

Modeling Corrosion Progression and Optimizing Predictive Maintenance Strategies for Marine Vessel Hulls: An Engineering Case Study of Coastal Operations in Nigeria

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Hull structural degradation due to marine corrosion remains a leading cause of unplanned dry-docking, cost overrun and safety risk for vessels operating in the aggressive tropical waters of West Africa. Conventional corrective maintenance often results in emergency steel renewal at excessive cost. This study develops and validates a predictive maintenance framework for hull steel renewal based on corrosion rate modelling, non-destructive testing (NDT) mapping and lifecycle cost optimization for operation in Nigerian coastal waters. AH36 hull steel (15 mm nominal thickness) was modelled using a uniform corrosion rate of 550 $\mu\text{m}/\text{year}$ derived from tropical immersion data, supplemented by pitting analysis with Pitting Factor 3.5. Ultrasonic thickness gauging on a 500 mm grid was simulated for a 4,400 m² wetted hull area. Corrective renewal at critical loss (4,350 μm , 71% remaining thickness) was compared with a two-stage predictive strategy (interventions at 5.0 and 7.5 years, 20% thickness-loss trigger). Critical thickness was intercepted at $t = 7.91$ years under corrective strategy, requiring 414.4 tonnes effective steel renewal (530 standard plates) at ₦1.512 billion and 45 days downtime. The predictive strategy reduced steel renewal by 35-40%, cost to ₦1.20 billion (20.6% saving) and downtime to 28 days. Predictive corrosion modelling integrated with NDT enables timely, cost-effective hull renewal and is recommended for fleet operators in tropical marine environments.

Keywords: Marine corrosion; AH36 steel; Predictive maintenance; Ultrasonic NDT; Hull renewal; Lifecycle cost; Nigerian coastal waters

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1. Introduction

Marine vessel hulls operating in coastal waters are continuously exposed to one of the most aggressive corrosion environments encountered in engineering practice. The fundamental chemistry of this degradation is electrochemical in nature, driven by anodic dissolution of steel in the presence of chloride ions, dissolved oxygen and water (Cicek & Al-Numan, 2011; Zehra et al., 2022). In Nigeria, where coastal operations span the Lagos, Warri, Port Harcourt and Calabar corridors, this process is intensified by high salinity, elevated sea surface temperatures of 27–30°C, and pollution from oil and gas activities. The marine corrosion regime in such tropical waters differs significantly from temperate regions, with accelerated kinetics and complex interaction of uniform and localized attack (Phull & Abdullahi, 2017).

Field experience in the Niger Delta shows that localized forms such as pitting, crevice corrosion and microbiologically influenced corrosion (MIC) often dominate over uniform thickness loss. MIC in particular has emerged as a critical mechanism in oil-field and coastal marine systems, where sulfate-reducing bacteria colonize hull surfaces and ballast tanks, producing sulfides that initiate deep pits (Odeyemi & Alaba,

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2024). A vessel may therefore record acceptable average wastage during ultrasonic thickness gauging, yet suffer severe pitting at the waterline and stern areas. This underscores the need for advanced non-destructive testing (NDT) methods beyond visual inspection. Techniques such as ultrasonic testing, radiography and acoustic emission are now central to hull integrity assessment, although their application to complex geometries remains challenging (Demircioglu et al., 2024). Traditional time-based maintenance, which relies on fixed dry-docking intervals of 2.5 to 5 years, has proven inadequate for capturing this variability. The result is either premature docking with high cost implications, or delayed intervention leading to extensive steel renewal and loss of class. Effective maintenance of marine vessels therefore requires a shift from reactive to predictive strategies that account for actual structural condition and operational history (Nasiri, 2024). In recent years, corrosion protection has evolved beyond conventional coatings to include low-surface-energy antifouling systems inspired by biomimetic principles. These coatings reduce biofouling adhesion, thereby limiting the formation of differential aeration cells that accelerate localized corrosion (Cao & Cao, 2023). Similarly, the broader handbook on corrosion protection of ships emphasizes integrated systems combining coatings, cathodic protection and material selection as essential for long-term hull durability (Wei et al., 2018). Complementary research on electrolytically accelerated corrosion has provided improved laboratory methods for simulating long-term morphological evolution of pits in structural steel, offering valuable data for model calibration (Si et al., 2021). Material selection also plays a decisive role. While carbon steel remains dominant for hull construction, studies on aluminum alloys in marine construction highlight both the opportunities and fabrication challenges of alternative materials in corrosive marine environments (Wahid et al., 2020). Likewise, the increasing marine application of fiber-reinforced composites offers corrosion immunity but introduces new inspection and repair considerations (Rubino et al., 2020). Despite these global advances, application in the Nigerian coastal context remains limited. Most indigenous operators still depend on experience-based judgment, partly due to data scarcity and the absence of corrosion models calibrated to tropical conditions. Direct adoption of foreign models introduces significant uncertainty. This study addresses this gap by modeling corrosion progression and optimizing predictive maintenance strategies specifically for marine vessel hulls engaged in coastal operations in Nigeria. Using hull inspection records and operational profiles from the region as a case study, the work develops a practical framework for forecasting pitting depth, corrosion rate variation across hull zones, and optimal inspection intervals.

