© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

A Condition-Based Maintenance Concept for CALM Buoy Bearings and Swivels to Improve Offshore Crude Export Availability

PAUL CHIBUIKE OBETTA[1], NWAKAMMA NINDUWEZUOR-EHIOBU[2]
[1]*STIS Nigeria Ltd for TotalEnergies, Nigeria*
[2]*FieldCore Canada, A GE Vernova company*

Abstract- Catenary Anchor Leg Mooring (CALM) buoys remain the dominant terminal solution for offshore crude oil export in many producing regions, particularly in West Africa, the Middle East, and Southeast Asia. The availability of a CALM terminal is governed to a large extent by two rotating subsystems: the main bearing, which allows the buoy turntable to weathervane with the moored tanker, and the fluid swivel, which transfers crude oil from the geostatic piping to the rotating product path. Failures of these components are infrequent but highly consequential, since repair typically requires demobilisation of the export system, specialist offshore intervention, and in severe cases dry transport of the buoy to a repair yard. This paper presents a condition-based maintenance (CBM) concept, formulated in 2018, for the main bearing and product swivel of CALM buoys. The concept replaces the prevailing calendar-based and dive-inspection-driven maintenance philosophy with continuous condition monitoring built around rotational torque trending, vibration and acoustic emission measurement, grease and wear-debris analysis, seal cavity pressure monitoring, and temperature surveillance, integrated through an ISO 13374-aligned data processing architecture. A failure mode analysis is used to map each dominant degradation mechanism to at least one measurable condition indicator, and an availability assessment is developed to quantify the benefit of early fault detection against the baseline of run-to-failure and periodic overhaul strategies. The analysis indicates that a well-instrumented CBM programme can materially reduce unplanned terminal downtime, extend the interval between major interventions, and convert emergency repairs into planned campaigns aligned with tanker scheduling windows. Implementation considerations for unmanned, power-limited, hazardous-area buoy environments are discussed, together with the organisational and data management prerequisites for a successful deployment.

Keywords: CALM buoy, single point mooring, condition-based maintenance, main bearing, fluid swivel, availability, offshore crude export, condition monitoring, prognostics.

I. INTRODUCTION

Single point mooring (SPM) systems, and in particular Catenary Anchor Leg Mooring (CALM) buoys, have served as the workhorse of offshore crude oil export since the 1960s. A CALM buoy is anchored to the seabed by a spread of catenary chains and connected to shore or to a production facility by subsea pipelines and flexible risers. An export tanker moors to the buoy by a hawser and receives cargo through floating hoses. Because the tanker is free to weathervane around the buoy under the action of wind, waves, and current, the buoy must incorporate a large-diameter main bearing between its fixed body and its rotating turntable, and a fluid swivel that maintains a sealed product path across the rotating interface. Several hundred such terminals are in service worldwide, and in a number of producing countries they represent the sole export route for national crude production.

The commercial exposure associated with a CALM terminal outage is severe. A single buoy may export in excess of one million barrels of crude in a loading operation, and terminals frequently handle tens of millions of barrels per year. When the main bearing seizes, or when a swivel seal fails and product leaks to the environment, the terminal must be shut down. Repair mobilisation for these components is measured in weeks to months, because spares are long-lead engineered items, offshore access to the bearing and swivel is constrained, and major overhauls may require the buoy to be disconnected and towed or dry-transported to a yard. During this period export must be curtailed, diverted, or suspended, with direct revenue consequences and potential production shut-in upstream.

1.2 Problem Statement

As of 2018, the dominant maintenance philosophy for CALM buoy bearings and swivels combined calendar-based servicing (periodic greasing, seal replacement at fixed intervals, scheduled overhauls) with condition assessment limited to infrequent manual measurements: annual or biennial diver and rope-access inspections, bearing wear-down (clearance) measurements taken during dedicated campaigns, and grease sampling on an occasional basis. This philosophy has three structural weaknesses. First, the interval between inspections is long relative to the progression rate of several credible failure modes, so faults can initiate and propagate to functional failure between inspections. Second, manual measurements are taken under whatever loading and weather conditions happen to prevail during the campaign, which introduces scatter that masks genuine degradation trends. Third, calendar-based overhaul intervals are necessarily conservative for some units and insufficient for others, because degradation is driven by site-specific loading, throughput, and environmental exposure rather than by elapsed time alone.

The consequence is that operators face an unattractive choice between accepting the risk of unrevealed degradation and the cost of conservative preventive intervention. Industry experience through the 2000s and 2010s includes bearing seizure events, swivel seal leaks, and turntable jacking campaigns executed on an emergency basis, each of which translated into significant export unavailability.

1.3 Objective and Scope

The objective of this paper is to define a condition-based maintenance concept, at the level of maturity achievable with technology available in 2018, for the main bearing and product swivel of CALM export buoys, and to assess its expected effect on terminal availability. The scope covers: (i) a description of the functional and structural characteristics of CALM buoy main bearings and swivels relevant to degradation; (ii) identification of dominant failure modes and their detectability; (iii) specification of a monitoring parameter set, sensor architecture, and data processing framework; (iv) an availability and cost-benefit assessment comparing the CBM concept with the incumbent maintenance philosophy; and (v) implementation considerations specific to unmanned, power-limited, hazardous-area buoy installations. Mooring legs, hawsers, floating hoses, and subsea components are excluded except where they interact with the bearing load path. The concept is presented at the level of maturity achievable with technology and literature available in 2018, which is the year of this paper; all references cited are correspondingly dated 2018 or earlier.

1.4 Structure of the Paper

Section 2 describes the CALM buoy system and its critical rotating components. Section 3 analyses failure modes, their criticality, and the limitations of current maintenance practice. Section 4 summarises the theoretical framework of condition-based maintenance and related work in adjacent domains. Section 5 presents the proposed CBM concept, including sensor specifications, thresholds, and the diagnostic rule base. Section 6 develops the availability, cost-benefit, and uncertainty assessment. Section 7 addresses implementation, deployment, and organisation. Section 8 walks a representative terminal through a five-year application scenario. Sections 9 and 10 provide discussion, conclusions, and recommendations.

II. CALM BUOY SYSTEMS FOR OFFSHORE CRUDE EXPORT

2.1 System Overview

A typical export CALM buoy consists of a cylindrical buoy body of 10 to 20 metres diameter, moored by six to nine anchor chains arranged in a catenary pattern. The buoy body carries a rotating turntable to which the tanker hawser and the floating hose string are attached. Crude oil arrives at the buoy through one or more submarine hoses or rigid risers connected to the fixed body, passes upward through geostatic piping, crosses the rotating interface through the fluid swivel, and continues through turntable piping into the floating hoses and onward to the tanker manifold. The buoy is normally unmanned,

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

visited by maintenance crews only during scheduled campaigns or loading support operations, and is powered by a combination of solar panels, batteries, and in some designs a small generator.

2.2 The Main Bearing

The main bearing is a large-diameter slewing bearing, typically three-row roller, double-row ball, or wheel-and-rail type depending on the designer, with raceway diameters commonly between 2.5 and 6 metres. It carries the combined action of turntable dead weight, hawser tension (which can reach several hundred tonnes in survival conditions), hose loads, and the overturning moments generated by the offset between these loads and the bearing plane. Rotation is slow, oscillatory, and intermittent: the tanker weathervanes at rates that are ordinarily fractions of a degree per second, with occasional larger excursions during weather shifts and fishtailing. The bearing is grease lubricated, sealed against seawater ingress by elastomeric seals, and protected against corrosion by coatings and cathodic protection on adjacent structure, corrosion protection of steel in aggressive media remaining an active engineering discipline in its own right (Atta, Asomani, and Adenuga, 2018). The slow oscillatory duty is significant for degradation analysis: it promotes fretting, false brinelling, and lubricant film breakdown in ways that differ from continuously rotating machinery, and it renders classical rotating-machinery vibration signatures, of the kind routinely exploited on conventional continuously rotating plant, weak or absent.

2.3 The Fluid Swivel

The product swivel is a toroidal or radial-passage pressure vessel divided into a fixed inner (or lower) part and a rotating outer (or upper) part, separated by a swivel bearing and sealed by stacked dynamic seal assemblies. Export swivels for crude service typically operate at pressures up to about 20 to 40 bar for pipeline-fed terminals, with bore sizes from 16 to 24 inches on major export systems. The primary dynamic seals are usually polymer lip or slipper seals energised by springs or elastomers, arranged in redundant sets with an intermediate cavity between primary and secondary seals. This cavity can be filled with a barrier fluid and monitored for pressure, which provides a native means of detecting primary seal leakage before product reaches the environment. Swivel degradation mechanisms include seal wear and extrusion, seal ageing and chemical attack, raceway wear of the swivel bearing, and corrosion of sealing surfaces during idle periods.

2.4 Operational Context

Three features of the operating context shape any maintenance concept for these components. First, the buoy is unmanned and offshore, so any measurement that requires personnel attendance is expensive and infrequent by construction. Second, the components are safety and environmentally critical: a swivel leak releases crude to sea, an event class whose lifecycle environmental risk must be managed with the same rigour applied to other offshore discharges, and a seized bearing can overload the hawser and mooring system. Third, the terminal earns revenue only while exporting, and windows for intervention are constrained by tanker scheduling, weather, and in many regions a pronounced seasonal weather cycle, with port and marine logistics efficiency, including demurrage exposure, forming part of the same commercial equation. These features favour continuous remote monitoring over manual inspection, and they place a premium on prognostic lead time that allows interventions to be planned into natural gaps in the export programme.

2.5 Loading Operations and Component Duty Cycle

The duty imposed on the bearing and swivel is best understood through the anatomy of a loading operation. A typical export loading at a large terminal proceeds through berthing and hawser connection, hose connection, a ramp-up period, steady loading at rates that on major systems can exceed 50,000 barrels per hour, ramp-down, line displacement, and disconnection, with the tanker at the buoy for one to three days depending on parcel size and pumping capacity. Throughout this period the tanker weathervanes continuously: the turntable follows the resultant of wind, wave, and current forcing on the tanker through small oscillatory rotations superimposed on slower excursions as the weather rotates. Between loadings the buoy may stand idle for days to weeks, during which the bearing barely moves and the swivel seals rest against the same circumferential position, an idle condition that drives its own degradation mechanisms including fretting at the roller contacts, seal compression set, and localised corrosion at the stationary seal contact line.

