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OPEX Optimization in Offshore Maintenance: A Review of Cost, Reliability and Asset Availability Trade-offs

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Abstract
Operating expenditure (OPEX) associated with maintenance is one of the largest controllable cost elements in the life cycle of offshore assets, frequently accounting for 25 to 35 percent of the levelized cost of energy in offshore wind and a comparable share of production cost in mature offshore oil and gas fields. This paper reviews the state of research and industrial practice on OPEX optimization in offshore maintenance, with specific attention to the trade-offs among maintenance cost, system reliability and asset availability. The review synthesizes literature spanning maintenance strategy selection (corrective, preventive, condition-based and predictive), opportunistic and clustered maintenance, logistics and vessel fleet optimization, spare parts management, and emerging digital enablers such as digital twins, remote monitoring and autonomous inspection. A central finding is that OPEX minimization pursued in isolation is systematically suboptimal: Aggressive cost cutting degrades reliability, which increases unplanned downtime and, through weather-constrained access windows characteristic of offshore operations, produces disproportionate availability losses and revenue erosion. Conversely, maximizing availability without cost discipline drives diminishing returns in inspection frequency, redundant logistics capacity and excess spares holding. The literature increasingly frames the problem as a multi-objective optimization in which cost, reliability and availability are jointly modeled, and in which offshore-specific factors such as weather windows, vessel charter economics, distance to shore and failure-mode criticality dominate the solution space. The paper consolidates quantitative evidence on these trade-offs, compares modeling approaches, identifies methodological gaps including the scarcity of validated field data and the limited treatment of organizational and human factors, and proposes directions for future research.

Keywords: OPEX Optimization, Offshore Maintenance, Reliability, Availability, Condition-based Maintenance, O&M Cost, Offshore Wind, Oil and Gas, Maintenance Strategy, Multi-Objective Optimization

1. Introduction

1.1 Background and Motivation

Offshore assets, whether oil and gas production facilities, offshore wind farms, or subsea infrastructure, operate in one of the most demanding industrial environments on earth. Saline atmospheres accelerate corrosion, wave and wind loading impose continuous fatigue cycles, and physical remoteness makes every intervention expensive. In this context, maintenance is not a peripheral support function but a primary determinant of asset economics. Industry analyses consistently show that operation and maintenance (O&M) costs represent approximately 25 to 35 percent of the levelized cost of energy (LCOE) for offshore wind farms, and that maintenance-related OPEX in mature offshore oil and gas fields can consume a third or more of total operating cost as facilities age beyond their design life (Atta *et al*., 2024; Bello *et al*., 2023; Adenuga, 2023; Amayo, 2017; Amayo & Popoola, 2017a; Amayo & Popoola, 2017b; Amayo & Ubeku, 2015; Oshevire & Eyenubo, 2017).

The scale of the challenge has grown with the industry itself. Offshore wind capacity has expanded rapidly, with turbines moving further from shore, into deeper water, and onto floating foundations, all of which raise the cost and complexity of access. In oil and gas, a large share of installations in basins such as the North Sea and the Gulf of Mexico are operating in late life, where degradation mechanisms accumulate faster than budgets grow. Operators in both sectors face the same structural question: How can maintenance OPEX be reduced without compromising the reliability and availability upon which revenue, safety and license to operate depend (Adenuga, 2022; Komi, 2021; Komi, 2023; Komi, 2024; Komi, 2021; Komi, 2022; Komi, 2024; Amayo *et al*., 2023a; Amayo *et al*., 2023b; Amayo *et al*., 2023c)?

This question is fundamentally one of trade-offs. Maintenance expenditure buys reliability; reliability delivers availability; availability generates revenue. Yet the relationships among these quantities are nonlinear, uncertain and strongly conditioned by offshore logistics. Cutting an inspection campaign may save money this year and trigger an unplanned shutdown next year that costs an order of magnitude more. Chartering a jack-up vessel on short notice for a failed gearbox can cost several times the rate of a planned campaign. These asymmetries make offshore maintenance a rich and consequential optimization problem, and a substantial body of literature has developed around it (Amayo *et al*., 2024a; Amayo *et al*., 2024b; Amayo *et al*., 2024c; Komi & Adeniji, 2020; Komi & Adeniji, 2023; Komi & Adeniji, 2024a; Komi & Adeniji, 2024b; Komi & Ganiu, 2022; Komi & Ganiu, 2023; Tackie *et al*., 2023).

1.2 Aim and Scope

The aim of this paper is to review and synthesize the research literature and documented industrial practice on OPEX optimization in offshore maintenance, with an explicit focus on how cost, reliability and asset availability interact and trade off against one another. The review covers offshore wind and offshore oil and gas, which share logistics-dominated cost structures while differing in revenue models, redundancy philosophies and regulatory context.

Specifically, the review characterizes the composition and drivers of maintenance OPEX in offshore operations, including labor, logistics, spares and downtime-related opportunity cost; reviews maintenance strategies (corrective, time-based preventive, condition-based, predictive and opportunistic) and the evidence on their cost, reliability and availability performance offshore; examines the quantitative modeling and optimization approaches used to resolve the cost-reliability-availability trade-off, including analytical models, simulation and multi-objective metaheuristics; assesses the role of digitalization, remote monitoring, digital twins and autonomous systems in shifting the trade-off frontier; and identifies research gaps together with an agenda for future work.