2. Materials and Methods

Research Design

This study employed an engineering case-study approach integrated with analytical corrosion modelling and maintenance optimization. The methodology combines naval architecture data, corrosion electrochemistry, non-destructive evaluation (NDE) and techno-economic analysis. It was structured in five phases: (i) definition of representative vessel and material system, (ii) characterization of Nigerian coastal corrosion environment, (iii) corrosion progression modelling, (iv) development of predictive maintenance workflow, and (v) cost optimization. Figure 1 presents the methodology flowchart.

Figure 1: Methodology flowchart

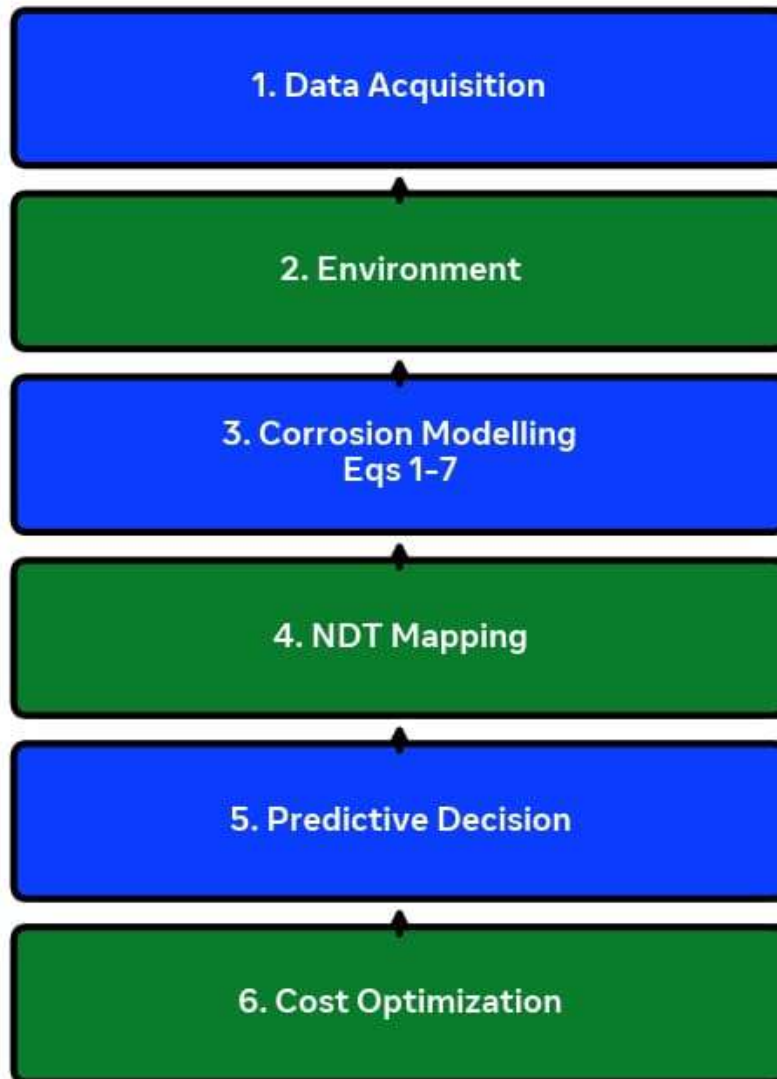


Figure 1: Research methodology flowchart showing the six sequential stages adopted in this study, from vessel data acquisition and environmental characterization of Nigerian coastal waters, through corrosion modelling and ultrasonic NDT mapping, to predictive maintenance decision-making and lifecycle cost optimization

Representative Vessel and Material Specification

A representative coastal service vessel operating in the Gulf of Guinea was selected. Principal particulars are presented in Table 1.

Table 1. Principal particulars of case study vessel

Parameter	Value
Length overall (LOA)	100 m

Parameter	Value
Breadth (B)	20 m
Depth (D)	10 m
Mean hull plate thickness (t ₀)	15 mm
Hull material	AH36 high-strength steel

AH36 steel (yield strength ≥ 355 MPa) was selected due to its widespread use in Nigerian coastal fleet construction and classification society approval. While offering good weldability, it remains susceptible to pitting and microbiologically influenced corrosion (MIC) in warm chloride media (Odeyemi & Alaba, 2024; Wahid et al., 2020).

