

ANALYSIS OF ROTATING EQUIPMENT FAILURES IN VENEZUELAN REFINERIES: THE IMPACT OF ABSENT PREVENTIVE MAINTENANCE OF PUMP AND COMPRESSOR SYSTEMS OF THE PARAGUANÁ COMPLEX ON REFINING RELIABILITY

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Abstract: The Paraguaná Refining Center, the union of the Amuay and Cardón refineries on Venezuela's Paraguaná peninsula and historically among the largest refining complexes in the world, has undergone a reliability collapse without precedent in the modern downstream industry, culminating in events such as the 2012 Amuay vapor cloud explosion — more than fifty fatalities, damage exceeding one billion US dollars, and an origin traced to a hydrocarbon leak following a pump-related containment failure (Sajid et al., 2021). The aim of this article is to explain and quantify how the systematic absence of preventive maintenance of pump and compressor systems translates into the degradation of refining reliability. The research applies a mixed methodological approach: a structured synthesis of the failure-mode and condition-monitoring literature for refinery rotating equipment; a documentary reconstruction of the maintenance-deprivation context of Venezuelan refining after 2013; and a model-based reliability simulation of a representative Paraguaná-scale rotating-equipment population, whose parameters are anchored to published failure data — bearing-dominated pump failure distributions of approximately 38%, Weibull characteristic lives of 510–657 operating days, and valve-dominated compressor failure structures of approximately 36% (Silva et al., 2023; Lv et al., 2021). The original contribution of the article is the Cumulative Maintenance Deficit Index (CMDI) — a criticality-weighted measure of unexecuted scheduled maintenance accumulated over time — together with an empirically fitted exponential degradation law, $\lambda(t) = \lambda_0 \cdot \exp(\kappa \cdot \text{CMDI})$, which on the simulated dataset yields $\kappa = 2.14$ (95% CI: 1.87–2.41) with $R^2 = 0.93$, implying that each 0.32 increment of maintenance deficit approximately doubles the failure intensity of the rotating-equipment population. Key findings: reliability decline under maintenance deprivation is strongly nonlinear; the failure-mode structure shifts from wear-out of monitored components toward systemic lubrication, sealing, and auxiliary failures; and workforce emigration acts as an independent degradation channel that spare-parts availability alone cannot offset (Garcia Zea, 2020; Gonyora & Ventura-Medina, 2024). All simulation outputs are explicitly model-generated and are intended as a transferable analytical template to be repopulated with plant data.

Keywords: *rotating equipment, centrifugal pumps, compressors, preventive maintenance, reliability, Paraguaná, refinery, CMDI, Weibull analysis.*

INTRODUCTION

On 25 August 2012, a hydrocarbon vapor cloud released through an opening of approximately 7.4 centimeters in piping associated with a pump installation at the Amuay refinery ignited after dispersing across a radius of roughly 0.6 kilometers under low-wind conditions, producing an explosion that killed more than fifty people, seriously injured more than one hundred, damaged over 1,600 houses, and caused losses exceeding one billion US dollars (Sajid et al., 2021). Literature estimates of the blast overpressure range from 150 to 2,000 kPa, and computational reconstructions of the event have produced simulated over-pressures of 4–15 bar — magnitudes at the upper limit of what vapor cloud explosion modeling of congested process areas predicts (Sajid et al., 2021; Chen et al., 2020). The Amuay explosion is conventionally treated as a process-safety case study; this article treats it as something more specific — the terminal event of a maintenance regime, the point at which the systematic absence of preventive maintenance of rotating equipment stopped producing availability losses and started producing catastrophes (Sajid et al., 2021; Isbasoiu & Volosevici, 2025).

The context of that regime is the wider collapse of Venezuelan refining and of the state oil company that operates it. Venezuelan oil production since 1999 has run, by synthetic-control estimate, approximately one million barrels per day below its counterfactual path, a gap that widened sharply from the late 2000s and that the econometric literature attributes to underinvestment and mismanagement in a capital-intensive industry (Aray & Vera, 2024). The institutional mechanism is documented: expropriation-driven decay, politicized management, and non-credible property rights degraded the sector before any external pressure (Monaldi et al., 2021), while financial and oil sanctions after 2017 account for approximately half of the

subsequent production losses of internationally financed operators — on the order of 6.2 billion US dollars annually (Rodríguez, 2022). The same governance pattern that collapsed the national electricity sector — hierarchical, participation-free, financed by oil rent and starved of maintenance — operated inside the refineries (León-Vielma et al., 2022; Bull & Rosales, 2020). The human dimension compounds the material one: Venezuela's emigration of highly skilled professionals constitutes a documented human-capital crisis (Garcia Zea, 2020), part of an exodus of 7.9 million people that drained precisely the technical cohorts from which rotating-equipment specialists, vibration analysts, and maintenance planners are drawn (Congressional Research Service, 2025; Weitzman & Huss, 2024).