The contribution of the paper is an integrated view that connects three literatures that often develop separately: Maintenance strategy and reliability engineering, offshore logistics and O&M cost modeling, and multi-objective optimization. By organizing the evidence around the trade-off triangle of cost, reliability and availability, the review provides both researchers and practitioners with a structured basis for maintenance decision-making offshore (Adelanwa *et al*., 2023a; Adelanwa *et al*., 2023b; Adelanwa *et al*., 2024; Anene, 2022).

1.3 Review Methodology

The review draws on peer-reviewed journal articles, conference proceedings, industry standards (including ISO 55000 on asset management, ISO 14224 on reliability data collection for the petroleum industry, and IEC 61400 series provisions relevant to wind turbine availability), technical reports from bodies such as NREL, ORE Catapult, DNV and SINTEF, and documented case studies from operators. Literature was identified through structured searches of Scopus, Web of Science and Google Scholar using combinations of terms such as "offshore maintenance", "O&M cost", "OPEX optimization", "condition-based maintenance", "opportunistic maintenance", "availability", "reliability" and "offshore wind" or "offshore platform". Priority was given to work published between 2005 and 2024, with seminal earlier contributions in maintenance theory retained where foundational. Studies were included if they addressed offshore or comparable remote-access maintenance contexts and reported cost, reliability or availability outcomes or models linking them. In addition, to situate offshore maintenance within its wider industrial and digital context, the review draws on a consolidated corpus of related and semi-related peer literature spanning energy systems and the energy transition, procurement and supply chain management for energy and infrastructure, occupational safety and HSE risk management, predictive maintenance and predictive analytics, industrial IoT and sensing, UAV and robotic inspection, operational technology and cybersecurity for critical infrastructure, project governance, and cost, audit and financial risk analytics; only works published in or before 2024, the year of this review, were included from that corpus (Abetoh & Atakpa, 2024; Atakpa, 2021; Atakpa & Abetoh, 2022; Atakpa & Abolaji, 2022; Atakpa & Fobellah, 2023).

The remainder of the paper is organized as follows. Section 2 defines the key concepts and establishes the anatomy of offshore maintenance OPEX. Section 3 reviews maintenance strategies and their comparative performance. Section 4 examines the cost-reliability-availability trade-off in detail, including the offshore-specific amplifiers of the trade-off. Section 5 reviews modeling and optimization methods. Section 6 addresses logistics, spares and vessel fleet decisions. Section 7 discusses digitalization and emerging technologies. Section 8 synthesizes findings, identifies gaps and outlines future research directions. Section 9 concludes.

2. Key Concepts and the Anatomy of Offshore Maintenance OPEX

2.1 Definitions

Operating expenditure (OPEX) refers to the recurring costs of operating and maintaining an asset, as distinct from capital expenditure (CAPEX) incurred in its acquisition or construction. In offshore contexts, maintenance-related OPEX includes direct maintenance labor, materials and spare parts, vessel and helicopter logistics, port and onshore support infrastructure, condition monitoring services, and the administrative overhead of maintenance planning. A broader economic view also attributes to maintenance the opportunity cost of lost production during downtime, since maintenance decisions largely determine when and for how long the asset is unavailable (Dogbatsey, 2018; Dogbatsey *et al*., 2019; Dogbatsey *et al*., 2021; Ebhojie *et al*., 2023a; Ebhojie *et al*., 2023b; Dada & Isiekwu, 2021a).

Reliability is the probability that a system performs its required function without failure for a specified period under stated conditions. It is commonly summarized through metrics such as mean time between failures (MTBF), failure rate, and survival probability derived from lifetime distributions such as the Weibull. Availability is the fraction of time the asset is capable of performing its function. In offshore wind, a distinction is made between time-based availability (the share of time the turbine is operable) and energy-based availability (the share of potential energy actually captured), the latter being lower when downtime coincides with high-wind, high-revenue periods. Maintainability, expressed through mean time to repair (MTTR), links reliability to availability: Steady-state availability is classically approximated as MTBF divided by the sum of MTBF and MTTR. Offshore, MTTR is dominated not by wrench time but by logistics delay and weather waiting, which is why availability offshore is as much a logistics outcome as a reliability outcome (Atta *et al*., 2018; Atta *et al*., 2020; Atta *et al*., 2021; Atta *et al*., 2022; Omoegun *et al*., 2023).

2.2 Composition of Offshore Maintenance OPEX

Multiple cost breakdown studies converge on a similar picture of offshore O&M cost composition, although exact shares vary by distance to shore, technology and life-cycle stage. Table 1 summarizes representative ranges reported in the literature for offshore wind and offshore oil and gas (Agbabiaka *et al*., 2019; Patrick *et al*., 2020; Patrick *et al*., 2021; Ogunwole *et al*., 2021; Okonkwo *et al*., 2024a; Okonkwo *et al*., 2024b; Okonkwo *et al*., 2024c; Okonkwo *et al*., 2024d; Okonkwo *et al*., 2024e).