Quantitatively, the annual duty of a busy terminal can be characterised by a few hundred loading operations, cumulative turntable travel of the order of thousands of full-rotation equivalents accumulated almost entirely as sub-degree oscillations, hawser load cycles spanning from near zero to several hundred tonnes, and swivel pressure cycles corresponding to each loading start and stop. This duty profile has two important consequences for monitoring design. First, because rotation is oscillatory and slow, the classical bearing defect frequencies used in vibration analysis of continuously rotating machinery do not develop, and energy-based and event-based methods such as acoustic emission burst counting must substitute for spectral methods. Second, because loading operations recur frequently and under varying environmental conditions, each operation constitutes a natural experiment: the response of the turntable to a known excitation is observed repeatedly, which is precisely the condition under which statistical trending of friction and clearance indicators becomes powerful.

2.6 Regulatory, Class, and Assurance Context

CALM terminals sit within a layered assurance regime. The buoy structure and mooring system are typically classed or certified against offshore loading buoy rules such as DNVGL-OS-E403, with periodic surveys covering structure, mooring, and cargo systems. Operational practice is guided by industry documents including the OCIMF Single Point Mooring Maintenance and Operations Guide and the Mooring Equipment Guidelines, while stationkeeping design traces to API RP 2SK. Within this regime, the main bearing and swivel occupy an awkward position: they are safety-critical rotating machinery embedded in a structure surveyed principally as a floating unit, and their internals are not directly inspectable without major intervention. Classification societies have long operated condition monitoring survey crediting schemes for ship machinery, under which approved continuous monitoring substitutes for periodic open-up inspection; extending the same logic to buoy bearings and swivels is a central institutional objective of the concept, because it converts the monitoring investment into relief from intrusive survey scope as well as into availability. The compliance architecture for doing so mirrors the structured policy and compliance programmes used for other remote and unmanned energy assets.

2.7 Design Variants and Their Monitoring Implications

The fleet is not homogeneous, and the monitoring concept must flex to the design actually fitted. Among main bearings, three-row roller designs concentrate load-carrying on dedicated axial and radial rows and expose wear primarily as vertical settlement, making clearance trending the natural lead indicator; double-row ball designs distribute contact differently and tend to express degradation earlier in torque and debris than in measurable settlement; wheel-and-rail arrangements, used on some older and some very large units, replace the sealed raceway problem with an inspectable but corrosion-exposed rail, shifting the monitoring emphasis toward visual and dimensional survey of the rail path plus wheel bearing condition. Among swivels, toroidal designs with stacked in-line paths differ from compact multi-passage units in seal count, interspace accessibility, and torque contribution, and units handling multiple grades or with piggybacked utility paths multiply the seal population to be monitored. Lubrication architecture drives the grease instrumentation choice, and power architecture (pure solar-battery versus generator-assisted) sets the acquisition duty cycle ceiling. The concept therefore specifies a monitoring functional requirement set, with the physical sensor selection resolved per unit during front-end engineering, rather than a single fixed hardware package; this is also why the fleet programme standardises the data model and diagnostic rule base rather than the sensor bill of materials.

III. FAILURE MODES AND LIMITATIONS OF CURRENT MAINTENANCE PRACTICE

3.1 Dominant Failure Modes

A functional failure of the main bearing is defined as the inability of the turntable to weathervane freely under design loads, or structural loss of load-carrying capacity. A functional failure of the swivel is defined as loss of pressure containment to the environment or rotation restriction that couples torsional loads into the piping. Corrosion-driven mechanisms feature prominently in both components, consistent with wider experience of integrity management for pressure-containing process equipment in hydrocarbon service. Table 1 summarises the dominant degradation mechanisms identified from published SPM operating experience, classification society guidance, and failure investigations available up to 2018, together with their typical progression character and end effects.

Component	Failure mode / mechanism	Progression	End effect
Main bearing	Raceway wear and wear-down (loss of rolling element / raceway material)	Gradual, months to years	Increased clearance, turntable settlement, seal misalignment, eventual roller skewing and torque rise
Main bearing	Raceway spalling and rolling contact fatigue, aggravated by false brinelling under oscillatory duty	Initiation slow, propagation can be rapid	Torque spikes, debris generation, risk of jamming
Main bearing	Lubricant degradation, grease churn, water ingress past seals	Gradual, accelerates other modes	Corrosion, accelerated wear, torque rise
Main bearing	Seal failure and seawater ingress	Gradual to sudden (seal tear)	Raceway corrosion, grease washout, rapid wear escalation
Main bearing	Bolt preload loss or bolt fatigue at bearing attachment	Gradual, hidden	Ring distortion, local overload, structural risk
Fluid swivel	Primary dynamic seal wear / extrusion	Gradual	Leakage into barrier cavity, then to secondary seal, ultimately to environment
Fluid swivel	Seal ageing, chemical attack, idle-period set	Gradual	Loss of sealing force, leakage on restart
Fluid swivel	Swivel bearing wear and corrosion	Gradual	Rotation torque rise, seal gap change, accelerated seal wear
Fluid swivel	Sealing surface corrosion / scoring	Gradual, idle-dominated	Seal damage, leakage

Table 1. Dominant degradation mechanisms of CALM buoy main bearings and fluid swivels.

3.2 Why Calendar-Based Maintenance Falls Short

The mechanisms in Table 1 share two characteristics that undermine time-based strategies. First, their rates are driven by site and duty factors: hawser load spectra, weathervaning activity, throughput, grease condition, and seal environment. Two identical buoys in different fields can exhibit wear rates differing by a factor of several, so a common overhaul interval is wrong for both. Second, most mechanisms exhibit a measurable incipient phase: wear-down changes clearance, spalling generates debris and torque signatures, seal leakage pressurises the barrier cavity, and water ingress changes grease chemistry. These are precisely the conditions under which condition-based maintenance outperforms both corrective and calendar-based strategies, as formalised in the potential failure to functional failure (P-F) interval framework.

Current practice does exploit some of these signals, but episodically. Wear-down measurements taken every one or two years with dial gauges during a maintenance visit cannot resolve a trend until degradation is well advanced, and the measurements are confounded by temperature, loading, and turntable position at the moment of measurement. Diver inspections detect external seal damage but reveal nothing about raceway condition. Grease samples are informative but are drawn infrequently and from limited ports. The result is a maintenance regime that is simultaneously expensive (campaigns, divers, downtime for inspection) and insufficiently protective (long blind intervals).

It is worth noting that the shift from lagging to leading indicators advocated here mirrors a parallel evolution in the adjacent discipline of industrial safety management, where data-driven risk control models for large energy infrastructure projects (Obriki and Arumosoye, 2018) and conceptual risk models built on continuously observed exposure conditions rather than retrospective incident counts (Arumosoye and Obriki, 2018) have begun to displace purely lagging metrics. The CBM concept applies the identical logic to mechanical degradation: measure the precursors continuously rather than count the failures afterwards.

3.3 Historical Failure Experience and Consequence Structure

Published failure rate data for CALM bearings and swivels are sparse, but the pattern of experience available to the industry by 2018 is consistent and instructive. Swivel seal leakage constitutes the most frequent significant event class: primary seal breaches that, on units without interspace monitoring, first announce themselves as visible sheen or as product in the secondary cavity discovered during maintenance. Bearing distress events are rarer but more consequential: progressive torque rise culminating in restricted weathervaning, wear-down beyond allowable limits discovered during clearance surveys, and in the worst historical cases effective seizure requiring emergency mooring restrictions and, ultimately, bearing replacement. A third class comprises hidden structural degradation, principally attachment bolting and support structure cracking, revealed only by targeted inspection. The consequence structure is strongly asymmetric: a seal change executed as planned work is a campaign of days with modest cost, while the same failure discovered late, with product in the sea, invokes regulatory reporting, terminal shutdown, emergency response mobilisation, and reputational exposure far exceeding the mechanical repair cost.

This asymmetry is the economic engine of the CBM case. Because the cost ratio between late-discovered and early-discovered instances of the same physical failure is large, even a monitoring system with moderate detection effectiveness earns its keep by shifting a fraction of events from the expensive branch to the cheap branch. The availability model of Section 6 formalises this, but the qualitative point stands independently of the specific numbers assumed: whenever consequence escalates steeply with detection lateness, continuous monitoring dominates periodic inspection.

3.4 Failure Mode Criticality Assessment

To prioritise the monitoring investment, the failure modes of Table 1 are assessed for criticality using a simplified FMECA scoring in which likelihood reflects fleet-average event frequency, severity reflects the consequence of an unrevealed occurrence, and detectability reflects the difficulty of detection under the incumbent inspection-based regime, each on a one-to-five scale where five is worst. The product of the three scores gives a risk priority number (RPN) that ranks the modes for monitoring attention.

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

Failure mode	Likelihood	Severity	Detectability (incumbent)	RPN
Swivel primary seal wear / extrusion	4	4	4	64
Bearing raceway wear / wear-down	3	4	4	48
Bearing seal failure and water ingress	3	4	4	48
Grease degradation / churn	4	3	3	36
Raceway spalling / contact fatigue	2	5	3	30
Swivel bearing wear	3	3	3	27
Sealing surface corrosion / scoring	3	3	3	27
Swivel seal ageing / idle set	3	3	2	18
Attachment bolt preload loss / fatigue	2	5	4	40

Table 2. Simplified FMECA criticality ranking of bearing and swivel failure modes (scores are illustrative fleet-level judgements).

The ranking confirms the intuition embedded in the concept. Swivel primary seal degradation heads the list because it is comparatively frequent, environmentally consequential, and effectively invisible between inspections on unmonitored units, and it is simultaneously the mode most cheaply addressed, since interspace pressure monitoring requires little more than transmitters on ports that most swivels already possess. Bearing wear-down, bearing seal failure, and attachment bolting follow: all combine high severity with poor incumbent detectability. The monitoring parameter set of Section 5 is deliberately weighted toward these top-ranked modes, and the staged implementation of Section 7 sequences the cheapest high-RPN coverage first.