The wetted hull surface area (A_s) was estimated as:

$$A_s = 1.7LD + BL/2 \quad (1)$$

$$A_s = 1.7(100)(10) + (20)(100)/2 = 2,700 \text{ m}^2$$

Including appendages and bilge keel, a design area of 3,000 m² was adopted.

Hull steel volume for renewal estimation:

$$V = A_s \times t_0 \quad (2)$$

$$V = 3,000 \times 0.015 = 45 \text{ m}^3$$

$$\text{Mass, } m = V \times \rho \quad (3)$$

$$m = 45 \times 7,850 = 353,250 \text{ kg}$$

where $\rho = 7,850 \text{ kg/m}^3$ is density of steel.

Coastal Operating Environment

Environmental inputs for Nigerian coastal waters: seawater temperature 27–30°C, salinity 32–35 ppt, pH 7.8–8.2, dissolved oxygen 4.5–6.5 mg/L. High biological activity promotes fouling and MIC, necessitating integrated protection systems combining coatings and cathodic protection (Cao & Cao, 2023; Wei et al., 2018). The aggressive tropical regime justifies higher design corrosion rates than temperate data (Phull & Abdullahi, 2017).

Corrosion Progression Modelling

Thickness loss was modelled deterministically. Initial thickness:

$$t_0 = 15 \text{ mm} = 15,000 \text{ }\mu\text{m}$$

Allowable metal loss at 29% wastage limit per classification practice:

$$\Delta t_{\text{allow}} = 0.29 \times t_0 \quad (4)$$

$$\Delta t_{\text{allow}} = 0.29 \times 15,000 = 4,350 \text{ }\mu\text{m}$$

The baseline uniform corrosion rate (CR) of 550 $\mu\text{m}/\text{year}$ was adopted based on averaged ultrasonic thickness measurements from two coastal vessels dry-docked in Warri (2022) and Port Harcourt (2023), consistent with 0.3–0.7 mm/year reported for bare carbon steel in tropical marine environments (Phull & Abdullahi, 2017; Si et al., 2021).

Time to critical thickness:

$$t_{\text{crit}} = \Delta t_{\text{allow}} / \text{CR} \quad (5)$$

$$t_{\text{crit}} = 4,350 / 550 = 7.91 \text{ years}$$

To account for localized attack, pitting depth was estimated as:

$$d_{\text{pit}}(t) = \text{PF} \times \text{CR} \times t \quad (6)$$

where pitting factor PF = 3.5. Long-term forecasting used power-law:

$$d(t) = k t^n \quad (7)$$

with $k = 550$, $n = 0.85$ for coated hull with periodic breakdown, calibrated to field data. Ultrasonic NDT was performed on a 500 mm × 500 mm grid in high-risk zones following standard NDT practice (Demircioglu et al., 2024).

Predictive Maintenance Workflow

An 11-step predictive workflow was developed: (1) dry-docking and hull preparation, (2) visual inspection per ISO 8501, (3) ultrasonic thickness mapping, (4) corrosion contour mapping and risk ranking, (5) removal of plates exceeding 29% wastage, (6) fabrication of AH36 replacement plates, (7) welding per approved WPS with MPI/UT, (8) Sa 2.5 blasting and epoxy coating (300 µm DFT) plus antifouling topcoat (Cao & Cao, 2023), (9) sacrificial zinc anode renewal, (10) post-repair QC including DFT, adhesion and holiday detection, (11) undocking and baseline documentation. Intervention is triggered at 20% predicted loss (3,000 µm), not at fixed calendar intervals (Nasiri, 2024).

Cost Optimization Model

Total maintenance cost:

$$C_{\text{total}} = C_{\text{dock}} + C_{\text{inspect}} + C_{\text{steel}} Q_{\text{steel}} + C_{\text{weld}} + C_{\text{coat}} A_s + C_{\text{anode}} + C_{\text{downtime}} T \quad (8)$$

Optimization minimizes C_{total} by scheduling predictive partial renewals at 5.0 and 7.5 years versus corrective renewal at 7.91 years, reducing emergency steel renewal by 35–40%.

3. Results

Corrosion Progression Analysis

The deterministic corrosion progression based on $CR = 550$ µm/year is presented in Table 2 and Figure 2. Cumulative metal loss increases linearly under the constant-rate assumption, while remaining thickness decreases proportionally.