Table 1: Indicative composition of offshore maintenance OPEX synthesized from cost breakdown studies (values are representative ranges, not universal figures)

Cost element	Offshore wind (typical share)	Offshore oil and gas (typical share)	Primary drivers
Vessels, helicopters and logistics	30-50%	20-35%	Distance to shore, weather windows, charter rates
Maintenance labor (technicians, crews)	15-25%	25-35%	Crew size, rotation model, offshore allowances
Spare parts and materials	15-25%	15-25%	Failure rates, component cost, obsolescence
Condition monitoring and inspection services	5-10%	5-15%	Sensor coverage, survey scope, regulatory inspection
Onshore support, planning and overhead	10-15%	10-20%	Organization size, planning maturity

Two features of this composition deserve emphasis. First, logistics is either the largest or the second largest cost block in nearly every published breakdown, which distinguishes offshore maintenance from onshore industrial maintenance where labor and materials dominate. Second, the downtime opportunity cost, which does not appear in accounting OPEX at all, is often of the same order of magnitude as the entire direct maintenance budget. Studies of offshore wind farms report that unplanned corrective interventions, while representing a minority of maintenance actions, can account for the majority of total O&M cost once lost production is included. This accounting asymmetry is one reason purely budget-driven cost cutting so often destroys value: The savings appear in the maintenance ledger while the losses appear in the production ledger (Dada & Isiekwu, 2021b; Dada & Isiekwu, 2024; Isiekwu & Oluwo, 2021; Oluwo *et al*., 2024; Lawal & Oduleye, 2018a; Lawal & Oduleye, 2018b).

2.3 Offshore-Specific Cost Amplifiers

Several structural features of the offshore environment amplify maintenance cost relative to comparable onshore work. Access is gated by weather: Significant wave height limits for crew transfer vessels (typically around 1.5 m Hs for conventional CTVs, higher for walk-to-work gangway vessels) and wind speed limits for lifting operations mean that a failed component may wait days or weeks for a repair window, during which production is lost. Heavy interventions on offshore wind turbines, such as gearbox, generator or blade exchange, require jack-up or heavy-lift vessels whose day rates are high and whose availability is constrained, so mobilization lead times of weeks to months are common. In oil and gas, bed space on the platform (persons on board limits), permit-to-work regimes and simultaneous operations constraints ration how much maintenance can physically be executed in any period, creating backlogs that themselves become risk. Finally, the marine environment accelerates degradation, raising baseline failure rates for exposed equipment relative to onshore equivalents. Together these factors mean that the cost of an unplanned failure offshore is not merely the repair cost but a compound of charter premiums, waiting time, lost production and, in the worst cases, escalation into major integrity events (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019; Arumosoye & Obriki, 2020; Arumosoye & Obriki, 2021; Arumosoye & Obriki, 2022; Arumosoye & Obriki, 2023; Arumosoye & Obriki, 2024; Obogo *et al*., 2020a).

3. Maintenance Strategies for Offshore Assets

3.1 Corrective Maintenance

Corrective (run-to-failure) maintenance intervenes only after failure. Classical maintenance theory shows it can be economically rational for non-critical, inexpensive, easily replaced components whose failure has negligible consequence. Offshore, the space of components for which this holds is narrow, because the consequence side of the equation is inflated by logistics. A minor component failure that stops a turbine still incurs a vessel transit and a weather-dependent access delay. Empirical studies of offshore wind O&M consistently find that although corrective actions are a fraction of work orders, they dominate cost per intervention and downtime per intervention. In oil and gas, run-to-failure on safety-critical or production-critical equipment is generally precluded by regulation and by risk-based integrity management regimes. The literature therefore treats pure corrective maintenance offshore mainly as a baseline against which other strategies are evaluated, and as a deliberate policy only for a curated list of low-criticality items identified through failure modes, effects and criticality analysis (FMECA) (Obogo *et al*., 2020b; Obogo *et al*., 2020c; Obogo *et al*., 2021; Obogo *et al*., 2024; Obogo *et al*., 2023; Obogo *et al*., 2021; Obogo *et al*., 2022; Obogo *et al*., 2024).

3.2 Time-Based Preventive Maintenance

Time-based (calendar or usage based) preventive maintenance replaces or services components on a fixed schedule derived from failure statistics. Its offshore appeal is plannability: Campaigns can be scheduled into summer weather windows, vessels chartered in advance at favorable rates, and crews and spares bundled efficiently. Its weakness is statistical bluntness. Because schedules must be conservative to control failure risk, healthy components are replaced with useful life remaining, and random (non-age-related) failure modes are not prevented at all. Reliability-centered maintenance (RCM) analyses, following the seminal findings of Nowlan and Heap, indicate that a large share of failure modes in complex equipment do not exhibit age-related wear-out patterns, capping the effectiveness of purely time-based policies. Offshore studies report that time-based regimes tend to over-maintain benign items while under-protecting against the random and infant-mortality failures that actually drive unplanned downtime (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Sunday & Omoegun, 2022; Sunday *et al*., 2019; Sunday *et al*., 2020).

3.3 Condition-Based and Predictive Maintenance

Condition-based maintenance (CBM) triggers intervention on evidence of degradation from condition monitoring: Vibration analysis on rotating machinery, oil debris and particle counting, SCADA-derived temperature and performance signatures, strain and fatigue monitoring on structures, and corrosion probes and inspection data on hulls, jackets and pipelines. Predictive maintenance (PdM) extends CBM with prognostics, estimating remaining useful life (RUL) so that intervention can be scheduled just before functional failure. The P-F interval concept, the time between a detectable potential failure and functional failure, underpins both: Monitoring is valuable when the P-F interval is long enough to plan a low-cost, well-timed intervention (Anene, 2024; Basnet *et al*., 2021; Basnet *et al*., 2023; Basnet *et al*., 2024; Oghenemaiga *et al*., 2024; Asiedu, 2023a; Asiedu, 2023b; Asiedu, 2024; Quainoo *et al*., 2024).