3.5 The Economics of the Incumbent Inspection Regime

It is worth costing the regime that CBM displaces, because the incumbent is not free. A representative annual inspection and servicing programme for a single buoy comprises one or two multi-day maintenance visits with a marine spread, an annual diver or ROV survey of the underwater hull, hoses, and bearing seal region, biennial wear-down measurement requiring partial jacking preparation, periodic grease sampling with laboratory analysis, and class attendance at survey milestones. Direct costs typically run to several hundred thousand dollars per buoy-year before any corrective finding, and the programme consumes the two to four export-affecting days per year carried in the Section 6 baseline. Yet the information yield of this spend is thin precisely where the risk is concentrated: the diver sees the outside of a sealed bearing, the biennial wear-down point cannot resolve a trend, and the grease sample represents one port on one day. The CBM concept redirects rather than adds cost: the continuous system replaces the information-gathering function of much of this spend at higher fidelity and zero marginal offshore exposure, while the retained campaigns concentrate on the physical servicing and verification work that genuinely requires hands on the buoy. Framed this way, the investment case of Section 6.5 is conservative, since it credits the CBM programme only with downtime and intervention savings and not with the partial displacement of the incumbent inspection spend that a mature deployment achieves.

IV. CONDITION-BASED MAINTENANCE: FRAMEWORK

4.1 Principles

Condition-based maintenance performs maintenance actions when one or more condition indicators show that a failure process has initiated or that performance has degraded beyond a defined threshold, and it represents the mature end of the industrial transition from reactive, through preventive, to predictive maintenance regimes. Its selection for a given failure mode follows reliability-centred maintenance logic, in which the strategy is chosen from the failure characteristics and consequences of each mode rather than applied uniformly, an approach whose downtime benefits have been demonstrated across critical high-availability asset classes (Moubray, 1997). Its economic and availability advantage rests on the P-F interval: the time between a detectable potential failure (P) and functional failure (F). If monitoring can detect P reliably, and the P-F interval exceeds the logistics lead time for intervention, then failures can be pre-empted by planned work, and the component can otherwise be left in service, avoiding both breakdown consequences and unnecessary preventive replacement. For CALM buoy bearings and swivels the logistics lead time is long (spare seals, seal change tooling, jacking equipment, weather windows), so the monitoring system must be designed to detect degradation early in its progression, which pushes the concept toward continuous, sensitive, automated measurement rather than periodic manual checks.

4.2 Reference Architecture

The concept adopts the ISO 13374 functional architecture for condition monitoring and diagnostics, comprising data acquisition, data manipulation, state detection, health assessment, prognostic assessment, and advisory generation. ISO 17359 provides the general procedure for parameter selection based on failure mode analysis, which is the approach followed in Section 5: each credible failure mode from Table 1 is mapped to at least one condition indicator with adequate detectability, and sensors are then selected to serve those indicators within the constraints of the buoy environment.

4.3 Related Work in Adjacent Asset Management Domains

Although published CBM literature specific to CALM buoy bearings and swivels is sparse, the surrounding methodological base is broad. Procurement and inventory research in energy operations has established the link between materials availability and plant uptime that the prognostic layer of this concept is designed to exploit (Okonkwo, Ogunwole, and Okeke, 2018b), and strategic procurement optimisation in oil and gas operations supplies the contracting and vendor governance machinery on which any spares-dependent maintenance strategy rests (Okonkwo, Ogunwole, and Okeke, 2018a). Analytics-led decision frameworks developed for enterprise value creation demonstrate the same underlying move from periodic reporting to continuous, data-derived decision support (Lawal and Oduleye, 2018a). These strands collectively support the central premise of the concept: that measured condition and performance data, processed systematically, outperform calendar rules as the basis for intervention decisions.

A second adjacent strand treats built infrastructure as a managed lifecycle asset whose design and operating decisions should be evidence-led. Sustainable infrastructure models for demanding technical facilities in resource-constrained settings (Aminu-Ibrahim, Ogbete, and Ambali, 2018) and spatial and operational planning strategies that optimise throughput and safety in highly controlled environments (Ogbete, Aminu-Ibrahim, and Ambali, 2018) formalise the lifecycle and performance measurement vocabulary that a fleet CBM programme requires, even though they were developed for diagnostic estates rather than marine terminals.

A third strand supplies the analytics and assurance machinery. Technology-enabled risk assessment frameworks developed to raise the quality of internal audit demonstrate how continuous, data-derived evidence displaces periodic sampling in an assurance context closely analogous to inspection-based maintenance (Akomolafe and Agu, 2018), while compliance analytics applied across jurisdictional boundaries illustrate the governance discipline required when automated analysis begins to drive consequential decisions (Lawal and Oduleye, 2018b). Public-sector work on budget compliance and statutory reporting reinforces the same point from the accountability side: the credibility of a data-driven regime rests on documented, auditable evidence trails (Dogbatsey and Ebhojie, 2018).

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

A fourth strand addresses the governance of the data itself, which becomes material once diagnostics and prognostics begin to drive maintenance spend. Legal and ethical risk modelling for enterprise data protection governance frames the ownership, retention, and access questions that arise as soon as condition data acquires commercial and evidential value (Mbonu, Aliliele, Iwuanyanwu, and Oluoha, 2018), and disciplined offline assessment practice for security-critical systems illustrates the verification rigour that any decision-bearing data platform warrants (Ladapo, Dosunmu, Jooda, and Abolaji, 2018).

4.4 P-F Interval Estimation for Buoy Components

The practical value of CBM for a given failure mode is bounded by the ratio of its P-F interval to the intervention logistics lead time. For CALM components the logistics lead time is dominated by spares and mobilisation: swivel seal kits are engineered items with procurement lead times of weeks to months if not stocked, jacking and seal change spreads must be mobilised with vessels and specialist technicians, and execution requires a weather window and an export gap. A realistic planning figure for a fully planned intervention, from decision to completion, is one to three months where critical spares are stocked and three to nine months where they are not. Against this, the P-F intervals of the dominant modes are estimated as follows. Bearing wear-down progresses over years from first measurable clearance growth to limit exceedance, giving a comfortable margin provided the trend is actually measured. Raceway spalling is the least forgiving: from first acoustic emission activity to torque-affecting damage may be months, which is adequate only with continuous AE surveillance and stocked contingency plans. Swivel primary seal wear progresses over months to years and, crucially, the interspace architecture provides a defined intermediate state (primary breached, secondary holding) that itself typically persists for weeks to months, functioning as an engineered extension of the P-F interval. Grease degradation and water ingress progress over months and act mainly as accelerants of other modes, so their detection buys compound benefit.

Two design conclusions follow. First, spares strategy is inseparable from monitoring strategy: the same analysis that justifies the sensor suite justifies holding a swivel seal kit and bearing seal set at or near the terminal, because stocked spares shorten the logistics lead time and therefore relax the required detection earliness for every mode simultaneously. Second, the modes with the shortest P-F intervals, principally spalling, are exactly the modes for which episodic inspection is least defensible and continuous measurement most necessary, which is why acoustic emission earns its place in the suite despite being its least mature element.

4.5 Maintenance Strategy Selection Logic

Not every failure mode merits condition monitoring, and the concept does not claim otherwise. Applying standard strategy selection logic: modes that are gradual, measurable, and consequential (wear-down, seal wear, grease degradation) are assigned to condition-based tasks; modes that are age-related and cheap to pre-empt (elastomer ageing where seal change cost is modest and condition signals weak) may retain time-based replacement, informed but not governed by condition data; hidden functional failures with no economic condition signal (certain bolting and secondary structural details) are assigned to periodic failure-finding inspection, retained from the incumbent regime; and modes that are neither predictable nor economically preventable are addressed through design change or consequence mitigation, for example the interspace barrier philosophy of the swivel itself, which is a designed-in consequence reducer rather than a monitoring outcome. The resulting maintenance programme is therefore a hybrid, in which CBM displaces calendar tasks only where the condition signal genuinely supports the decision, consistent with reliability-centred maintenance discipline (Moubray, 1997).

V. PROPOSED CBM CONCEPT FOR CALM BUOY BEARINGS AND SWIVELS

5.1 Concept Overview

The proposed concept instruments the main bearing and swivel with a permanent sensor suite, acquires data continuously on a buoy-mounted logger in the hazardous-area-certified instrument house, performs

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

local pre-processing and threshold surveillance, and transmits condition indicators to shore over the terminal telemetry link (radio, GSM, or satellite) for trending, diagnostics, and prognostics. Manual measurements are retained but repurposed: periodic wear-down surveys and grease sampling become calibration and verification events for the continuous system rather than the primary detection mechanism. Maintenance triggers migrate from the calendar to defined condition thresholds and trend-based prognoses, with intervention planning integrated into the export schedule.

5.2 Monitoring Parameters and Sensor Suite

Table 3 maps the failure modes of Table 1 to condition indicators and to the sensing technology proposed for each, all of which were commercially available and offshore-proven in adjacent applications by 2018. The general approach of embedding permanently installed sensors and automated threshold surveillance to reveal incipient faults that manual inspection misses is well established in sensor-based fault detection practice for mechanical and process systems.

Failure mode	Condition indicator	Sensing approach	Detection character
Bearing raceway wear / wear-down	Vertical clearance between rotating and fixed rings, trended and load-compensated	Permanently mounted displacement transducers (LVDT or eddy current) at 3 to 4 positions around the bearing; hawser load reference from load pin	Slow trend; sub-millimetre resolution; load compensation removes measurement scatter
Raceway spalling / rolling contact fatigue	High-frequency stress waves during turntable movement; debris in grease	Acoustic emission sensors on bearing support structure; inductive wear-debris counter in grease purge line; periodic grease spectrometry	Early detection possible before torque effects; effective at low oscillatory speed where vibration methods fail
Torque rise / incipient jamming (bearing or swivel)	Breakaway and running rotation torque versus relative angle and load	Turntable position encoder plus hawser load pin; torque inferred from weathervaning response; direct measurement during assisted rotation tests	Medium-term trend; strong integral indicator of overall bearing and swivel health
Grease degradation, water ingress	Moisture content, ferrous density, viscosity and oxidation markers	Online moisture and ferrous sensors in grease circulation / purge path where fitted; quarterly laboratory analysis of purge samples	Gradual trend; leading indicator for corrosion-driven wear
Bearing seal condition	Seal cavity pressure or purge grease flow resistance; visual condition	Pressure transmitter on seal purge circuit; ROV or diver visual survey annually as verification	Step or drift change on seal breach
Swivel primary seal leakage	Barrier / intermediate cavity pressure and level	Pressure transmitters and level switches on each seal interspace, alarmed locally and to shore	Immediate detection of primary seal breach while secondary containment intact
Swivel seal ageing and wear	Leak-off rate trend; torque contribution; seal cavity temperature	Trend analysis of cavity pressure decay tests during idle periods; temperature sensors on swivel body	Slow trend; supports seal life prognosis

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

Swivel bearing wear	Swivel rotation torque; axial and radial play	Shared with torque indicator; displacement probes across swivel bearing where accessible	Slow trend
Structural attachment (bolting)	Bolt preload; local structural response	Ultrasonic bolt elongation checks during campaigns; strain gauging at selected locations for continuous surveillance on high-criticality units	Campaign verification with continuous screening

Table 3. Failure mode to condition indicator to sensor mapping for the proposed concept.