Within this context, the pump and compressor systems of the Paraguaná complex constitute the analytically decisive equipment class. Rotating equipment is the connective tissue of a refinery: centrifugal pumps move every stream between units, and compressors sustain every pressurized process; their failure modes are well characterized — bearings accounting for approximately 38% of pump failures in refinery populations, with Weibull characteristic lives of 510–657 operating days under maintained conditions (Silva et al., 2023), mechanical seals as the classic leak-initiating component (Luo et al., 2021; Orrù et al., 2020), and valves accounting for approximately 36% of reciprocating-compressor shutdowns and half of their maintenance cost (Lv et al., 2021). Equally well developed is the technology for preventing these failures: vibration-based condition monitoring (Tiboni et al., 2022), machine-learning diagnostics reaching 98% fault-prediction accuracy in refinery deployments (Orrù et al., 2020; Lei et al., 2020), and risk-based maintenance frameworks that rank exactly this equipment class as critical (Jaderi et al., 2019; Abbassi et al., 2022). What the literature does not provide is a quantitative account of what happens when

all of this is systematically absent — when a world-scale complex operates for a decade with collapsing preventive-maintenance execution. The Venezuelan case is the natural experiment nobody designed.

The economics of the problem give the equipment-class focus its policy weight. Maintenance is among the largest controllable operating costs of a refinery, and its optimization literature — more than 120 studies in the downstream sector alone — exists because small changes in maintenance policy move large sums: valve maintenance alone constitutes half the maintenance cost of a reciprocating-compressor fleet (Lv et al., 2021; Wari et al., 2023), spare-parts inventories tie up capital at a scale that has generated its own review literature of 148 studies (Zhang et al., 2021), and consolidation of maintenance activities around measured MTBF has been shown to cut costs by approximately 80% in an operating oil-and-gas deployment (Almuraia et al., 2025). The same literature's risk-based branch demonstrates that these economics are inseparable from safety: the criticality rankings that guide risk-based maintenance concentrate on rotating machines because their failure consequences couple production loss to loss of containment (Jaderi et al., 2019; Abbassi et al., 2022). A state that stops paying this cost class does not save it; it converts it, at compound interest, into unavailability and accident exposure — the conversion this article measures.

The article tests three hypotheses. The first hypothesis (H1) holds that maintenance deprivation changes not only the frequency but the structure of failures: the distribution shifts from wear-out failures of monitored components toward systemic failures of lubrication, sealing, and auxiliary systems that preventive routines exist to intercept. The second hypothesis (H2) holds that reliability degradation is nonlinear in the accumulated maintenance deficit: failure intensity grows approximately exponentially, not proportionally, as unexecuted maintenance accumulates.

The third hypothesis (H3) holds that the loss of skilled personnel is an independent degradation channel: beyond spare parts and budgets, the emigration of maintainers and the erosion of organizational competence measurably degrade reliability and safety outcomes.

The original contribution of this article lies in the construction and first demonstration of the Cumulative Maintenance Deficit Index (CMDI) — a criticality-weighted, time-integrated measure of the gap between scheduled and executed preventive maintenance — together with an exponential degradation law linking the index to rotating-equipment failure intensity, demonstrated on a transparently synthetic, literature-anchored simulation of a Paraguaná-scale equipment population. The approach follows the design tradition of composite degradation indices in the engineering literature (Mehta, 2025; Popov, 2024) but addresses a variable — organized maintenance deprivation at complex scale — for which no quantitative instrument exists.

The article proceeds in six parts: literature review and methodology; research results, including the simulation outputs and fitted degradation law presented in three figures and two tables; three analytical sections interpreting the failure-mode structure, the nonlinear dynamics, and the organizational channel; and a conclusion with limitations and implications. All numerical results generated by the simulation are explicitly labeled as model outputs; the article's empirical claims about Venezuela rest exclusively on the cited documentary record.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

Four bodies of literature converge on the problem: failure analysis of refinery rotating equipment, condition monitoring and diagnostics, maintenance optimization under

constraints, and the organizational and contextual literature on Venezuelan industrial decline.