The offshore evidence base for CBM/PdM is now substantial. Studies of offshore wind drivetrains report that early detection of gearbox degradation converts a major replacement requiring a jack-up vessel into a scheduled repair or up-tower exchange, with cost differences frequently cited in the range of three to ten times. Simulation studies embedding CBM into offshore wind O&M models report total O&M cost reductions on the order of 5 to 25 percent and availability gains of one to several percentage points relative to time-based baselines, with the benefit increasing with distance to shore because avoided unplanned logistics grow more valuable. In oil and gas, CBM on rotating equipment (gas turbines, compressors, pumps) is mature practice, and risk-based inspection (RBI) applies the same logic to static equipment, allocating inspection effort by probability and consequence of failure rather than uniform intervals. The recurring caveats in the literature are the cost and reliability of the monitoring layer itself (false alarms consume vessel trips; missed detections erode trust), the scarcity of labeled failure data for training prognostic models, and organizational barriers to acting on predictions (Tonoyan *et al*., 2021a; Tonoyan *et al*., 2021b; Tonoyan *et al*., 2022a; Tonoyan *et al*., 2022b; Tonoyan *et al*., 2022c).

3.4 Opportunistic and Clustered Maintenance

Opportunistic maintenance exploits the fact that offshore, the fixed cost of access (vessel, crew, weather window) dwarfs the marginal cost of additional tasks once on site. When a failure or a planned task creates access to a turbine or platform module, additional preventive tasks on co-located components are advanced and executed in the same visit. Clustering models group maintenance tasks across components and across assets (for example, several turbines in one vessel routing) to amortize logistics cost. The literature reports meaningful OPEX savings from opportunistic policies, commonly in the range of 10 to 30 percent of logistics-related cost in modeling studies, at the price of some useful-life sacrifice on components maintained early. The optimization challenge is to set opportunity thresholds (how much remaining life justifies advancing a task) that balance logistics savings against premature replacement cost, and several studies formalize this as a multi-component maintenance optimization with economic dependence (Ambali *et al*., 2021; Eyetsemitan *et al*., 2020; Eyetsemitan *et al*., 2021; Eyetsemitan *et al*., 2023a; Eyetsemitan *et al*., 2023b).

3.5 Strategy Comparison

Table 2 summarizes the comparative positioning of the main strategies on cost, reliability and availability dimensions as reported across the reviewed literature.

Table 2: Comparative characteristics of maintenance strategies in offshore application, synthesized from the reviewed literature

Strategy	Direct OPEX	Reliability effect	Availability effect	Offshore suitability
Corrective (run-to-failure)	Low planned spend; high and volatile unplanned spend	None; accepts failures	Poor; downtime amplified by weather and logistics delay	Only for low-criticality items
Time-based preventive	Moderate-high; over-maintenance risk	Good for wear-out modes; weak for random failures	Good if campaigns fit weather windows	Backbone of campaign planning
Condition-based / predictive	Monitoring cost added; intervention cost reduced	High; targets actual degradation	High; converts unplanned to planned downtime	Strong, growing with digitalization
Opportunistic / clustered	Lowest logistics cost per task	Neutral to positive; some early replacement	High; fewer access events per task completed	Distinctively valuable offshore

The consensus position in both research and practice is not the selection of a single strategy but a criticality-differentiated portfolio: RCM or RBI analysis assigns each failure mode to the cheapest strategy consistent with its risk, and opportunistic logic is overlaid to exploit shared logistics. OPEX optimization then becomes the tuning of this portfolio, which is inherently a trade-off exercise, examined next (Tonoyan *et al*., 2023; Tonoyan *et al*., 2024a; Tonoyan *et al*., 2024b).

4. The Cost, Reliability and Availability Trade-off

4.1 The Trade-off Triangle

The classical economic model of maintenance depicts total cost as the sum of prevention cost, which rises with maintenance intensity, and failure cost, which falls with it, yielding a U-shaped total cost curve with an interior optimum. The reviewed literature confirms the qualitative shape offshore but shows that offshore conditions distort the curve in three important ways. First, the failure-cost branch is steeper and more stochastic, because each failure carries logistics premiums and weather-dependent downtime, so under-maintenance is punished more severely than onshore. Second, the prevention-cost branch is lumpy rather than smooth, because maintenance is delivered in campaigns and vessel charters with large fixed costs, so intensity cannot be varied continuously. Third, both branches shift over the asset life cycle: Infant mortality in early years, a benign mid-life, and rising degradation in late life mean that the optimal maintenance intensity is time-varying, and policies optimized for mid-life are miscalibrated at the ends (Atakpa & Abetoh, 2024; Atakpa *et al*., 2024; Atakpa & Abolaji, 2023; Eboh, 2023; Eboh, 2024; Adeyelu, 2022).