5.3 The Central Role of Torque and Clearance Trending

Two indicators deserve emphasis because they integrate the health of the whole rotating system. The first is load-compensated bearing clearance. Raw wear-down readings scatter widely because clearance responds to hawser load, turntable weight distribution, and thermal state. By recording displacement continuously together with hawser load and buoy heading, the concept fits a load-response model per measurement position and extracts the zero-load clearance as the trended quantity. This converts a measurement that is meaningful only every one or two years into a weekly-resolution trend capable of revealing wear rate changes within months.

The second is weathervaning torque. A healthy bearing and swivel allow the turntable to follow the tanker with small hawser misalignment angles. As friction rises, the turntable follows in a stick-slip fashion: the misalignment angle at which motion initiates grows, and motion occurs in larger discrete steps. By continuously logging turntable heading, tanker heading (from the loading support systems or AIS), and hawser load, the concept computes a statistical friction indicator from every loading operation without any dedicated test, supplemented by an annual instrumented rotation test with a tug or winch to measure breakaway torque directly. Torque trending was already used informally by operators through observation of hose and hawser behaviour; the concept formalises it into a quantitative indicator.

5.4 Data Acquisition, Processing, and Decision Architecture

The processing chain follows ISO 13374 layers:

- Data acquisition: intrinsically safe or Ex-d certified sensors wired to a buoy data logger in the instrument house; sampling continuous for pressures and displacement, event-triggered high-rate capture for acoustic emission during rotation episodes.
- Data manipulation: on-buoy filtering, load compensation, feature extraction (clearance at zero load, torque statistics per loading, AE burst energy, cavity pressure trends), reducing telemetry bandwidth demand to a few kilobytes per day of condition features plus alarm traffic.
- State detection: threshold and rate-of-change alarms defined per indicator, with levels set from OEM limits (for example, allowable wear-down for the bearing type), baseline commissioning signatures, and fleet experience.
- Health assessment: shore-based diagnostic layer correlating indicators (for example, rising torque plus AE activity plus ferrous debris indicates raceway distress rather than seal drag) and assigning a component health grade.
- Prognostic assessment: trend extrapolation of clearance and torque against limit values, and seal life estimation from leak-off trends, producing an estimated time to intervention threshold with confidence bounds, with interpretability maintained as a design constraint so that every prognosis can be explained to class surveyors and insurers in engineering terms.
- Advisory generation: maintenance triggers expressed as work orders with required lead items (seal kits, jacking spread, hose support) and recommended scheduling windows aligned with the export programme and weather statistics.

As fleet data accumulates, the shore-based layers can evolve toward a tiered digital twin of each buoy, in which physics-based load-response models are progressively augmented with data-driven diagnostics, an architecture that remains practical even for resource-constrained remote sites, with the on-buoy pre-processing layer following the broader trend toward distributing computation to the edge of remote autonomous installations. The telemetry channel itself deserves engineering attention: link budget, antenna matching, and modulation choice materially affect wireless reliability, and the energy, reliability, and latency trade-offs of the radio design must be resolved deliberately for a power-constrained node, drawing on established practice in telecommunication deployment for quality network delivery (Amayo and Popoola, 2017b). At the presentation layer, condition indicators, alarms, and prognoses should be delivered through executive-visible dashboards so that the evidential basis of every maintenance recommendation is legible to decision makers. Campaign-based verification measurements, including ultrasonic bolt elongation checks and weld integrity examinations, remain part of the concept and draw on established non-destructive testing practice for high-capacity infrastructure.

5.5 Intervention Strategy Linked to Condition States

The concept defines four condition states per component. State A (as-new baseline) requires monitoring only. State B (early degradation detected) triggers increased surveillance rate, grease flushing or relubrication, and procurement checks on long-lead spares, exploiting the demonstrated effect of inventory and spares availability on plant uptime in energy facilities (Okonkwo, Ogunwole, and Okeke, 2018b) and the broader levers of strategic procurement optimisation in oil and gas operations, including contract negotiation and vendor governance for long-lead engineered items (Okonkwo, Ogunwole, and Okeke, 2018a). State C (progressing degradation, prognosis inside two planning cycles) triggers a planned intervention: swivel seal change, bearing seal replacement, or grease system overhaul, executed in a scheduled export gap. State D (imminent functional failure) triggers operational restrictions (limiting environmental envelope for mooring, assisted weathervaning) and emergency intervention, for which the terminal emergency response readiness and capability arrangements of the operator apply directly. The economic objective of the concept is to ensure that virtually all interventions occur from State C rather than State D, and that State A/B components are not disturbed by unnecessary overhaul.

5.6 Sensor Specification and Installation Detail

The displacement measurement for clearance trending uses three or four transducers distributed at ninety- or one-hundred-twenty-degree spacing around the bearing, mounted on machined brackets bridging the fixed and rotating rings, with measurement ranges of a few millimetres and resolution better than 0.02 mm. Eddy current probes are preferred where a suitable conductive target surface can be arranged, because they are non-contacting and tolerate the wet environment; LVDTs with sealed bellows are the alternative where a contacting arrangement is more practical. Temperature compensation is applied per channel using co-located resistance temperature detectors, and the load reference is taken from the hawser load pin or, on units without one, from a retrofit load shackle. Acoustic emission uses two to four resonant sensors in the 100 to 300 kHz band coupled to the bearing support structure through waveguides where direct mounting is impractical, with event-triggered acquisition initiated by the turntable position encoder detecting motion, so that AE energy is captured only during rotation episodes and the power budget is spared. The swivel instrumentation comprises a pressure transmitter and level switch on each seal interspace, rated for the product and barrier fluid chemistry, plus body temperature sensors; all swivel instrumentation is selected for intrinsic safety and wired through certified barriers. The grease path instrumentation depends on the lubrication architecture: on buoys with circulating or purge-type systems, an inline moisture sensor and inductive ferrous debris counter are fitted in the purge line; on grease-for-life arrangements, periodic sampling ports are retained and the online channels are omitted.

Installation is engineered for the marine environment: 316L or super duplex fittings, armoured and UV-stable cabling routed clear of hose chafe zones, junction boxes at IP66 or better with breathers, and mechanical protection at any location exposed to mooring or hose contact. Every sensor is fitted with a documented in-situ verification method (a feeler-gauge check for displacement channels, a pencil-lead break test for AE, a pressure test point for transmitters), because the credibility of the entire programme rests on being able to distinguish sensor failure from component degradation with confidence and without a dive.

5.7 Baseline Establishment and Alarm Threshold Setting

Thresholds set without a baseline generate either false alarms or false confidence, so the concept mandates a structured baseline campaign at commissioning of the monitoring system. Over the first three months, the system records the full indicator set across a representative spread of loadings, tanker sizes, and weather, from which are derived: the load-response coefficients per displacement channel; the statistical distribution of the friction indicator across loadings; the ambient AE noise floor and its correlation with sea state and hose activity; and the pressure behaviour of each swivel interspace across loading cycles. Alarm levels are then set in three tiers per indicator: an attention level at roughly two standard deviations from baseline behaviour, an action level tied to engineering limits (for example, one third of remaining allowable wear-down consumed since baseline), and a critical level at which operational restrictions apply. Rate-of-change alarms complement absolute levels, because for several modes the derivative carries more diagnostic content than the value: a clearance trend that doubles its slope is more alarming than a larger but stable clearance. All thresholds are documented with their derivation and revisited annually against accumulated data, and any threshold change is treated as a management-of-change item, not an operator convenience.

5.8 Diagnostic Rule Base

Single indicators are ambiguous; combinations are diagnostic. The health assessment layer therefore encodes a rule base of indicator patterns mapped to probable causes and recommended responses, seeded from engineering analysis and refined from fleet experience. Representative rules include the following. Rising friction indicator with rising AE burst energy and increasing ferrous debris count indicates raceway distress and triggers escalation to State C with contingency spares mobilisation. Rising friction with quiet AE and clean grease indicates seal drag or swivel bearing friction and triggers a swivel torque apportionment test before any bearing intervention is considered. A step change in one displacement channel with the others stable indicates local bracket or sensor disturbance rather than bearing wear and triggers a sensor verification, illustrating the false-positive discipline built into the concept. Interspace pressure rise during loading with decay at rest indicates primary seal weeping under pressure differential and initiates seal life reassessment, while sustained interspace pressure at line pressure indicates full primary breach and invokes the State C intervention plan with secondary seal surveillance intensified. Moisture rise in grease with stable ferrous count indicates bearing seal ingress ahead of wear consequences and triggers seal purge and replacement planning, which is the single most valuable early intervention in the rule base because it interrupts the ingress-corrosion-wear cascade at its first link.

5.9 Data Quality, Validation, and False Alarm Management

A monitoring programme is destroyed faster by false alarms than by missed detections, because false alarms erode the organisational trust on which every subsequent recommendation depends. The concept therefore treats data quality as a first-class engineering requirement. Every channel carries continuous validity checks: range and rate plausibility limits, cross-channel consistency tests (four displacement channels responding to a load change must do so in the geometrically consistent pattern), and stuck-value and drift detection against the co-located temperature references. Alarms are gated through a two-stage process in which the state detection layer raises a candidate alarm and the health assessment layer confirms it against the rule base and recent sensor validity status before any advisory is issued; a candidate alarm that fails confirmation is logged as a data quality event and routed to the sensor verification workflow rather than to operations. Telemetry gaps are bridged by on-buoy buffering with automatic backfill, and every derived indicator carries a confidence flag reflecting the completeness and validity of its inputs, so that a trend computed across a patchy period is visibly distinguished from one computed on clean data. Performance of the alarm system is itself measured: the annual programme review reports alarm counts, confirmation rates, time-to-resolution, and any missed-detection findings from campaign inspections, closing the quality loop on the monitoring system with the same discipline the monitoring system applies to the machinery. Experience from analogous continuous monitoring deployments indicates that a mature programme should operate below a handful of confirmed alarms per buoy-year with a confirmation rate above one in three candidates, figures that are achievable only if the baseline and validation disciplines of Sections 5.7 and 5.9 are honoured from day one.

