-existing work management, introduce the proposed decision protocol in phases, and compare outcomes while accounting for age, production duty and turnaround timing. Reviewers should distinguish avoided loss claims inferred from scenarios from actually recorded interruptions. Independent adjudication of alarms and maintenance findings would reduce confirmation bias, particularly when the same team develops the algorithm and judges its usefulness.

Practical, Managerial and Policy Implications:-

For operators, the first deliverable is a reconciled asset hierarchy connecting each turbine, compressor and pump to its duty, standby provision, process consequences, maintenance history and protection functions. Reliability personnel should standardise defect taxonomies and identify which observations genuinely discriminate a credible failure. Maintenance planners should confirm parts, competence, and outage windows before treating a model alert as an executable plan. Control-room teams need concise instructions specifying when to continue monitoring, change operating conditions, seek expert diagnosis or initiate a protective response.

For management, dashboard governance should separate equipment health, major-hazard exposure and information confidence. Suitable assurance indicators include unresolved high-consequence defects, overdue barrier tests, repeated protective trips, sensor availability and the interval between validated warning and intervention. Procurement decisions should assess lifecycle maintainability, access to raw measurements and interoperability rather than prioritising proprietary prediction scores. Contractors providing algorithms must disclose training boundaries, retraining triggers and responsibility for model changes.

For policy and assurance functions, the framework supports documented decision trails, competence requirements and periodic independent checks of high-consequence assumptions. Existing national rules, applicable plant codes and operator safety systems remain authoritative; the proposed model does not claim regulatory approval or substitute for statutory obligations. The appropriate governance objective is traceability: every high-risk decision should identify evidence, uncertainty, accountable approval, implemented action and post-action verification.

Assess implementation cost across the complete information lifecycle. Instrument installation, data retention, specialist interpretation, cybersecurity review, calibration and retraining may outweigh nominal software licensing. On older assets, adding one well-positioned sensor and improving maintenance-event coding could be more useful than a comprehensive digital twin. Managers should authorise instrumentation investments against specified failure mechanisms, demonstrable decision benefits and expected maintenance burden. A phased business case also preserves an exit option if field evidence is weak.

An integrity committee should review the highest-consequence scenarios periodically, not only when an alarm occurs. Its agenda can examine new operating modes, outstanding corrective work, impaired protection, inspection deferrals and recently learned failure mechanisms. Responsibilities should be fixed in a decision-rights matrix: operations controls immediate safety, engineering validates physical diagnosis, maintenance confirms intervention readiness, and management accepts residual business risk only within authorised limits. Signed decisions and dated revalidation points provide a stronger audit record than a dashboard colour alone.

Limitations:-

This review constructs a conceptual framework from heterogeneous peer-reviewed studies rather than evaluating operational plant datasets. The bibliography is curated, not exhaustive, and no database screening totals are represented as observed. Experimental machine diagnostics, cross-industry reviews and process-safety research provide different kinds of evidence, which restricts direct effect-size comparison. Several individual algorithms may be sensitive to unreported operating conditions, sensor placement and failure definitions. The proposed risk gates and workflow have not been calibrated against facility incident histories, applicable regulations or operator-approved risk matrices. Accordingly, the paper supports framework design and testable hypotheses, not a claim of quantified safety improvement, reduced failure frequency or demonstrated economic benefit.

Conclusion:-

A coherent integrity model for rotating equipment in oil and gas facilities must begin with credible failure consequences and machine-specific physics, then use monitored evidence to support rather than dictate intervention. The review establishes why turbines, compressors and pumps require distinct indicators, why predictive accuracy is insufficient without operational validation, and why major-hazard screening should remain separate from economic scheduling. The proposed six-function model links asset hierarchy, failure scenarios, contextual measurements, consequence-sensitive risk evaluation, authorised action and outcome verification. Its essential innovation is not another diagnostic algorithm but an auditable interface between prediction, protection and maintenance governance. The next research step is prospective testing on representative machinery trains across diverse oil and gas facilities with transparent event definitions, uncertainty reporting, barrier-performance measures and independently assessed decisions. Until such evidence is available, use the model as a structured design proposal rather than a validated industrial standard.

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