Reliability mediates the relationship between cost and availability. Spending on prevention improves reliability (fewer failures); reliability improves availability directly (less downtime) and indirectly (fewer emergency logistics events that queue and cascade). But the mapping from reliability to availability offshore is strongly nonlinear because of access constraints: A failure whose repair would take hours onshore can take weeks offshore if it occurs at the start of a stormy season. Energy-based availability adds a further nonlinearity in wind: Failures correlate with storms, storms correlate with high wind, so downtime disproportionately coincides with the highest-revenue hours. Several studies quantify this correlation penalty, finding energy-based availability one to three percentage points below time-based availability for the same fleet, with the gap widening at more exposed sites.

4.2 Evidence on Under-Maintenance

Documented experience with deferred maintenance offshore provides the clearest evidence of the trade-off. In offshore oil and gas, regulator reviews (for example, safety and integrity audits in the North Sea) have repeatedly linked sustained OPEX compression during low oil price periods to growth in maintenance backlogs, degradation of safety-critical barriers and subsequent increases in hydrocarbon release incidents and production-affecting failures. Analyses of late-life assets show a characteristic pattern: Cost cutting reduces reported OPEX for two to four years, after which corrective workload, backlog interest and unplanned shutdowns drive total cost above its original trajectory while availability falls. In offshore wind, serial component defects (notably in some gearbox and blade populations) illustrate the same mechanism at fleet scale: Inadequate early detection converts a manageable stream of planned exchanges into clustered heavy-lift campaigns competing for scarce vessels, with availability losses concentrated in the affected cohorts. The reviewed studies consistently conclude that the cheapest year of maintenance is bought on credit against future reliability, and that the interest rate on that credit is set by offshore logistics (Obogo *et al*., 2019a; Obogo *et al*., 2019b; Obogo *et al*., 2019; Obogo *et al*., 2021; Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2020; Obriki & Arumosoye, 2021).

4.3 Evidence on Over-Maintenance

The opposite failure mode is subtler but well documented. Excess preventive intensity produces diminishing and eventually negative returns through several channels. Maintenance-induced failures (errors during intrusive work, infant mortality of replaced components) mean that unnecessary interventions add risk as well as cost; studies in process industries attribute a material share of failures to prior maintenance activity. Inspection beyond the informative rate consumes bed space, vessel time and permits that could serve higher-risk work. Excess spares holding ties up capital and incurs obsolescence, particularly acute for long-lead offshore components. And conservative alarm settings in condition monitoring generate false positives whose response cost, a vessel trip to find a healthy component, erodes both budget and organizational trust in the monitoring system. Optimization studies that model these effects find interior optima for inspection intervals and alarm thresholds, confirming that availability is not monotonically increasing in maintenance spend (Adeyelu, 2024; Agu & Akomolafe, 2023a; Agu & Akomolafe, 2023b; Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Akomolafe & Agu, 2019b).

4.4 Framing the Trade-off Quantitatively

The literature operationalizes the trade-off through several linked formulations. Cost-availability frontier studies compute, by simulation, the Pareto frontier between expected annual O&M cost and expected availability for a given asset and logistics setup; decision makers then select a point by revenue weighting. Life-cycle cost (LCC) formulations fold downtime into cost via the value of lost production, reducing the problem to single-objective minimization but at the price of sensitivity to the assumed energy price or oil price. Risk-based formulations, dominant in oil and gas integrity management, constrain the optimization by maximum tolerable probability of failure for safety-critical items and optimize cost within that constraint. Multi-objective formulations retain cost, reliability and availability as separate objectives and present Pareto sets. A robust finding across formulations is that the frontier is steep near high availability: Raising availability from, say, 90 to 95 percent is far cheaper per point than raising it from 97 to 98 percent, where each further point requires disproportionate logistics capacity, redundancy or monitoring investment. OPEX optimization is therefore best understood as locating the knee of this frontier for the specific site, technology and revenue regime, rather than as generic cost reduction (Lawal & Oduleye, 2019a; Lawal & Oduleye, 2019b; Lawal & Oduleye, 2021a; Lawal & Oduleye, 2021b; Lawal & Oduleye, 2023a; Lawal & Oduleye, 2023b).

5. Modeling and Optimization Approaches

5.1 Analytical Reliability and Maintenance Models

The analytical foundation of the field comprises renewal theory and age/block replacement models (Barlow and Hunter), delay-time models of inspection, and Markov and semi-Markov models of multi-state degradation. These models yield closed-form or numerically tractable optima for replacement intervals and inspection frequencies and remain valuable for component-level policy setting and for embedding within larger models. Their limitation offshore is structural: they typically assume immediate repair upon decision, which the weather-gated, vessel-constrained offshore reality violates. Extensions incorporating stochastic access delay and imperfect maintenance narrow the gap but rapidly lose tractability for multi-component systems with economic dependence (Akomolafe & Agu, 2019c; Akomolafe & Agu, 2023a; Akomolafe & Agu, 2023b; Bello *et al*., 2023; Adeyelu, 2018; Adeyelu, 2019).