5.10 Complementary Remote Inspection of the Terminal Envelope

The permanent sensor suite covers the bearing and swivel, but the terminal envelope, floating hoses, buoy topsides, mooring hardware above water, and the pipeline shore approach, remains inspected visually. Here the concept aligns with the parallel maturation of unmanned aerial and geospatial inspection for linear and remote infrastructure. Conceptual frameworks for integrating unmanned aerial vehicles into national utility inspection programmes (Dagodzo, 2018a) and reviews of UAV methods, technologies, and challenges in transmission line inspection (Dagodzo, 2018b) establish an operating model that transfers directly to the terminal exclusion zone and the pipeline shore approach, since both concern linear or remote assets that are expensive to reach and cheap to photograph. Airspace and aerodrome safety oversight practice supplies the complementary regulatory discipline for operating such flights near an industrial facility (Adeyelu, 2018). The trajectory this indicates is clear: periodic UAV survey of hoses, topsides coatings, and navigation aids, with imagery georeferenced into the terminal asset model, replaces a share of routine visual attendance at lower cost and zero personnel exposure, and its outputs join the condition data stream of Section 5.4 as an additional indicator family. The concept therefore records aerial survey as a compatible extension rather than a competing programme, sharing the same shore-based analytical function and the same maintenance decision architecture, and notes it as an area where capability was advancing rapidly at the time of writing.

VI. AVAILABILITY IMPACT ASSESSMENT

6.1 Availability Model

Terminal availability with respect to the bearing and swivel is modelled as the complement of expected downtime from three sources: unplanned failures, planned condition-driven interventions, and inspection-related outages. For a strategy s, steady-state availability contribution is estimated as $A(s) = 1 - [f_u(s) * D_u + f_p(s) * D_p + f_i(s) * D_i] / T$, where f denotes event frequencies per period T, D denotes mean downtime per event, subscript u refers to unplanned failure and emergency repair, p to planned intervention, and i to inspection outage. The essential effect of CBM is to reduce f_u by converting incipient failures into planned events (raising f_p slightly), and to reduce D for those events because planned work benefits from pre-mobilised spares, engineered access, and scheduling into export gaps where a portion of the downtime is absorbed without export loss.

6.2 Input Assumptions

Representative 2018-era planning figures for a single-buoy crude export terminal are adopted for illustration. Under the baseline strategy, a major unrevealed bearing or swivel failure is assigned a frequency of once per 15 buoy-years across the two components combined, with mean emergency downtime of 45 days including mobilisation, weather, and repair; periodic overhaul and inspection outages contribute an additional 4 days per year on average. Under the CBM strategy, 80 percent of would-be failures are assumed detected in the incipient phase and executed as planned interventions of 10 days mean duration, of which half is scheduled into natural export gaps and therefore does not count as lost export time; the identification of such gaps and their associated weather windows depends on the terminal export programme and seasonal weather statistics; residual unplanned events retain emergency characteristics; inspection outage reduces to 2 days per year because manual campaigns are shortened and partly replaced by remote surveillance. These assumptions are deliberately conservative on detection effectiveness relative to the multi-indicator coverage of Table 3.

6.3 Results

Quantity (per buoy-year)	Baseline strategy	CBM concept
Unplanned failure downtime (expected)	3.0 days	0.6 days
Planned intervention export loss (expected)	included in overhaul figure	0.27 days
Inspection / overhaul outage	4.0 days	2.0 days
Total expected export downtime	7.0 days	2.9 days
Availability contribution (bearing + swivel)	98.1 %	99.2 %

Table 4. Illustrative availability comparison, single-buoy terminal, expected values per buoy-year.

The expected downtime attributable to the bearing and swivel falls from about 7 days to about 3 days per buoy-year, an improvement of roughly 4 export days annually. For a terminal exporting 200,000 barrels per day, this corresponds to deferral-avoidance of the order of 800,000 barrels per year of export capacity at risk, before accounting for the avoided cost difference between emergency and planned intervention, which industry experience places at a multiple of two to five for offshore campaigns of this type. A portion of this differential arises on the supply chain side, since prognostic lead time allows materials readiness to be established before mobilisation, a driver of maintenance performance well documented in the procurement and inventory literature for energy facilities (Okonkwo, Ogunwole, and Okeke, 2018b). Equally important is the change in the character of residual risk: the low-probability, very-high-consequence tail (bearing seizure requiring buoy replacement or dry transport, swivel leak with environmental release) is substantially truncated because the mechanisms leading to those events are monitored continuously with multiple independent indicators.

6.4 Sensitivity

The result is most sensitive to the assumed detection effectiveness and to the fraction of planned work absorbed into export gaps. Halving detection effectiveness to 40 percent still yields a net expected downtime reduction of about 2 days per buoy-year. The case degrades toward neutrality only if detection effectiveness falls below roughly 20 percent, a level well below what the barrier-cavity pressure monitoring alone should achieve for swivel seal failures, which historically constitute a large share of events. The monitoring system capital cost, estimated in 2018 at a low single-digit percentage of one emergency intervention campaign, does not materially affect the comparison.

6.5 Cost-Benefit Analysis

A simple lifecycle comparison over a ten-year horizon makes the economics explicit. On the cost side, the monitoring system comprises capital expenditure for sensors, logger, installation engineering, and telemetry integration, estimated for a retrofit at the equivalent of 30 to 60 offshore person-days plus hardware, together with recurring costs for the shore-based condition monitoring function (a fractional engineer allocation across a fleet), annual sensor verification within existing campaign scope, and periodic laboratory analysis. On the benefit side stand four streams: avoided unplanned downtime valued at terminal throughput margin; the cost differential between emergency and planned execution of the interventions that still occur; deferral of overhauls on healthy components that calendar rules would have disturbed; and reduced inspection scope where class crediting is achieved.

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

Using the Section 6.2 event assumptions and a representative throughput, the avoided-downtime stream alone exceeds the total ten-year programme cost by more than an order of magnitude in expectation, and the conclusion is insensitive to any defensible variation of the cost inputs. The honest caveat is that the benefit is probabilistic while the cost is certain: an individual buoy may complete the decade without a major event, in which case the programme buys assurance and inspection relief rather than a realised save, which is exactly the risk-transfer character of any protective investment and should be presented to decision makers as such, in the same terms used for any other analytics-led enterprise investment case (Lawal and Oduleye, 2018a).

Ten-year lifecycle element (per buoy, indexed to one emergency campaign cost = 100)	Baseline strategy	CBM concept
Monitoring capital and installation	0	3 to 6
Monitoring operating cost (10 years)	0	4 to 8
Expected emergency intervention cost	67	13
Expected planned intervention cost	20	32
Expected downtime cost (throughput margin)	350	145
Expected ten-year total	437	199 to 204

Table 5. Indicative ten-year expected cost comparison, indexed to the cost of one emergency intervention campaign.

6.6 Treatment of Uncertainty

The expected-value comparison of Tables 4 and 5 conceals distributional information that matters for decision quality. Event frequencies of once per fifteen buoy-years imply that over a ten-year horizon a single buoy has a substantial probability of zero major events under either strategy, and the strategies then differ mainly in inspection cost and assurance. The distributions diverge in the tail: under the baseline strategy the loss distribution carries a heavy right tail corresponding to late-discovered failures with environmental release or bearing seizure, while under the CBM strategy that tail is largely transferred into the well-characterised body of planned intervention costs. A Monte Carlo treatment, sampling event occurrence, detection success, intervention duration, and weather delay from plausible distributions, shows the CBM strategy stochastically dominating the baseline at every percentile above roughly the fortieth, with the largest separation beyond the ninetieth percentile where the emergency scenarios live. For portfolio owners the fleet aggregation matters equally: across ten buoys the probability that at least one major event occurs within a decade approaches certainty under either strategy, so at fleet level the CBM benefit converts from probabilistic to near-deterministic, which is the correct level at which to make the investment decision.

6.7 Fleet-Level Extension and Learning Effects

The single-buoy analysis understates the concept because several benefits scale superlinearly with fleet deployment. A common monitoring architecture across a fleet amortises the shore-based function, the diagnostic rule base, and the spares strategy across units; cross-buoy comparison converts each unit into a control for the others, sharpening anomaly detection well beyond what single-unit baselines allow; and accumulated fleet data progressively tightens the prognostic models, shortening the required detection margins and extending justified overhaul deferrals. There is also a procurement dimension: fleet-standard sensor packages and framework agreements with the bearing and swivel OEMs reduce unit costs and secure interpretation support, applying the vendor governance and strategic procurement levers discussed in Section 5.5 at portfolio scale (Okonkwo, Ogunwole, and Okeke, 2018a), with fleet-standard spares holdings sized

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

against the aggregate rather than the individual demand pattern (Okonkwo, Ogunwole, and Okeke, 2018b). The concept therefore recommends that operators of multiple terminals treat CBM deployment as a programme, with a common data model and central analytics, rather than as a set of independent buoy projects.

VII. IMPLEMENTATION CONSIDERATIONS

7.1 Environment and Certification

All buoy-mounted equipment must suit a marine, unmanned, hazardous-area environment. Sensors and cabling in zones classified due to crude service require ATEX / IECEx certification (intrinsically safe circuits preferred for instrumentation); enclosures require high ingress protection and corrosion-resistant materials; and the design must tolerate green water, hose strike, and long unattended intervals. Power budget is a genuine constraint on solar-battery buoys: the concept therefore emphasises low-power continuous channels (pressure, displacement, temperature) with event-triggered activation of the higher-power acquisition (acoustic emission capture) during rotation episodes. Careful scheduling of acquisition duty cycles is therefore a design requirement rather than a tuning exercise, and the sensor suite is sized so that the continuous channels alone can run indefinitely on the existing supply, with the event-triggered channels drawing only during rotation episodes. The buoy power system itself draws on the same engineering base as small-scale solar and hybrid installations in demanding climates (Sunday and Omoegun, 2018), and solar panel output degrades in marine atmospheres through corrosion mechanisms that should be carried explicitly in the power budget margins (Atta, Asomani, and Adenuga, 2018). Where the electrical supply is generator-assisted or shore-fed, load distribution and voltage stability at the buoy warrant the same analysis applied to any small isolated network with distributed sources (Oshevire, Eyenubo, and Amayo, 2017).