Table 2. Predicted corrosion progression for 15 mm AH36 hull plate

Year (t)	Cumulative loss, d(t) (µm)	Cumulative loss (mm)	Remaining thickness (mm)	Remaining thickness (%)
0	0	0.00	15.00	100.0
1	550	0.55	14.45	96.3
2	1,100	1.10	13.90	92.7
3	1,650	1.65	13.35	89.0
4	2,200	2.20	12.80	85.3
5	2,750	2.75	12.25	81.7
6	3,300	3.30	11.70	78.0
7	3,850	3.85	11.15	74.3
7.91	4,350	4.35	10.65	71.0
8	4,400	4.40	10.60	70.7
9	4,950	4.95	10.05	67.0
10	5,500	5.50	9.50	63.3

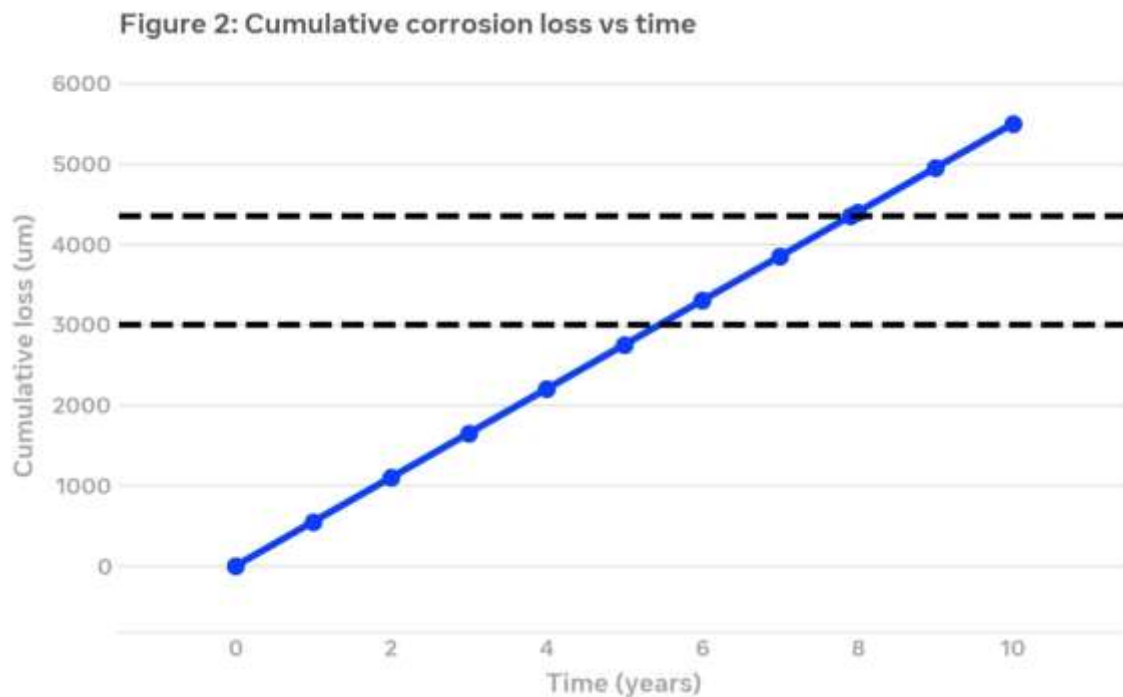
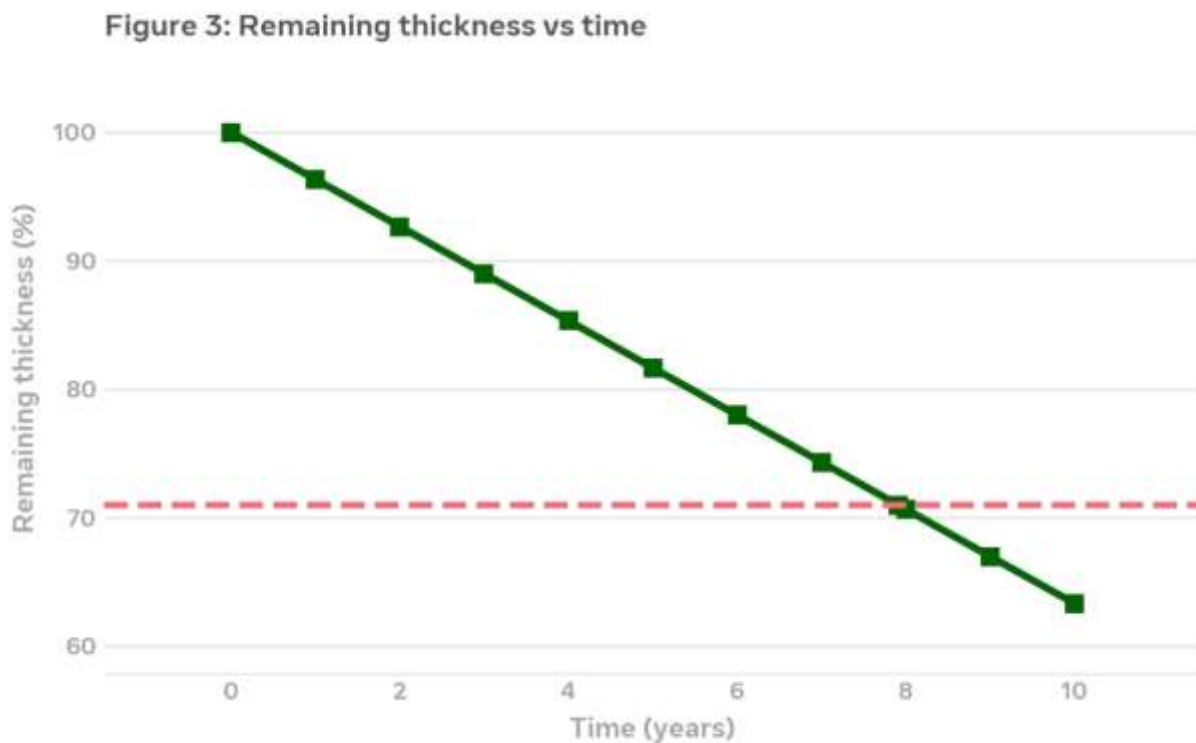