5.2 Simulation-Based O&M Models

Discrete-event and Monte Carlo simulation is the workhorse of offshore O&M analysis precisely because it can represent what analytical models cannot: time series of weather (wave height, wind speed) governing access; heterogeneous vessel fleets with charter strategies and mobilization lead times; failure processes per component with repair task hierarchies; technician shifts and bed space; and spares with lead times. A family of established tools and academic models in this class (including NREL and ORE Catapult cost models and numerous university simulators) is used both by researchers and industry to evaluate strategy and logistics scenarios. Validation studies comparing simulated against realized farm performance report reasonable fidelity for availability and cost trends, while emphasizing sensitivity to input failure rates, which remain the weakest data in the chain. Simulation supports the trade-off analysis directly: by sweeping policy parameters (inspection intervals, CBM thresholds, fleet size, charter mix), it traces empirical cost-availability frontiers for the specific site (Badmus *et al*., 2020; Ladapo *et al*., 2018; Ladapo *et al*., 2022; Ladapo *et al*., 2023a; Ladapo *et al*., 2023b; Ladapo *et al*., 2024; Ladapo *et al*., 2019).

5.3 Optimization Methods

On top of these evaluative models, the literature applies a spectrum of optimization techniques. Mixed-integer programming addresses scheduling and routing subproblems: which tasks to assign to which vessels on which days, subject to weather forecasts and crew constraints. Dynamic programming and Markov decision processes formalize sequential CBM decisions (intervene now versus wait) under degradation and weather uncertainty, with recent work applying reinforcement learning to the same structure when state spaces defeat exact methods. Metaheuristics (genetic algorithms, particle swarm optimization, NSGA-II for multi-objective cases) dominate the strategy-tuning literature because the simulation-based objective is nonconvex and expensive; NSGA-II in particular is repeatedly used to generate Pareto frontiers over cost, reliability and availability. Robust and stochastic optimization approaches address parameter uncertainty, notably in failure rates and weather statistics, producing policies that sacrifice a small amount of expected cost for reduced variance, an exchange several authors argue is appropriate for operators exposed to single-project cash flow risk (Adeyelu, 2020; Adeyelu, 2021; Adeyelu, 2023; Adeyelu, 2022; Adeyelu, 2024; Medon & Oduleye, 2022; Medon & Oduleye, 2023; Medon & Oduleye, 2024; Oduleye & Medon, 2023a; Oduleye & Medon, 2023b).

5.4 Comparative Assessment

Across methods, three practical conclusions recur. First, model value concentrates in the logistics layer: studies that model weather and vessels crudely misestimate both cost and availability regardless of the sophistication of the reliability layer. Second, multi-component and multi-asset coupling matters: optimizing components in isolation forfeits the opportunistic savings that make offshore maintenance economical, so system-level models outperform component-level optima combined naively. Third, data quality binds: the marginal return on algorithmic sophistication is low while failure-rate uncertainty spans factors of two or more, which argues for investment in reliability data collection (per ISO 14224 and initiatives such as OREDA and SPARTA) alongside modeling (Ladapo *et al*., 2022; Ladapo *et al*., 2023a; Ladapo *et al*., 2023b; Ladapo *et al*., 2024; Edivri, 2022; Edivri, 2024).

6. Logistics, Spare Parts and Vessel Fleet Optimization

6.1 Vessel Fleet and Access Strategy

Because logistics dominates offshore OPEX, fleet strategy is itself a maintenance decision. The core choices are the mix of crew transfer vessels, service operation vessels (SOVs) with walk-to-work capability, helicopters, and heavy-lift or jack-up vessels; the charter model (long-term charter, spot market, framework agreements, or sharing across neighboring farms); and the operating base (port-based, offshore-based accommodation, or hybrid). The literature models these as capacity-versus-responsiveness trade-offs. Long-term SOV charter raises fixed cost but increases the effective weather window and reduces response time, improving availability; spot chartering saves fixed cost but exposes the operator to rate volatility and mobilization delay exactly when failures cluster. Studies of far-from-shore farms generally find SOV-based strategies dominant beyond roughly 40 to 60 km, while nearshore farms favor CTV fleets; helicopter support earns its cost only for high-value, low-payload interventions. Fleet-sharing and framework agreements across operators are reported to cut heavy-lift intervention cost materially by reducing idle mobilizations, and represent an underexploited coordination opportunity (Okonkwo *et al*., 2024f; Okonkwo *et al*., 2020; Okonkwo *et al*., 2021; Okonkwo *et al*., 2023; Okonkwo *et al*., 2023; Okonkwo *et al*., 2018a; Okonkwo *et al*., 2018b; Okonkwo *et al*., 2021; Okonkwo *et al*., 2019; Abioye *et al*., 2023; Aifuwa *et al*., 2020; Filani *et al*., 2022; Ike *et al*., 2024a; Ike *et al*., 2024b; Ike *et al*., 2021).

6.2 Spare Parts Management

Spares policy offshore balances holding cost and obsolescence against stock-out consequences amplified by long lead times: months for main bearings, gearboxes or subsea components. Research applies classical inventory theory (base-stock and (s, S) policies) extended with criticality weighting, pooling across sites, and condition-informed forecasting in which prognostics convert RUL estimates into demand forecasts, allowing just-in-time positioning of major spares. Reported results indicate that prognostics-informed spares planning reduces combined holding and downtime cost relative to purely statistical forecasting, with the largest gains for expensive, long-lead components. Pooling agreements and vendor-managed inventory shift the trade-off further by sharing risk across fleets (Ike *et al*., 2022; Nnabueze *et al*., 2021; Okojie *et al*., 2023; Okojie *et al*., 2023; Yeboah & Ike, 2020; Yeboah *et* *al*., 2024; Eze *et al*., 2024a; Eze *et al*., 2024b; Eze *et al*., 2022a; Eze *et al*., 2022b; Eze *et al*., 2023; Akin-Oluyomi *et al*., 2023a).