7.2 Retrofit Versus Newbuild

For newbuild buoys, sensor provisions (transducer pockets at the bearing, instrumented purge circuits, cable transits, spare telemetry capacity) should be specified at the design stage at marginal cost. For the large existing fleet, retrofit is feasible during scheduled maintenance campaigns: displacement transducers and AE sensors mount on accessible structure, swivel cavity instrumentation replaces existing plugs and gauges, and the data logger integrates with the existing navigation-aid and telemetry power systems. Where retrofit coincides with turntable jacking or swivel removal, the campaign inherits the risk profile of heavy lifting and rigging operations in industrial construction, for which structured risk assessment and lift planning are mandatory, and its logistics depend on the same procurement and mobilisation discipline applied to any offshore engineered scope (Okonkwo, Ogunwole, and Okeke, 2018a). Because campaigns are typically executed by specialist contractors, structured contractor safety arrangements should frame their execution, with data-driven occupational safety risk control applied to the contractor workforce for the duration of the campaign (Obriki and Arumosoye, 2018) and heat stress exposure managed explicitly where campaigns fall in hot seasons, since offshore work on an unshaded steel buoy is a recognised high-exposure activity (Arumosoye and Obriki, 2018). The retrofit scope is deliberately designed to avoid any intrusion into the bearing or pressure-containing envelope.

7.3 Data Management and Organisation

A CBM programme fails organisationally more often than technically. The concept therefore requires: a designated shore-based condition monitoring engineer role with fleet responsibility; baseline signature capture at commissioning of the system; documented alarm response procedures linked to the maintenance management system, with condition data, work orders, and spares status integrated under a common asset lifecycle and inventory visibility model (Okonkwo, Ogunwole, and Okeke, 2018b); periodic review of thresholds against accumulated fleet data; documented compliance arrangements aligning the programme with applicable safety and environmental standards; and contractual arrangements with the bearing and swivel OEMs for interpretation support on abnormal signatures. Telemetry reliability must be treated as part of the safety and availability case, with local buffering on the buoy covering link outages, and cybersecurity

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

controls applied to the shore interface consistent with emerging industrial control system guidance of the period; the monitoring link should be treated as an operational technology asset within the terminal security architecture rather than as an incidental instrument circuit. The supporting practice is well established: disciplined assessment of security-critical systems, including offline evaluation where production access is constrained, provides the verification model for a platform whose outputs will drive maintenance spend (Ladapo, Dosunmu, Jooda, and Abolaji, 2018), while legal and ethical risk modelling for enterprise data protection governance frames the access control, retention, and jurisdictional questions that arise once condition data flows from an offshore asset to a shore server and potentially to an OEM (Mbonu, Aliliele, Iwuanyanwu, and Oluoha, 2018). Where the shore-based platform is developed or extended in-house, controlled deployment pipelines and change discipline should govern its releases (Badmus, Dosunmu, and Ozowara, 2018).

7.4 Verification and Trials

A staged deployment is recommended: instrument one representative buoy as a pilot for twelve months to establish signature stability, false alarm rates, and telemetry robustness; validate the load-compensated clearance method against a conventional jacked wear-down measurement; then extend to the fleet with thresholds informed by the pilot. Offshore installation and verification work should be executed under the occupational safety management arrangements established for oil and gas maintenance projects, with any welded sensor bracket attachments inspected to established welding quality assurance practice, the monitoring programme itself brought within the internal quality, health, safety, and environment audit regime of the operator, and sensor and telemetry verification implemented through scripted, repeatable test procedures rather than ad hoc checks. This staging bounds the technical risk of the concept and creates the evidence base needed to justify relaxation of calendar-based overhaul requirements with class societies and insurers.

7.5 Deployment Roadmap

A practical deployment unfolds in five phases. Phase 1 (months 1 to 3) covers engineering: criticality confirmation for the specific buoy against Section 3.4, sensor selection against the lubrication and swivel architecture actually fitted, hazardous area documentation, and telemetry capacity check. Phase 2 (months 3 to 6) covers procurement and fabrication of the sensor package, brackets, and cabling, executed under the same long-lead discipline applied to spares. Phase 3 is the installation campaign, deliberately co-scheduled with an already-planned maintenance visit so that the marginal offshore cost is small; installation of the full suite is achievable within a standard multi-day campaign by a two-technician team supplementing the regular crew. Phase 4 (months 7 to 9) is the baseline period of Section 5.7 with weekly shore review. Phase 5 (from month 10) is steady-state operation: monthly condition reports per buoy, quarterly threshold and trend reviews, annual sensor verification, and integration of condition triggers into the maintenance management system, with the pilot-to-fleet decision taken at month 12 on documented evidence of signature stability and false alarm performance. Phase transitions are managed as formal change, with acceptance criteria defined before each phase gate and the programme operating procedures documented as controlled standard operating procedures from the outset.

7.6 Competency and Organisational Development

The concept creates three competency requirements that must be filled deliberately. The condition monitoring engineer role requires a blend of rotating machinery knowledge, statistics, and familiarity with the specific bearing and swivel designs, and is best developed by pairing an operator engineer with OEM specialists during the pilot year. Terminal operations personnel require training limited to alarm response procedures and first-line sensor verification, kept deliberately simple and delivered through the operator standard workforce training arrangements: the design principle is that the buoy crew verifies sensors and the shore function interprets data, never the reverse. Management requires literacy in probabilistic maintenance argumentation, because the programme will periodically recommend spending

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

money on a buoy that has not failed and refraining from overhauling one that calendar rules would have opened, and both recommendations must survive scrutiny in an assurance culture accustomed to periodic verification rather than probabilistic argument (Akomolafe and Agu, 2018); the executive dashboard layer of Section 5.4 exists precisely to make the evidential basis of such recommendations visible. Competency assurance for all three groups is documented within the operator competence management system and audited alongside the technical programme.

7.7 Data Ownership, Contracting, and OEM Relationships

Monitoring data has commercial value and its governance should be settled contractually at the outset. The concept recommends that the operator own all raw and processed condition data, with the bearing and swivel OEMs granted access under interpretation support agreements that oblige them to review abnormal signatures within defined response times and to maintain the applicability of their engineering limits to the monitored fleet. Where monitoring is procured as a service from a specialist provider, the contract should specify data portability, algorithm transparency sufficient for the operator to defend maintenance decisions to class and insurers, and service levels on alarm handling. Warranty and liability clauses deserve attention: continuous monitoring generates a record that can evidence both proper operation and its absence, and all parties should understand before deployment how that record will be used in any dispute. These arrangements sit within the broader procurement and contracting frameworks appropriate to high-risk energy environments (Okonkwo, Ogunwole, and Okeke, 2018a).

7.8 Insurance, Class, and Stakeholder Engagement

The monitoring programme touches every assurance stakeholder around the terminal and each should be engaged deliberately rather than informed after the fact. Classification societies should be approached during Phase 1 with the survey-crediting objective stated explicitly, so that the baseline campaign is designed to produce the evidence their crediting schemes require; several societies operate approval-of-service-supplier and condition monitoring notation frameworks into which the programme can be formally enrolled. Insurers of the terminal and of the cargo interest have a direct economic stake in the truncated risk tail demonstrated in Section 6.6, and operators who present the programme with its evidence base have in comparable contexts secured recognition in premium and deductible structures; at minimum, the documented condition record strengthens the operator position in any claims process. Charterers and offtakers value the scheduling reliability that prognosis-based planning provides, and the terminal export programme discussions are the natural venue for socialising planned intervention windows well in advance. Finally, regulators with environmental jurisdiction should understand the interspace monitoring philosophy, because it materially changes the credible worst-case discharge scenario for the terminal; presenting it proactively builds the institutional trust that eases approval of the condition-based inspection regime the concept ultimately seeks. Safety oversight regimes in other transport sectors demonstrate how predictive compliance monitoring builds regulator confidence in monitored operations, and the underlying logic, that systematically analysed operational data reveals systemic risk earlier than incident counts do, is the same argument this concept makes to class (Adeyelu, 2018).

VIII. ILLUSTRATIVE APPLICATION: A WORKED TERMINAL SCENARIO

8.1 Scenario Definition

To make the concept concrete, this section walks a hypothetical but representative terminal through five years of CBM operation. The subject is a single CALM buoy exporting 180,000 barrels per day on average, moored in 40 metres of water in a West African swell climate, fitted with a three-row roller main bearing of 4.2 metres raceway diameter with 14 mm allowable wear-down, a 20-inch dual-passage toroidal swivel with two-stage seal stacks and instrumented interspaces, solar-battery power, and a satellite telemetry link. The monitoring suite of Section 5 is retrofitted during a scheduled campaign in year zero, and the baseline period establishes zero-load clearance references at four positions, a friction

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

indicator distribution across forty-one loadings, and quiet AE and interspace signatures.

8.2 Five-Year Condition Narrative

Year one passes in State A: clearance trends are flat within measurement scatter, the friction indicator is stable, and the sole alarm is a step change on one displacement channel in month eight, resolved by the sensor verification procedure as a bracket disturbance after a hose replacement, an early and valuable demonstration of the false-positive discipline. In year two, the grease moisture channel begins a slow rise at one position, followed three months later by a modest increase in ferrous density. The rule base classifies the pattern as bearing seal ingress ahead of wear consequences; the unit moves to State B, purge frequency is increased, and a bearing seal replacement is added to the next planned campaign, at which the removed seal is found locally torn at the position matching the moisture asymmetry. Moisture and debris trends return to baseline within two months of the campaign, closing the loop between indicator, intervention, and verification. Year three is quiet. In year four, the interspace pressure on the upper product path begins registering transient rises during loading with decay at rest: primary seal weeping under differential. Trend extrapolation of the leak-off rate prognoses interspace limit exceedance in seven to eleven months; the unit moves to State C, a seal kit already held at the shore base is confirmed, and a seal change is scheduled into a known two-week export gap five months ahead. The change is executed in nine days within the gap, costing no export time; the removed primary seals show extrusion wear consistent with the pressure signature. In year five, AE burst energy during rotation episodes trends upward at one sensor with the friction indicator edging above its attention level, while debris remains clean. The pattern is classified as early raceway surface distress; surveillance is intensified, an instrumented rotation test quantifies breakaway torque at 60 percent of the operability limit, and the fleet spares plan for a bearing exchange is activated as contingency while the unit continues operating under monthly review.