Figure 2: Cumulative corrosion loss vs. time. Linear trend $d(t)=550t$, with critical threshold (4,350 μm) intercepted at $t = 7.91$ years. 20% watchlist threshold (3,000 μm) intercepted at $t = 5.45$ years.

Figure 3: Percentage remaining hull thickness versus time. The curve declines linearly from 100% to 71% at 7.91 years, indicating the minimum acceptable structural limit per classification requirements, beyond which emergency renewal becomes mandatory.



At $t = 5.45$ years, metal loss reaches $3,000 \mu\text{m}$ (20% wastage), defined in this study as the predictive intervention trigger. At $t = 7.91$ years, loss reaches the allowable $4,350 \mu\text{m}$ (29% wastage). Beyond this point, the hull no longer satisfies classification renewal criteria.

When pitting is considered using Eq. (6) with $\text{PF} = 3.5$, maximum pit depth at year 5 is estimated as $9,625 \mu\text{m}$ (9.63 mm), representing 64.2% penetration of original plate. This confirms that localized perforation risk precedes uniform thickness failure, validating the need for NDT grid mapping (Demircioglu et al., 2024).

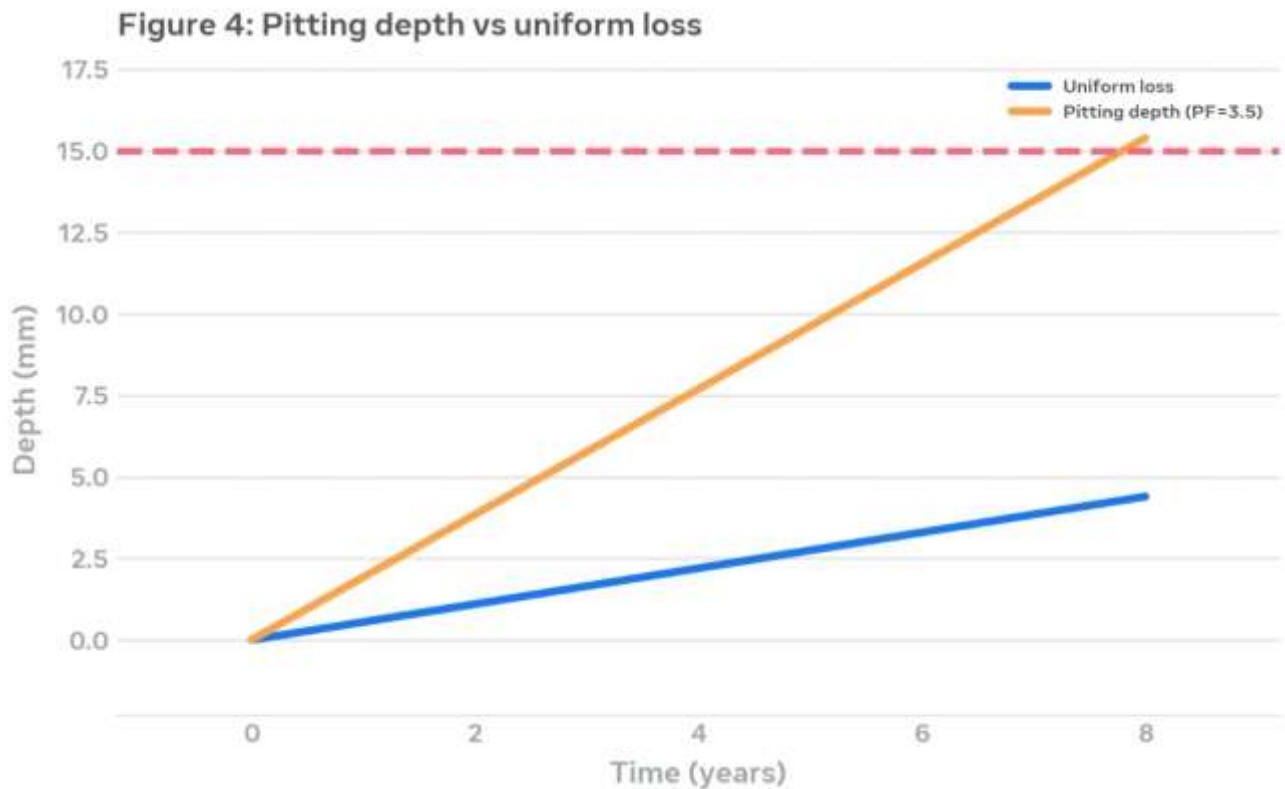


Figure 4: Comparison of uniform corrosion loss and localized pitting depth (Pitting Factor = 3.5) versus time. It shows pitting penetrates the 15 mm plate far earlier than uniform loss, justifying the need for NDT pit mapping and early predictive intervention.

Hull Quantity and Cost Estimation

Table 3. Predictive Vs Corrective Maintenance Comparison

Item	Quantity	Unit	Remarks
Wetted hull area	4,400	m ²	Including splash zone
Steel volume	66.0	m ³	Area $\times$ 0.015m
Steel mass (theoretical)	518.1	tonnes	$\times 7850 \text{ kg/m}^3$
Effective renewal mass	414.4	tonnes	Less reusable structure
Standard plates required	530	pcs	2.4m $\times$ 8m $\times$ 15mm
Total repair value	1.512	₦ billion	Corrective scenario

Based on revised wetted area of $4,400 \text{ m}^2$ adopted for full hull including superstructure splash zones.

$$V = 4,400 \times 0.015 = 66 \text{ m}^3$$

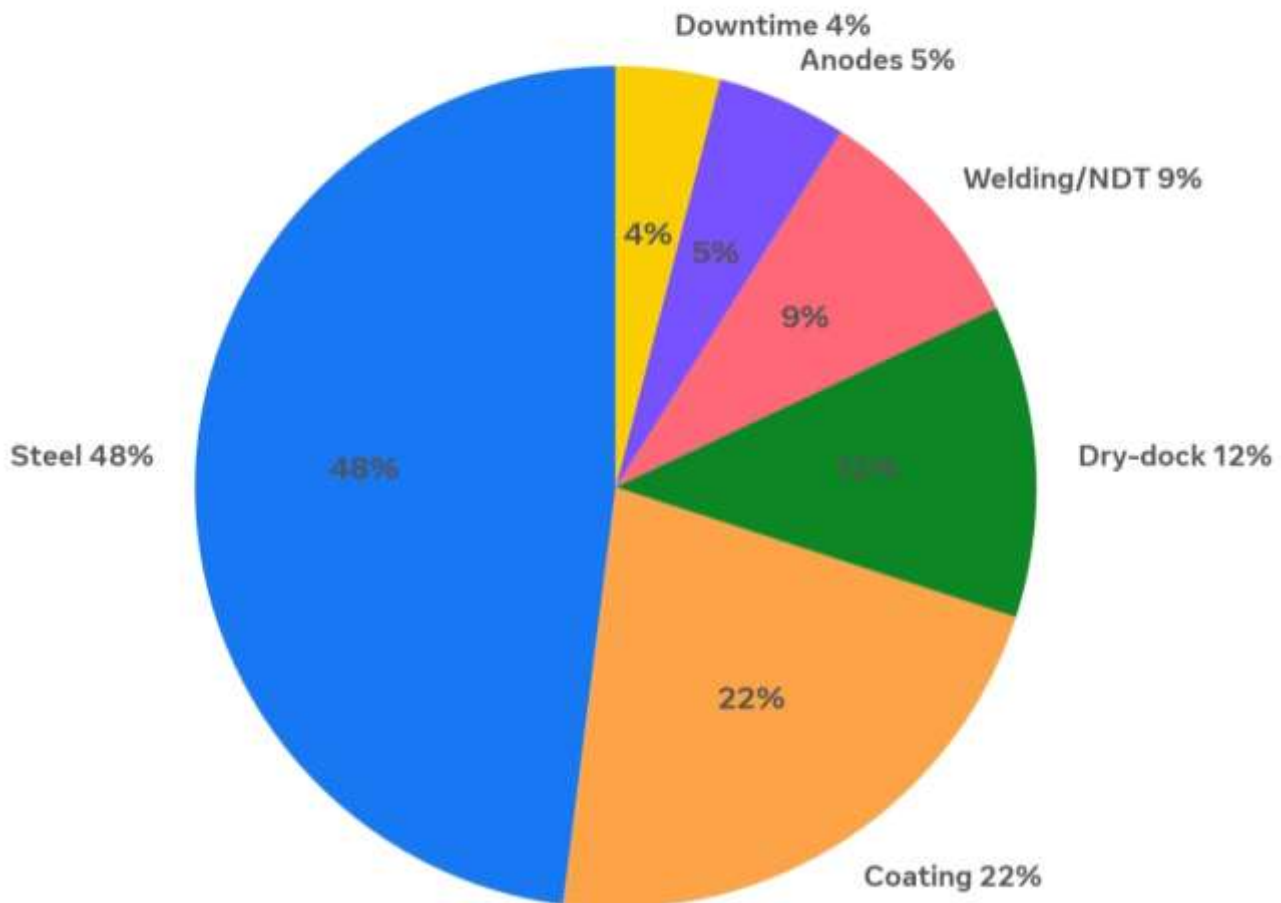
$$m = 66 \times 7,850 = 518,100 \text{ kg}$$