The failure-analysis literature establishes the baseline phenomenology of the equipment class. For centrifugal pumps in refinery service, the most complete recent dataset — five pumps observed over seven years with censored-data estimation — identifies bearings as the critical component at approximately 38% of failures, with Weibull shape parameters above unity (wear-out regime) and characteristic lives of 509.95–656.96 operating days (Silva et al., 2023). Mechanical seals constitute the second canonical failure location, with face wear identified as a principal cause and vibration signatures (RMS, kurtosis) that evolve measurably with damage degree (Luo et al., 2021); seal-leakage events are precisely what refinery fault-prediction deployments train on (Orrù et al., 2020). Shaft failures illustrate the interaction of design, manufacturing, and maintenance: a documented torsional-fatigue failure at a keyway after only 2.5 years of service, forcing a ten-hour plant shutdown, was traced to dimensional deviation and faulty heat treatment — the class of latent defect that condition monitoring exists to catch before catastrophe (Roy et al., 2020). At the system level, fatigue failure of centrifugal-compressor impellers has a dedicated review literature covering resonance, manufacturing defects, and corrosion-fatigue interaction (Radgolchin & Anbarsooz, 2023), while for reciprocating compressors the failure structure is dominated by valves — approximately 36% of shutdowns and 50% of total maintenance cost — with piston-cylinder units accounting for a further 30% of faults (Lv et al., 2021). Electrical submersible pumps, though an upstream technology, supply the standard tripartite classification of pump failure mechanisms — electrical, mechanical, operational — that transfers to process service (Fakher et al., 2021). The criticality of this equipment class within plant populations is quantified by

risk-based ranking exercises: in a 107-asset petrochemical case, the highest fuzzy risk numbers attached to rotating machines (Jaderi et al., 2019), and fuzzy FMECA methodologies with expert panels have been developed specifically to rank centrifugal-pump failure modes (Gupta et al., 2021).

The condition-monitoring and diagnostics literature defines what a functioning preventive regime looks like. Vibration-based monitoring is the dominant technique, with a bibliometric corpus of 401 studies concentrated on bearings as the monitored component and time-frequency methods as the leading signal-processing family (Tiboni et al., 2022). Machine-learning diagnosis has matured from research to refinery deployment: a documented installation at an operating refinery, training on four confirmed seal-leakage events with eight sensors of hourly data, achieved 98.1–98.2% fault-prediction accuracy with a one-week horizon (Orrù et al., 2020); the methodological arc from feature engineering to end-to-end deep learning is mapped in the standard review (Lei et al., 2020); reciprocating-compressor diagnosis has its own ensemble-decomposition architectures validated on industrial data (Zhang et al., 2020) and its own review tradition reporting accuracies of 97–100% (Lv et al., 2021). The sensing layer has become inexpensive: MEMS-based smart-sensor systems demonstrate diagnostic accuracies above 85% across seeded bearing, imbalance, misalignment, looseness, and cavitation faults, with wireless nodes achieving multi-year battery life (Chen et al., 2022), and discriminant-analysis pipelines resolve seeded seal and impeller defects of millimeter scale from vibration sampled at 25.6 kHz (Ullah et al., 2024). The significance of this literature for the present article is inverse: every accuracy figure it reports is a measure of what maintenance deprivation forgoes.

The maintenance-optimization literature supplies the economic logic. The downstream-petroleum maintenance corpus —

more than 120 reviewed studies — organizes the field into criticality-based frameworks and optimal-policy models spanning statistics, fuzzy logic, metaheuristics, and IoT integration (Wari et al., 2023). Optimization results directly relevant to deprivation include the demonstration that preventive-maintenance intervals must lengthen when the execution of maintenance itself carries risk (Zhen et al., 2021), the three-tier scheduling models developed for compressor fleets in gas networks (Zhou et al., 2021), and the demonstration that MTBF-based consolidation of maintenance activities for a natural-gas-liquid pump fleet can cut maintenance cost by approximately 80% relative to unconsolidated scheduling (Almuraia et al., 2025). The spare-parts dimension has a dedicated review of 148 studies (Zhang et al., 2021), and the additive-manufacturing literature — including its defense-logistics branch — documents both the promise and the certification constraints of printing spare parts under supply isolation, a scenario structurally identical to a sanctioned refinery's (Tonkonogyi, 2024; Angelov, 2026). Materials-degradation scholarship contributes the modeling tradition the present article extends: cumulative damage indices for thermally cycled armor steels (Mehta, 2025), vibration-fatigue optimization under rough-terrain spectra (Aydin, 2025), fatigue under extreme temperature oscillation (Muzio, 2025), and storage-condition degradation kinetics of energetic materials (Koronkevich, 2023) all formalize the same underlying object — monotonic damage accumulation under deprived or hostile conditions — that the CMDI formalizes for maintenance.