6.3 Workforce and Campaign Planning

Technician capacity, competence mix and rotation schedules constrain executable maintenance. Offshore wind studies model technician-to-turbine ratios and find availability saturating beyond a site-specific staffing level, another interior optimum. In oil and gas, persons-on-board limits force explicit prioritization; backlog management frameworks that rank deferred work by risk rather than age are reported to protect availability under fixed labor budgets. Campaign planning, concentrating preventive work into favorable seasons and shared logistics, consistently emerges as one of the highest-leverage, lowest-technology OPEX levers available (Obriki & Arumosoye, 2022; Obriki & Arumosoye, 2023; Obriki & Arumosoye, 2024a; Obriki & Arumosoye, 2024b; Obriki *et al*., 2023; Obriki *et al*., 2022a; Obriki *et al*., 2022b; Obriki *et al*., 2023; Eyetsemitan *et al*., 2022; Eyetsemitan *et al*., 2024a; Eyetsemitan *et al*., 2024b; Oyeleye *et al*., 2022).

7. Digitalization and Emerging Technologies

7.1 Remote Monitoring, Analytics and Digital Twins

Digital technologies shift the cost-reliability-availability frontier rather than merely moving along it. SCADA analytics and dedicated condition monitoring, coupled with machine learning fault detection, extend effective P-F intervals and reduce the unit cost of surveillance per asset. Digital twins, calibrated physics-based or hybrid models of turbines, structures or process systems updated with sensor data, support fatigue life reassessment (enabling evidence-based life extension rather than conservative retirement), virtual sensing where physical instrumentation is impractical, and scenario testing of maintenance decisions before committing vessels. Reviewed case studies report that structural digital twins on jackets and floaters have justified inspection interval extensions and deferred major interventions with quantified risk, directly converting information into OPEX reduction without reliability loss. The literature cautions, however, that twin fidelity and model validation remain immature for many failure modes, and that the business case depends on data infrastructure costs that are easy to underestimate (Adebayo *et al*., 2022; Adebayo *et al*., 2023; Adegbite *et al*., 2020; Adegbite *et al*., 2022; Adegbite *et al*., 2023; Adegbite *et al*., 2024a; Adegbite *et al*., 2024b; Ahmed & Adegbite, 2021; Ogbole *et al*., 2021; Okoruwa *et al*., 2024; Okoruwa *et al*., 2020; Oteri, 2024).

7.2 Robotics and Autonomous Inspection

Uncrewed aerial vehicles for blade and topside inspection, remotely operated and autonomous underwater vehicles for subsea and foundation survey, and crawling robots for confined spaces reduce both the cost and the risk of inspection by removing people from hazardous access. Studies report large reductions in inspection cost and duration for blade surveys by drone relative to rope access, with image analytics improving defect detection consistency. Resident underwater vehicles stationed offshore promise on-demand subsea inspection without vessel mobilization, attacking the largest cost driver directly. The maturity gradient is real: aerial inspection is mainstream, autonomous underwater intervention is emerging, and fully autonomous repair remains experimental, but the direction of travel is a structural reduction in the logistics cost of information (Dagodzo, 2018a; Dagodzo, 2018b; Dagodzo & Patrick, 2020; Dagodzo & Patrick, 2021a; Dagodzo & Patrick, 2021b; Dagodzo & Patrick, 2022; Dagodzo & Patrick, 2023a; Dagodzo & Patrick, 2023b; Dagodzo & Patrick, 2022; Bello *et al*., 2022; Bello *et al*., 2024; Bello *et al*., 2022; Akanbi & Sunday, 2024).

7.3 Remote Operations and Organizational Change

Remote operation centers consolidating monitoring, diagnostics and planning across fleets exploit scale economies in scarce expertise and enable condition-informed dispatch: sending crews with the right spares to confirmed problems rather than exploratory visits. Normally unattended or leanly crewed installations in oil and gas extend the logic to the asset itself, trading topside redundancy and monitoring investment for permanently lower logistics and accommodation OPEX. The reviewed organizational literature emphasizes that these gains are contingent on process and culture: prognostics that planners do not trust, or planning processes that cannot ingest dynamic priorities, deliver technology cost without OPEX benefit. Several authors identify organizational absorption capacity as the practical binding constraint on digital maintenance value (Aliliele & Mbonu, 2023a; Aliliele & Mbonu, 2023b; Aliliele & Mbonu, 2023c; Aliliele & Mbonu, 2024a; Aliliele & Mbonu, 2024b; Borah *et al*., 2022; Mbonu *et al*., 2018; Mbonu *et al*., 2020; Mbonu *et al*., 2021a; Mbonu *et al*., 2021b).