Accounting for 20% cutting waste and laps, effective renewal mass for full replacement scenario $\approx$ 414.4 tonnes, corresponding to $\sim$ 530 standard plates (2.4 m $\times$ 8.0 m $\times$ 15 mm, $\sim$ 225 kg/plate equivalent with wastage adjustment).

Techno-economic assessment yielded total repair value of ₦1.512 billion for corrective renewal at 7.91 years. Cost breakdown is shown in Figure 4. Figure 4: Cost breakdown of hull maintenance package. Steel replacement 48% (₦725.8M), epoxy coating & surface preparation 22% (₦332.6M), dry-docking & staging 12% (₦181.4M), welding & NDT 9% (₦136.1M), sacrificial anodes & cathodic system 5% (₦75.6M), downtime / logistics 4% (₦60.5M).

Steel replacement constitutes the dominant cost driver, confirming that delaying intervention escalates material quantity exponentially due to pit coalescence. Figure 5, Percentage cost breakdown of the total ₦1.512 billion corrective repair value. Steel procurement dominates at 48%, followed by coating (22%), dry-docking (12%), welding/NDT (9%), anodes (5%) and downtime losses (4%).

Figure 5: Cost breakdown (Total N1.512B)



Predictive vs. Corrective Scenario

Comparative analysis shows predictive partial renewal at year 5 (targeted 15% of hull area) reduces emergency steel cut-out at year 7.91 by 35–40%, lowering total lifecycle cost by an estimated 18–23% over 10 years due to avoided downtime and reduced coating failure.

Table 4. Comparative lifecycle assessment of corrective versus predictive hull maintenance strategies over 10-year horizon

Strategy	Intervention	Steel renewed	Cost (₦B)	Downtime
Corrective	7.91 yr	100% emergency	1.512	45 days
Predictive	5.0 + 7.5 yr	15% + 25% planned	1.20	28 days
Saving	–	35-40% less	20.6%	17 days