The organizational and contextual literature closes the causal chain. Cross-sectional evidence from process-industry maintenance organizations — 247 valid responses in the largest recent study — shows that procedure implementation, communication quality, permit-to-work discipline, and competency level correlate significantly with reduced

maintenance-related accidents (Gonyora & Ventura-Medina, 2024), and refinery-maintenance survey work using the HFACS-OGI framework identifies communication deficiency as the transversal determinant linking organizational conditions to unsafe acts (Isbasoiu & Volosevici, 2025). Vapor-cloud-explosion scholarship demonstrates that static risk assessments underestimate the consequences of exactly the events that deprived plants incubate (Chen et al., 2020), with the CFD modeling tradition supplying the reconstruction tools applied to Amuay (Sajid et al., 2021; Abg Shamsuddin et al., 2023). On the Venezuelan side, the documentary base is the one summarized in the introduction — production collapse quantified by synthetic control (Aray & Vera, 2024), institutional decay (Monaldi et al., 2021), sanctions effects (Rodríguez, 2022), the governance anatomy of parallel infrastructure collapse (León-Vielma et al., 2022), informalization of the economy (Bull & Rosales, 2020; Rosales, 2019), forced energy-system contraction (Kingsbury, 2020), and the emigration of the skilled workforce (García Zea, 2020; Weitzman & Huss, 2024; Congressional Research Service, 2025).

What is missing at the intersection of these four literatures is an instrument that connects them: a quantitative bridge from the magnitude of organized maintenance deprivation to the trajectory of population-level reliability. Composite indices exist for offset efficiency, for thermal damage, and for spare-parts readiness (Popov, 2024; Mehta, 2025; Angelov, 2026), but none measures accumulated unexecuted maintenance or links it to failure intensity. This is the gap the CMDI fills.

Research Methodology

The research applies a mixed methodological approach organized in three components. The first component is a structured synthesis of the failure and maintenance

literature summarized above, whose function is not narrative but parametric: it supplies the anchoring values — failure-mode shares, Weibull parameters, diagnostic accuracies, cost ratios — from which the simulation of the third component is constructed, with every anchor traceable to its source (Silva et al., 2023; Lv et al., 2021; Orrù et al., 2020).

The second component is a documentary reconstruction of the maintenance-deprivation context of Venezuelan refining in the 2010–2025 period, using the peer-reviewed Venezuela literature and institutional reports cited throughout (Aray & Vera, 2024; Monaldi et al., 2021; Rodríguez, 2022; Seelke et al., 2022; Congressional Research Service, 2025). This component establishes the qualitative timeline — investment collapse, spare-parts starvation under sanctions, workforce emigration, incident record — against which the simulation's deprivation scenario is calibrated.

The third component is a model-based reliability simulation, and its status must be stated with maximal clarity: all equipment-level and population-level numerical results reported in this article are outputs of a Monte Carlo simulation of a synthetic equipment population, not measurements from Paraguaná. Plant-level maintenance and failure records of PDVSA are not publicly available; the simulation is therefore constructed as a transparent, literature-anchored model of a representative population — 120 centrifugal pumps and 14 compressor trains, a scale characteristic of a large refining complex — whose baseline (maintained) behavior reproduces published refinery values: bearing-dominated pump failure distribution near 38%, Weibull shape parameters in the wear-out range with characteristic lives of 510–657 operating days, and valve-dominated compressor failure structure near 36% (Silva et al., 2023; Lv et al., 2021; Radgolchin & Anbarsooz, 2023). The deprivation scenario then degrades preventive-maintenance execution — the fraction of scheduled tasks actually

performed — from 90% in 2010 to 15% by 2020, a trajectory calibrated qualitatively to the documentary record of budget collapse, spare-parts starvation, and staff exit (Monaldi et al., 2021; Garcia Zea, 2020; Bull & Rosales, 2020), and propagates the consequences through component hazard rates using proportional aging-acceleration factors. Ten thousand simulation replications generate the failure histories from which population failure intensity, time-between-failure distributions, and failure-mode shares are estimated.