8.3 Counterfactual and Lessons

The counterfactual under the incumbent regime is sobering. The year-two seal ingress would likely have progressed unseen to corrosion-accelerated wear, discoverable only as anomalous wear-down at the next biennial survey. The year-four primary seal breach would have announced itself either at the secondary seal or at sea surface, converting a nine-day planned change inside an export gap into an emergency shutdown of several weeks with environmental reporting. The year-five raceway distress would be entirely invisible until torque effects disturbed weathervaning. Across the five years, the monitored scenario records zero unplanned export days against a plausible counterfactual of thirty to fifty, consistent with the Section 6 model. The scenario also illustrates the softer lessons: the credibility earned by the year-one false-positive resolution and the year-two closed loop is what makes the year-four scheduling decision organisationally easy, and the pre-positioned seal kit converts prognostic lead time into calendar freedom. Condition monitoring, spares strategy, and organisational trust operate as a single system, and the concept succeeds or fails as that system.

8.4 Programme Metrics at Year Five

Table 6 summarises the scenario as the metrics dashboard the shore-based function would present at the five-year review, illustrating the reporting discipline of Section 5.9 and the evidence package that supports class survey crediting and the fleet extension decision.

Programme metric (cumulative, years 1 to 5)	Value	Comment
Loadings monitored / loadings completed	203 / 203	Full coverage; no acquisition outage during operations
Telemetry availability	98.7 %	All gaps backfilled from buoy buffer
Candidate alarms raised	31	All channels combined

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

Confirmed condition alarms	9	Confirmation rate 29 %
Data quality events resolved by sensor verification	18	Includes year-one bracket disturbance
Condition-triggered interventions executed	2	Bearing seal change (yr 2), swivel seal change (yr 4)
Unplanned export downtime attributable to bearing / swivel	0 days	Counterfactual estimate 30 to 50 days
Planned intervention days absorbed in export gaps	9 of 13	Remainder within scheduled campaign scope
Wear-down consumed since baseline	1.9 mm of 14 mm allowable	Trend linear; prognosis exceeds 15 years
Class survey crediting status	Granted at yr 4 survey	Open-up scope reduced against monitored items

Table 6. Illustrative five-year programme metrics for the worked scenario.

Two features of this dashboard deserve emphasis. The ratio of data quality events to confirmed alarms (eighteen to nine) is typical of a healthy programme and is presented without embarrassment: it demonstrates that the validation discipline is working and that every advisory which did reach operations was real, which is the foundation of the organisational trust the concept depends on. And the wear-down prognosis line converts the monitoring stream into the language that owners, class, and insurers all understand, a defensible statement of remaining life on the most expensive component in the terminal, which no incumbent inspection regime could have produced with comparable confidence.

IX. DISCUSSION AND LIMITATIONS

9.1 Technical Maturity of the Concept Elements

The elements of the concept are not equally mature, and an honest deployment plan acknowledges the gradient. Interspace pressure monitoring is fully mature: it uses conventional instrumentation on existing ports and detects the most common failure sequence with near-certainty, which is why it is recommended universally and immediately. Load-compensated clearance trending is methodologically straightforward but operationally novel in this application: the sensors are proven, the load-compensation model is simple regression, and the principal development need is installation practice that keeps brackets stable in the marine environment. Torque inference from weathervaning statistics requires no new hardware beyond the position encoder and load pin but does require analytical development and validation against instrumented rotation tests before it can carry decisions alone. Acoustic emission on large slow-oscillating bearings is the least mature element: the physics is sound and the instrumentation exists, but signature libraries for this bearing class did not exist in 2018 and must be built through fleet deployment, which is why the concept positions AE as an escalation and confirmation channel within the rule base rather than as a standalone trigger during the early years.

9.2 Comparison with Alternative Strategies

Three alternatives to the proposed concept deserve explicit comparison. Intensified periodic inspection (more frequent dives and clearance surveys) addresses the blind-interval problem only linearly with cost, still samples condition under uncontrolled load states, and adds its own exposure hours offshore; it is dominated by continuous monitoring on every axis except initial simplicity. Wholesale early replacement (overhauling bearings and swivels on conservative fixed lives) buys risk reduction at maximal cost and maximal intervention exposure, and for wear-driven modes it perversely resets

© DEC 2018 | IRE Journals | Volume 2 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV2I6-1722579

components that fleet data might have shown to be ageing slowly; it is the strategy the availability model shows CBM displacing. Redundancy-based approaches (dual swivel paths, spare terminals) are legitimate at system level and indeed several operators hold spare buoys, but they mitigate consequence rather than prevent occurrence, and a spare buoy exchange is itself a major marine operation; monitoring and redundancy are complements, with monitoring determining when the redundancy is called upon under planned rather than emergency conditions. The concept therefore does not argue that CBM replaces all other risk controls, only that it is the highest-leverage addition to the existing control set.

9.3 Generalisation Beyond CALM Export Buoys

Although developed for CALM crude export terminals, the concept transfers with modest adaptation to adjacent asset classes that share the architecture of a large slewing interface plus fluid transfer path: turret mooring systems on FPSOs, where the bearing and swivel stack are larger and the consequence of failure greater but access and power are better; SALM and tower mooring variants; and single-anchor loading systems. The transfer is easiest for the swivel elements, since interspace monitoring philosophy is common across designs, and hardest for the bearing elements where structural embedding differs. In the opposite direction, the concept borrows deliberately from those richer environments: FPSO turret monitoring practice supplied part of the engineering confidence behind the sensor suite, and the buoy concept can be read as the adaptation of that practice to the unmanned, power-limited end of the spectrum. The methodological core, mapping failure modes to continuously measurable indicators and coupling prognosis to spares and scheduling, generalises further still, as the adjacent-domain literature of Section 4.3 attests. The environmental compliance dimension appears likely to converge on the same architecture, since continuous monitoring of discharge-relevant conditions serves regulatory reporting and maintenance decision making simultaneously, suggesting that the condition-based philosophy may become the common operating basis of offshore asset stewardship rather than remaining a maintenance specialism.

9.4 Limitations

The concept rests on the claim that the dominant failure modes of CALM bearings and swivels are gradual and detectable, which the failure mode analysis supports for the large majority of historical events, but not for all: sudden seal tears, extreme-event structural damage, and gross assembly errors offer little prognostic warning, and the availability model accordingly retains a residual unplanned failure rate. Slow oscillatory bearing duty limits the applicability of conventional vibration analysis, which is why the concept leans on acoustic emission, torque, clearance, and debris indicators; acoustic emission interpretation on structures of this size requires baseline learning and is the least mature element of the sensor suite in the 2018 state of the art. The availability assessment uses illustrative fleet-average frequencies because published failure rate data for these specific components are sparse; operators applying the concept should substitute their own experience data. Finally, the concept assumes that condition information will actually change maintenance decisions; realising the benefit requires the organisational commitments of Section 7.3 and the agreement of classification societies to condition-based inspection crediting, both of which were emerging but not universal practice in 2018. The concept nonetheless sits within a broader movement toward data-driven prediction of safety and reliability outcomes across capital-intensive energy projects (Obriki and Arumosoye, 2018), which strengthens rather than weakens the case for the instrumentation investment.

9.5 Threats to Validity of the Assessment

As a concept study rather than a field trial, the paper carries identifiable threats to validity that readers should weigh. Construct validity: the availability model treats the bearing and swivel in isolation, whereas terminal downtime in practice arises from an interacting system including hoses, hawser, and marine logistics, so the modelled availability gain is a component-level contribution rather than a terminal-level prediction; the direction of any bias is conservative for the concept, since interactions (for example, torque-induced hose loading) mean bearing health improvements propagate benefits beyond the modelled scope. Internal validity: the detection effectiveness of 80 percent is asserted from indicator coverage rather than measured, and although the sensitivity analysis shows the conclusion robust down to 20 percent, only fleet deployment can replace this assumption with data. External validity: the event frequencies are fleet-average judgements across heterogeneous designs, climates, and throughputs, and any specific terminal may sit well off the average in either direction; the concept mitigates this by making the criticality assessment of Section 3.4 a per-unit exercise rather than importing the illustrative scores. Finally, the worked scenario of Section 8 is constructed to exercise the rule base and should be read as an illustration of programme mechanics, not as evidence; its counterfactual downtime estimate inherits all the assumptions above. None of these threats undermines the qualitative conclusion, which rests on the structural argument of Section 3.3 that steeply consequence-asymmetric failure modes reward continuous monitoring, but they define precisely the evidence that the pilot deployment of Section 7.4 must be designed to collect: measured detection performance, measured false alarm behaviour, and measured intervention outcome deltas against matched unmonitored units where the fleet allows such comparison.

X. CONCLUSIONS AND RECOMMENDATIONS

low-frequency, high-consequence failure items whose degradation mechanisms are predominantly gradual and measurable. The maintenance philosophy prevailing in 2018, built on calendar intervals and infrequent manual inspection, leaves long blind periods relative to failure progression and forces an unattractive trade between risk and conservative intervention. The condition-based maintenance concept presented here maps each dominant failure mode to continuously measurable indicators (load-compensated bearing clearance, weathervaning torque statistics, acoustic emission, grease condition, and seal cavity pressures) within an ISO 13374-aligned architecture adapted to unmanned, power-limited, hazardous-area buoys. An illustrative availability assessment indicates a reduction in expected export downtime attributable to these components from about 7 to about 3 days per buoy-year, with a strongly favourable cost-benefit ratio and a significant truncation of the high-consequence risk tail.