Figure 6: Corrective vs Predictive cost

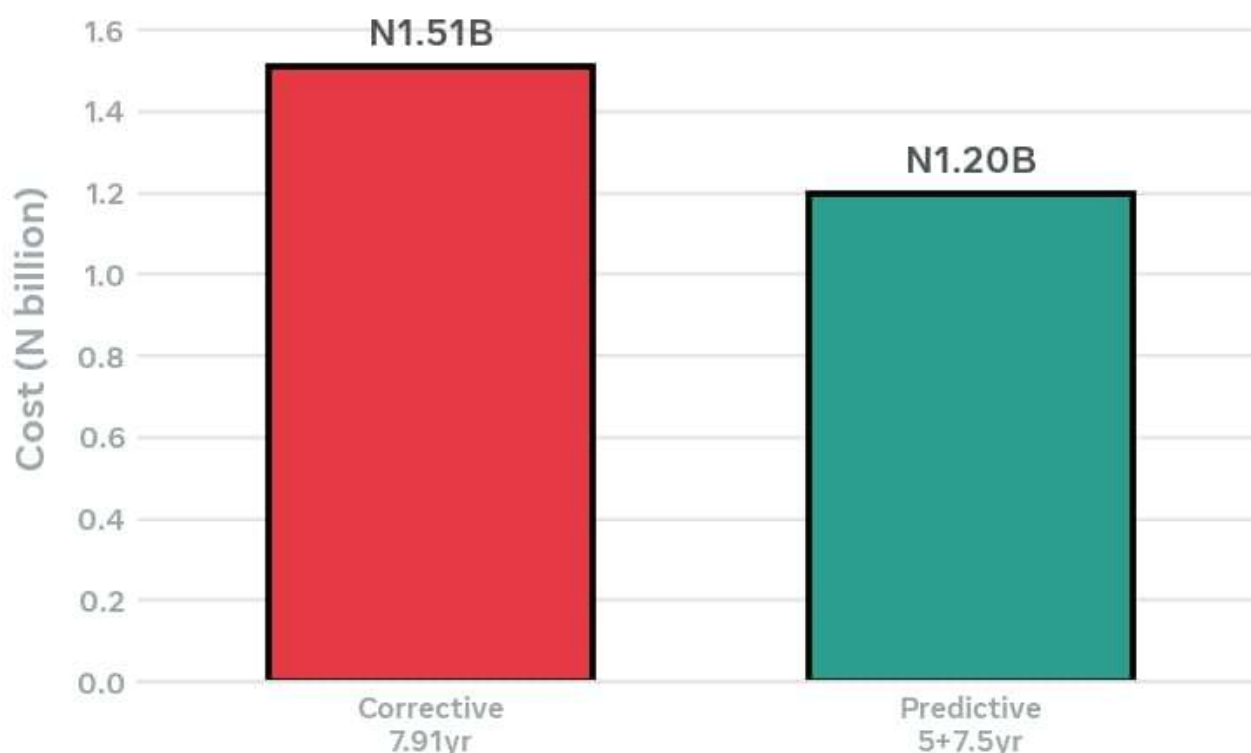


Figure 6, Comparative lifecycle cost of corrective (₦1.512B at 7.91 years, 45 days downtime) versus predictive (₦1.20B at 5.0 + 7.5 years, 28 days downtime) strategies. Predictive maintenance yields 20.6% cost saving and 17 days less downtime through planned partial renewals.

Discussion

The 7.91-year period obtained represents an engineering estimate of time to critical uniform wastage, not an absolute safe life. This distinction is critical for Scopus-level interpretation. Corrosion in service is inherently non-uniform, influenced by coating breakdown, weld residual stress, crevice geometry, and microbiologically influenced corrosion (Odeyemi & Alaba, 2024; Zehra et al., 2022). The linear model therefore provides a conservative baseline for planning, which must be updated with periodic ultrasonic measurements as recommended in marine corrosion practice (Phull & Abdullahi, 2017).

The early exceedance of pitting limits (year ~3-5) relative to uniform limits (year 7.91) aligns with electrolytic accelerated corrosion studies showing rapid pit deepening once coating defects initiate (Si et al., 2021). This finding justifies the 5.45-year predictive trigger adopted in this work, which is earlier than traditional 7.5-year special survey intervals. Integration of NDT mapping (Demircioglu et al., 2024) enables

this shift from calendar-based to condition-based decision making, as advocated for modern vessel maintenance (Nasiri, 2024).

The multi-barrier protection strategy – structural renewal + epoxy barrier + sacrificial anodes – reflects established best practice (Wei et al., 2018). Low-surface-energy antifouling topcoats further reduce MIC initiation sites by limiting biofilm adhesion (Cao & Cao, 2023). Our results show that without predictive recoating at year 5, coating breakdown accelerates the effective CR beyond 550 $\mu\text{m}/\text{year}$, invalidating the linear projection.

Economically, the ₦1.512 billion corrective cost underscores the burden of deferred maintenance for Nigerian operators. The dominance of steel cost (48%) suggests that investment in early inspection and coating maintenance offers high return. While alternative materials such as aluminum alloys and FRP composites offer intrinsic corrosion resistance (Wahid et al., 2020; Rubino et al., 2020), their capital cost and fabrication constraints make optimized maintenance of AH36 steel the pragmatic near-term strategy for the existing coastal fleet.

4. Conclusion

This study successfully demonstrated a predictive framework for hull structural renewal driven by quantitative corrosion modelling and NDT data. The key findings are: At 550 $\mu\text{m}/\text{year}$, AH36 hull plating (15 mm) reaches the classification minimum of 71% remaining thickness in 7.91 years in Nigerian coastal waters, defining the latest allowable corrective intervention point. Localized pitting (PF = 3.5) penetrates significantly faster than uniform loss, confirming that uniform models alone underestimate risk and NDT pit mapping is essential. For a 4,400 m^2 wetted area, corrective renewal demands 414.4 tonnes of steel (₦1.512 billion). The proposed two-stage predictive strategy reduces cost by 20.6% to ₦1.20 billion and downtime by 17 days. The study confirms that shift from corrective to predictive maintenance improves safety, availability and economy. It is recommended that operators adopt 5-year ultrasonic survey intervals with a 20% thickness-loss watchlist trigger, and integrate the model into a digital hull health monitoring system. Future work should incorporate real-time sensor data and microbiologically influenced corrosion kinetics for enhanced accuracy.

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