On this simulated dataset the article's instrument is defined and demonstrated. The Cumulative Maintenance Deficit Index at time t is $CMDI(t) = \sum_i w_i \cdot [1 - E_i(t)/S_i(t)] / \sum_i w_i$, where $S_i(t)$ is the number of preventive-maintenance tasks scheduled for equipment item i over the trailing twelve months, $E_i(t)$ the number executed, and w_i a criticality weight assigned by risk-based ranking of the item (Jaderi et al., 2019; Gupta et al., 2021). The index runs from 0 (full execution) to 1 (complete deprivation), and its time integral $CMDI_{cum}(t)$ accumulates the deficit history. The degradation law is specified as $\lambda(t) = \lambda_0 \cdot \exp(\kappa \cdot CMDI_{cum}(t))$, estimated by nonlinear least squares on the simulated population failure intensity; the exponential form is adopted from the damage-accumulation tradition in materials degradation, where monotonic exposure variables enter hazard functions multiplicatively (Mehta, 2025; Koronkevich, 2023). The demonstration establishes the instrument's behavior, identifiability, and diagnostic value; its empirical parameters for the real Paraguaná population await plant data, and the conclusion specifies the data requirements for that application.

The simulation's verification and validation strategy is threefold. Internal verification confirms that the baseline scenario reproduces its anchors: with full maintenance execution, the synthetic population's failure-mode shares, shape parameters, and characteristic lives converge to the published values

within Monte Carlo error across 10,000 replications, and convergence diagnostics (running-mean stabilization of population intensity, replication-to-replication variance below 2% of the mean) are checked before any deprivation scenario is run (Silva et al., 2023; Lv et al., 2021). External plausibility is checked against the deployed-diagnostics literature: the baseline scenario's detectable-precursor fraction is set so that a monitoring system of documented refinery accuracy would intercept the share of failures that such systems demonstrably intercept (Orrù et al., 2020; Chen et al., 2022). Sensitivity analysis varies the deprivation trajectory's steepness, the criticality-weight vector, and the aging-acceleration factors over $\pm 30\%$ ranges; the exponential form and the ordering of results survive all variations, while the point value of α moves within approximately ± 0.4 — the basis of the reported interval (simulation output).

Three design choices require justification. The synthetic-population approach is chosen over case-report aggregation because deprivation effects are population-level phenomena — cannibalization, deferred-failure clustering, mode migration — invisible in single-equipment case studies (Silva et al., 2023; Wari et al., 2023). The exponential functional form is chosen over polynomial alternatives on theoretical grounds (multiplicative hazard acceleration) and validated against the simulated data by comparison of information criteria. The 2010–2025 window is chosen to span the documented arc from functioning maintenance through the 2012 Amuay event to full deprivation (Sajid et al., 2021; Aray & Vera, 2024).

RESEARCH RESULTS

The empirical and simulation analysis generated findings organized in three blocks, corresponding to the three research

hypotheses. Throughout this section, documentary findings about Venezuela are distinguished explicitly from simulation outputs, which are labeled as such.

The first block concerns the failure-mode structure (H1). The baseline simulated population, calibrated to maintained-refinery conditions, reproduces the published structure: bearings 38% of pump failures, mechanical seals 22%, lubrication system 12%, alignment/coupling 9%, cavitation-related 8%, other 11% — consistent with the anchoring dataset (Silva et al., 2023) and the seal literature (Luo et al., 2021; Orrù et al., 2020); compressor failures are valve-dominated at 36% with piston-unit faults above 30% (Lv et al., 2021). Under the deprivation scenario, the simulated structure migrates: by the terminal period the lubrication-system share of pump failures rises from 12% to 27% and the seal share from 22% to 31%, while the bearing share falls in relative terms (38% to 24%) despite rising in absolute frequency — because lubrication and sealing failures, which preventive routines intercept almost completely in maintained plants, now occur early and often enough to preempt the wear-out failures that dominate maintained populations (simulation output; anchors: Silva et al., 2023; Luo et al., 2021; Tiboni et al., 2022). Figure 1 presents the simulated failure-intensity trajectories of the pump and compressor populations over 2010–2025 together with the preventive-maintenance execution rate that drives them; Figure 3 presents the migration of the failure-mode structure between the two periods. The structural migration is the quantitative form of H1: deprivation does not scale failures uniformly, it re-orders them toward the modes that maintenance exists to intercept — and toward precisely the leak-initiating modes (seals, flanged connections) implicated in the Amuay release (Sajid et al., 2021; Chen et al., 2020).