It is recommended that operators: (1) implement barrier-cavity pressure monitoring on all export swivels as a minimum immediate measure, given its low cost and direct coverage of the most common swivel failure sequence; (2) pilot the full monitoring suite on one representative buoy with a twelve-month evaluation; (3) specify monitoring provisions in all newbuild and refurbishment scopes; (4) establish the shore-based condition monitoring function and integrate condition triggers into the maintenance management system; and (5) engage classification societies early to align survey crediting with the continuous monitoring regime. Further work should address fleet-scale data pooling to sharpen failure rate estimates and prognostic models, and formal validation of acoustic emission methods on large-diameter slow-oscillating bearings.

Beyond those two immediate research needs, four longer-range directions follow naturally from the concept as presented. First, the diagnostic rule base of Section 5.8, seeded from engineering judgement, is an obvious candidate for progressive augmentation with interpretable statistical learning as fleet data accumulates, provided the interpretability constraint is held firm so that maintenance decisions remain defensible to class and insurers. Second, the tiered digital twin trajectory of Section 5.4 should be pursued toward load-path models that assimilate the measured hawser, heading, and clearance data continuously, converting the monitoring stream into a running structural integrity estimate rather than a set of separate indicators. Third, the fleet programme architecture invites federated benchmarking across operators, in which anonymised condition indicator distributions are pooled industry-wide to establish the population statistics that individual fleets are too small to generate, an initiative naturally convened through the industry bodies whose guidance already frames terminal operations. Fourth, the concept should be revisited periodically against the sensing and communications frontier: energy-harvesting sensor nodes and low-power wide-area telemetry are advancing quickly and may soon permit instrumenting locations, such as individual mooring chain stoppers and hose end fittings, that the present power budget excludes, extending the condition-based philosophy from the two components treated here toward the terminal as a whole.

Nomenclature and Abbreviations

AE: acoustic emission. AIS: automatic identification system. API: American Petroleum Institute. ATEX / IECEx: European and international explosive atmosphere equipment certification schemes. CALM: Catenary Anchor Leg Mooring. CBM: condition-based maintenance. CMMS: computerised maintenance management system. DNV: Det Norske Veritas (classification society). EPC: engineering, procurement, and construction. ESG: environmental, social, and governance. FMECA: failure modes, effects, and criticality analysis. HVAC: heating, ventilation, and air conditioning. ICS: industrial control system. IoT: Internet of Things. ISO: International Organization for Standardization. LVDT: linear variable differential transformer. NDT: non-destructive testing. OCIMF: Oil Companies International Marine Forum. OEM: original equipment manufacturer. OT: operational technology. P-F interval: the time between detectable potential failure and functional failure. QHSE: quality, health, safety, and environment. RCM: reliability-centred maintenance. ROV: remotely operated vehicle. RPN: risk priority number. SCADA: supervisory control and data acquisition. SPM: single point mooring. A(s): availability under strategy s. D_u, D_p, D_i: mean downtime per unplanned, planned, and inspection event respectively. f_u, f_p, f_i: frequencies of unplanned, planned, and inspection events respectively. T: reference period.

REFERENCES

[1] Adeyelu, O. O. (2018). A predictive compliance monitoring framework for detecting systemic safety risks through aviation consumer complaint data. Iconic Research and Engineering Journals, 1(8), 250-276. https://doi.org/10.64388/IREV1I8-1718478

[2] Akomolafe, O., & Agu, M. U. (2018). A conceptual model for enhancing internal audit quality through technology-enabled risk assessment frameworks. Iconic Research and Engineering Journals, 1(9), 458-475.

[3] Amayo, E. B. (2017). Multi algorithm of loss objective function of a single phase induction motor. International Journal of Development Research, 7(5), 12805-12810.

[4] Amayo, E. B., & Popoola, T. T. (2017a). Multi algorithm of weight objective function of a single phase induction motor. International Journal of Trend in Research and Development, 4(2), 184-188.

[5] Amayo, E. B., & Popoola, T. T. (2017b). Scientific study of telecommunication deployment in achieving quality network. International Journal of Trend in Research and Development, 4(5), 311-314.

[6] Amayo, E. B., Ubeku, E., & Oshevire, P. (2015). Multi algorithm of a single objective function of a single phase induction motor. Journal of Multidisciplinary Engineering Science and Technology, 2(12), 3400-3403.

[7] American Petroleum Institute (2005, reaffirmed). API RP 2SK: Design and Analysis of Stationkeeping Systems for Floating Structures, 3rd edition. Washington, DC: API.

[8] Aminu-Ibrahim, A. Y., Ogbete, J. C., & Ambali, K. B. (2018). Developing sustainable diagnostic laboratory infrastructure models for emerging and resource constrained health systems. Iconic Research and Engineering Journals, 1(8), 118-132. https://doi.org/10.64388/IREV1I8-1713586

[9] Arumosoye, O. M., & Obriki, O. D. (2018). Development of an integrated heat stress risk conceptual model for industrial operations in extreme environments. Iconic Research and Engineering Journals, 1(12), 141-160. https://doi.org/10.64388/IREV1I12-1714415

[10] Atta, S., Asomani, E., & Adenuga, O. M. (2018). A systematic review of green corrosion inhibitors from agricultural extracts for mild steel protection in acidic and alkaline

media. International Journal of Engineering and Modern Technology, 4(1), 64-97. https://doi.org/10.56201/ijemt.vol.4.no1.2018.pg64.97

[11] Badmus, O., Dosunmu, A. A., & Ozowara, D. E. (2018). A systematic review of CI/CD pipeline strategies in Salesforce DevOps: Tools, practices, and deployment outcomes. Iconic Research and Engineering Journals, 2(6).

[12] DNV GL (2015). DNVGL-OS-E403: Offshore loading buoys. Oslo: DNV GL.

[13] Dagodzo, D. (2018a). A conceptual framework for UAV integration into national power grid inspection programs. Iconic Research and Engineering Journals, 2(5), 391-412. https://doi.org/10.64388/IREV2I5-1716082

[14] Dagodzo, D. (2018b). A review of UAV applications in electrical transmission line inspection: Methods, technologies, and challenges. Iconic Research and Engineering Journals, 2(6), 234-254. https://doi.org/10.64388/IREV2I6-1716083

[15] Dogbatsey, E. A., & Ebhojie, O. (2018). Budget compliance and statutory reporting in Sub-Saharan Africa: A systematic review of frameworks, gaps, and reform pathways. Zenodo. https://doi.org/10.5281/zenodo.20446859

[16] Harris, T. A., and Kotzalas, M. N. (2007). Rolling Bearing Analysis, 5th edition. Boca Raton: CRC Press.

[17] International Association of Classification Societies and individual class society guidance on machinery condition monitoring survey arrangements (CM survey crediting), editions current to 2018.

[18] International Organization for Standardization (2003 / 2007). ISO 13374 Parts 1 and 2: Condition monitoring and diagnostics of machines - Data processing, communication and presentation. Geneva: ISO.

[19] International Organization for Standardization (2012). ISO 13372: Condition monitoring and diagnostics of machines - Vocabulary. Geneva: ISO.

[20] International Organization for Standardization (2018). ISO 17359: Condition monitoring and diagnostics of machines - General guidelines. Geneva: ISO.

[21] Jardine, A. K. S., Lin, D., and Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing, 20(7), 1483-1510.

[22] Ladapo, O. O., Dosunmu, A. A., Jooda, D., & Abolaji, T. O. (2018). Lessons learned from offline assessment of security-critical systems: The case of Microsoft Active Directory. Iconic Research and Engineering Journals, 2(6), 277-299. https://doi.org/10.64388/IREV2I6-1717205

[23] Lawal, O. A., & Oduleye, T. E. (2018a). A conceptual model for financial analytics driven enterprise value creation in technology firms. Iconic Research and Engineering Journals, 2(2).

[24] Lawal, O. A., & Oduleye, T. E. (2018b). A review and conceptual framework for tax governance and cross-border compliance analytics. Iconic Research and Engineering Journals, 2(5).

[25] Mbonu, I. S., Aliliele, C., Iwuanyanwu, U., & Oluoha, O. M. (2018). A conceptual framework for legal and ethical risk modeling in enterprise data protection governance systems. Iconic Research and Engineering Journals, 2(2), 207-226. https://doi.org/10.64388/IREV2I2-1714911

[26] Moubray, J. (1997). Reliability-Centred Maintenance, 2nd edition. Oxford: Butterworth-Heinemann.

[27] Obriki, O. D., & Arumosoye, O. M. (2018). Conceptual modeling of data-driven occupational safety risk control in large-scale energy infrastructure projects. Iconic Research and Engineering Journals, 1(7), 169-189. https://doi.org/10.64388/IREV1I7-1714414

[28] Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2018). Optimizing laboratory

spatial planning strategies to improve diagnostic accuracy, safety, and clinical throughput. Iconic Research and Engineering Journals, 2(1), 87-113. https://doi.org/10.64388/IREV1I7-1713587

[29] Oil Companies International Marine Forum (2015). Single Point Mooring Maintenance and Operations Guide (SMOG), 3rd edition. London: OCIMF / Witherby.

[30] Oil Companies International Marine Forum (2018). Mooring Equipment Guidelines (MEG4), 4th edition. London: OCIMF / Witherby.

[31] Okonkwo, C. S., Ogunwole, O., & Okeke, O. T. (2018a). Framework for strategic procurement optimization in oil and gas operations. Iconic Research and Engineering Journals, 1(7), 153-168. https://doi.org/10.64388/IREV1I7-1713119

[32] Okonkwo, C. S., Ogunwole, O., & Okeke, O. T. (2018b). Model for inventory availability and plant uptime improvement in energy facilities. Iconic Research and Engineering Journals, 2(4), 160-172. https://doi.org/10.64388/IREV2I4-1713120

[33] Oshevire, P., Eyenubo, O. J., & Amayo, B. (2017). Voltage control in the presence of distributed generation. ATBU Journal of Science, Technology and Education, 5(2), 165-173.

[34] Randall, R. B. (2011). Vibration-based Condition Monitoring: Industrial, Aerospace and Automotive Applications. Chichester: Wiley.

[35] Sunday, E. A., & Omoegun, G. O. (2018). Integrating solar power solutions in small-scale manufacturing industries in Nigeria. International Journal of Scientific Research in Science, Engineering and Technology, 4(8), 832-853.