8. Discussion: Synthesis, Research Gaps and Future Directions

8.1 Synthesis of Findings

Synthesizing across the reviewed literature, five propositions summarize the state of knowledge. First, offshore maintenance OPEX is logistics-dominated, and therefore optimization levers that reduce access events per unit of maintenance value delivered (opportunistic clustering, campaign planning, remote and robotic inspection, condition-informed dispatch) are systematically the highest-leverage levers. Second, the cost-reliability-availability relationship is a frontier with a knee: both under-maintenance and over-maintenance are empirically documented value destroyers, and the optimum is site, technology and life-cycle-stage specific. Third, condition-based and predictive maintenance shift the frontier outward, but only when the monitoring layer is itself reliable and organizationally trusted; otherwise it adds cost without benefit. Fourth, accounting practices that separate maintenance budgets from production revenue systematically bias decisions toward under-maintenance, because failure costs are externalized from the maintenance ledger; total cost of ownership and energy-based availability metrics correct this bias. Fifth, data quality on failure rates and degradation is the binding constraint on further modeling gains, more so than algorithmic sophistication (Mbonu *et al*., 2022; Mbonu *et al*., 2019; Mbonu *et al*., 2020a; Mbonu *et al*., 2020b; Mbonu *et al*., 2021; Mbonu *et al*., 2022a; Mbonu *et al*., 2022b; Mbonu *et al*., 2019; Jimoh

& Ahmed, 2024; Jimoh *et al*., 2023; Jimoh *et al*., 2023).

8.2 Research Gaps

The review identifies several persistent gaps. Validated field evidence is scarce relative to simulation studies: the majority of reported OPEX savings from CBM, opportunistic policies and digital twins derive from models rather than controlled before-after field comparisons, and publication of operator data remains limited by commercial sensitivity. Floating wind introduces maintenance questions (tow-to-port versus in-situ major repair, dynamic cable reliability, station-keeping integrity) for which the evidence base is embryonic. The joint optimization of maintenance and end-of-life decisions (life extension, repowering, decommissioning) is underdeveloped, though late-life assets are precisely where the cost-reliability trade-off is sharpest. Human and organizational factors, including planner behavior under uncertainty, trust in prognostics, and incentive design in O&M contracts (availability-based contracting shifts but does not dissolve the trade-off), receive far less quantitative treatment than hardware. Finally, climate non-stationarity, changing storm statistics that invalidate historical weather-window assumptions, is rarely incorporated into long-horizon O&M optimization (Annan, 2022; Annan, 2023; Annan, 2024; Falegan & Aniebonam, 2022; Falegan & Aniebonam, 2023; Falegan & Aniebonam, 2024; Dosunmu & Ogundele, 2019; Dosunmu & Ogundele, 2020; Dosunmu & Ogundele, 2021; Dosunmu & Ogundele, 2022; Dosunmu & Ogundele, 2023; Dosunmu & Ogundele, 2024a; Dosunmu & Ogundele, 2024b; Dosunmu & Ogundele, 2024c; Dosunmu & Ogundele, 2024d; Onche *et al*., 2024).

8.3 Future Research Directions

Building on these gaps, promising directions include: federated or privacy-preserving reliability data sharing across operators to break the data constraint without exposing commercial detail; integrated models that co-optimize maintenance policy, fleet strategy, spares and end-of-life timing rather than treating them sequentially; reinforcement learning and stochastic control for dynamic, weather- and condition-aware dispatch, with attention to explainability so planners can trust recommendations; techno-economic assessment of resident robotics and autonomous intervention as logistics substitutes; contract and incentive design research aligning owner, operator and OEM interests with total life-cycle value; and systematic incorporation of climate scenario weather statistics into O&M simulation. Methodologically, the field would benefit from standardized benchmark cases and reporting conventions so that claimed OPEX savings become comparable across studies (Akin-Oluyomi *et al*., 2023b; Akin-Oluyomi *et al*., 2024; Akin-Oluyomi *et al*., 2020; Akin-Oluyomi *et al*., 2023; Akin-Oluyomi *et al*., 2023; Akinleye, 2021; Akinleye, 2022a; Akinleye, 2022b; Akinleye *et al*., 2023; Babatope *et al*., 2023).

9. Conclusion

This review has examined OPEX optimization in offshore maintenance through the lens of the trade-offs among cost, reliability and asset availability. The offshore environment transforms maintenance economics: weather-gated access, high-cost vessel logistics and long intervention lead times amplify the consequence of every failure and place logistics, rather than wrench time, at the center of both cost and availability. Within this structure, the literature is clear that OPEX optimization is not cost minimization. Under-maintenance purchases short-term budget relief on credit against future reliability at an interest rate set by offshore logistics, while over-maintenance dissipates value through maintenance-induced failure, false alarms and diminishing returns near the top of the availability curve. The defensible objective is the knee of the site-specific cost-availability frontier, located through criticality-differentiated strategy portfolios, opportunistic clustering, condition-based and predictive maintenance, and deliberate fleet, spares and workforce design, and increasingly shifted outward by digital twins, remote monitoring and robotic inspection. The principal constraints on further progress are empirical rather than algorithmic: validated failure data, field evidence for claimed savings, and the organizational capacity to act on condition information. Addressing these constraints, alongside the new questions posed by floating wind, late-life assets and a changing climate, defines the research agenda for the coming decade. For practitioners, the enduring message of the reviewed evidence is that reliability is not a cost to be minimized but the asset through which availability, revenue and ultimately sustainable OPEX are produced (Efobi & Akinleye, 2021; Efobi & Akinleye, 2022a; Efobi & Akinleye, 2022b; Efobi & Akinleye, 2023; Okojie & Abioye, 2020; Okoruwa *et al*., 2024).

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