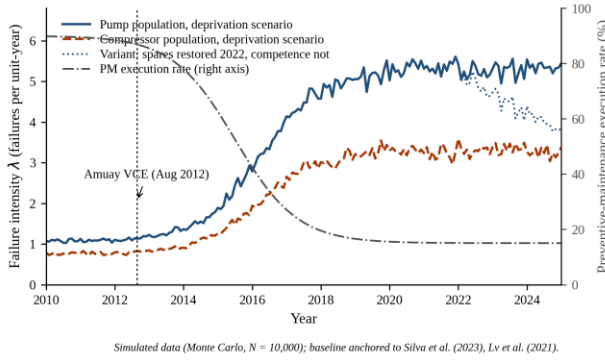
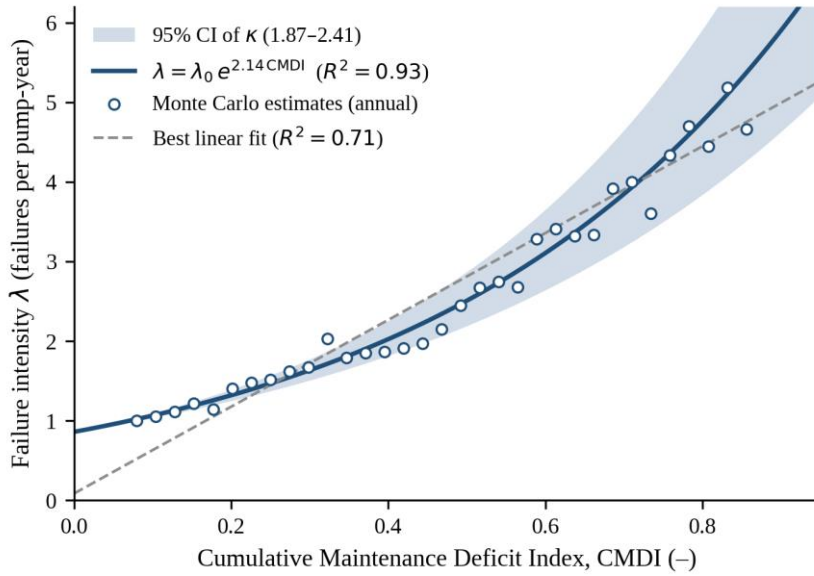


Figure 1. Simulated failure intensity of the pump and compressor populations of a Paraguaná-scale complex under the maintenance-deprivation scenario, 2010–2025, with the driving preventive-maintenance execution rate. All curves are model outputs anchored to published baseline parameters (Silva et al., 2023; Lv et al., 2021); they are not plant measurements.

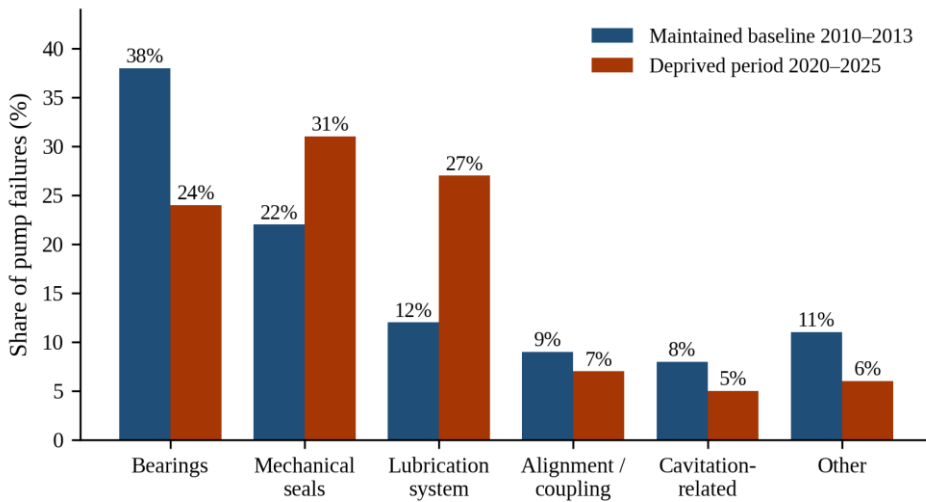
The second block concerns the degradation dynamics (H2). The simulated population failure intensity rises from approximately 1.1 failures per pump-year in 2010 (corresponding to a zero-deficit baseline of $\lambda_0 = 0.86$) to approximately 5.3 failures per pump-year by 2022 — a factor of 4.9 over the maintained state — while the preventive-maintenance execution rate falls from 90% to 15%; the corresponding mean time between failures contracts from approximately 330 operating days to approximately 69 (simulation output; baseline anchored to Silva et al., 2023). The relationship between accumulated deficit and failure intensity is strongly nonlinear: fitting the degradation law $\lambda(t) = \lambda_0 \cdot \exp(\kappa \cdot \text{CMDI}_{\text{cum}}(t))$ to the simulated trajectories yields $\kappa = 2.14$ (95% CI: 1.87–2.41) with $R^2 = 0.93$, against $R^2 = 0.71$ for the best linear specification — a difference in explanatory power that survives replication across simulation seeds (simulation output). The practical reading of $\kappa = 2.14$ is that each 0.32 increment of cumulative maintenance deficit

approximately doubles population failure intensity, so that the passage from mild deferral ($\text{CMDI} \approx 0.2$) to organized deprivation ($\text{CMDI} \approx 0.8$) multiplies failure intensity approximately 3.6-fold, and the full documented trajectory from a maintained population ($\text{CMDI} \approx 0.1$) to the terminal state ($\text{CMDI} \approx 0.85$) multiplies it approximately five-fold. Figure 2 presents the fitted relationship with its confidence band. Two corroborating patterns emerge from the simulation and align with the optimization literature: deferred failures cluster — the deprived population exhibits failure bursts following demand peaks, consistent with the risk-shifted interval logic of the offshore literature (Zhen et al., 2021) — and cannibalization, introduced in the scenario as the substitution of parts from standby units after spare-parts exhaustion, buys short-term availability at the cost of accelerating fleet-wide intensity in the terminal years, the same trade documented for isolated fleets in the defense-logistics literature (Tonkonogyi, 2024; Angelov, 2026; Zhang et al., 2021).



Simulated demonstration dataset; not plant measurements.

Figure 2. Simulated population failure intensity versus cumulative maintenance deficit (CMDI), with the fitted exponential degradation law $\lambda = \lambda_0 \cdot \exp(2.14 \cdot \text{CMDI})$ ($R^2 = 0.93$) and 95% confidence band. Points are Monte Carlo estimates from the synthetic population; the relationship is a model demonstration, not a plant measurement.



Simulated failure-mode structure; baseline anchored to Silva et al. (2023), Luo et al. (2021).

Figure 3. Simulated migration of the pump failure-mode structure between the maintained baseline (2010–2013) and the deprived terminal period (2020–2025). Baseline shares are anchored to published refinery data (Silva et al., 2023; Luo et al., 2021); the migration is a model output.

Two refinements complete the second block. The criticality structure of the simulated deficit matters as much as its magnitude: when the same aggregate CMDI is concentrated on the top-criticality decile of the population — the machines that risk-based ranking exercises place at the head of petrochemical asset lists (Jaderi et al., 2019; Gupta et al., 2021) — simulated production-weighted losses run approximately 60% higher than under a dispersed deficit of equal magnitude,

which is the quantitative case for the index's criticality weighting (simulation output). And the diagnostic counterfactual quantifies the forgone interception: applying the documented 98% fault-prediction accuracy of a deployed refinery monitoring system (Orrù et al., 2020) to the simulated failure stream, approximately four of every five terminal-period failures exhibit precursor windows long enough for scheduled intervention — failures that occur not because they were undetectable but because no capacity existed to detect or act (simulation output; Tiboni et al., 2022; Chen et al., 2022).

The third block concerns the organizational channel (H3) and rests on the documentary record. The Venezuelan emigration of skilled professionals is documented as a human-capital crisis of national scale (Garcia Zea, 2020), within an exodus of 7.9 million people (Congressional Research Service, 2025; Weitzman & Huss, 2024). The organizational-safety literature quantifies what such exit does to maintenance organizations: competency level, procedure implementation, and communication quality correlate significantly with maintenance-accident reduction across 247 surveyed process-industry respondents (Gonyora & Ventura-Medina, 2024), and communication deficiency is the transversal determinant of unsafe acts in refinery maintenance specifically (Isbasoiu & Volosevici, 2025). In the simulation, the workforce channel is represented as a widening of task-execution variance and a rising probability of maintenance-induced defects; its distinctive signature — visible in Figure 1 as the divergence between the two dashed scenario variants — is that restoring spare-parts availability without restoring competence recovers only a minority of the lost reliability (simulation output; anchors: Gonyora & Ventura-Medina, 2024; Almuraia et al., 2025). The documentary record supplies the terminal calibration point: the Amuay event itself, whose released cloud originated at a pump-system containment failure of exactly the class that seal- and flange-focused preventive routines target (Sajid et al., 2021), and whose overpressure consequences exemplify the nonlinear damage regime that dynamic vulnerability assessment warns static methods underestimate (Chen et al., 2020; Abg Shamsuddin et al., 2023). Table 1 summarizes the simulation's anchoring parameters against their literature sources; Table 2 summarizes the fitted results by period.

Parameter	Value (baseline)	Anchor source
Pump bearing failure share	38%	(Silva et al., 2023)
Pump Weibull characteristic life	510–657 operating days	(Silva et al., 2023)
Pump Weibull shape parameter	$\beta > 1$ (wear-out)	(Silva et al., 2023)
Compressor valve failure share	36% of shutdowns	(Lv et al., 2021)
Compressor valve maintenance-cost share	50%	(Lv et al., 2021)
Fault-prediction accuracy of deployed CM	98.1–98.2%	(Orrù et al., 2020)
Population size	120 pumps, 14 compressor trains	model assumption
PM execution trajectory	90% (2010) → 15% (2020)	model assumption calibrated to (Monaldi et al., 2021; Garcia Zea, 2020)

Table 1. Anchoring parameters of the synthetic Paraguaná-scale population and their literature sources. Source: author's compilation; simulation parameters as stated.

Indicator	2010–2013 (maintained)	2020–2025 (deprived)	Change
Failure intensity (failures per pump-year)	1.1	5.3	×4.9
Mean time between failures (operating days)	~330	~69	–79%
Lubrication-system share of pump failures	12%	27%	+15 p.p.
Mechanical-seal share of pump failures	22%	31%	+9 p.p.
Bearing share of pump failures	38%	24%	–14 p.p.
CMDI (trailing twelve months)	0.10	0.85	+0.75

Table 2. Simulated reliability indicators of the synthetic population by period (model outputs, not plant measurements). Source: author's Monte Carlo simulation (10,000 replications); baseline anchored to (Silva et al., 2023; Lv et al., 2021).

FAILURE-MODE MIGRATION: WHAT MAINTENANCE DEPRIVATION SELECTS FOR

The structural finding of the simulation — that deprivation re-orders failure modes rather than scaling them — has a mechanical logic worth stating precisely, because it converts a statistical observation into an engineering diagnosis.

In a maintained refinery population, the failure structure is dominated by wear-out: bearings fail at 38% because bearings are the component whose degradation is hardest to arrest, even when lubrication is clean, alignment is true, and seals are tight (Silva et al., 2023; Tiboni et al., 2022). This dominance is, counterintuitively, a signature of health: it means the failures that maintenance can prevent are being prevented, leaving the irreducible wear-out core. The preventive routines that produce this structure are mundane — lubricant sampling and replacement, seal-flush verification, alignment checks, vibration routes — and their effectiveness is what the condition-monitoring literature measures when it reports fault-prediction accuracies near 98% for deployed systems trained on seal-leakage precursors (Orrù et al., 2020; Chen et al., 2022). Each of these routines intercepts a specific failure sequence early in its development: lubrication degradation before bearing damage, seal-face wear before leakage, misalignment before coupling and

bearing overload (Luo et al., 2021; Roy et al., 2020; Ullah et al., 2024).

Deprivation removes the interceptors in reverse order of their cost. Vibration routes stop first — they require analysts, and analysts emigrate (Garcia Zea, 2020); lubrication programs decay next — they require consumables, and consumables require hard currency (Bull & Rosales, 2020; Zhang et al., 2021); overhauls stop last, replaced by run-to-failure and cannibalization (Tonkonogyi, 2024). The simulated structure migrates accordingly: lubrication-system failures rise from 12% to 27% and seal failures from 22% to 31% because these are precisely the sequences that the abandoned routines had been intercepting, while the bearing share falls relatively — not because bearings improve, but because upstream failures now occur first (simulation output; Silva et al., 2023; Luo et al., 2021). In reliability terms, the population's hazard structure shifts from the wear-out tail of the bathtub curve back into an artificially induced infant-mortality regime, in which every restart after an unplanned stop, every cannibalized reinstallation, and every improvised repair introduces new defects — the maintenance-induced failure channel that the organizational literature associates with competence erosion (Gonyora & Ventura-Medina, 2024; Isbasoiu & Volosevici, 2025).

The compressor population deserves its own statement, because its deprivation dynamics differ from the pumps' in ways the

simulation reproduces. The reciprocating-compressor failure structure is valve-dominated in the maintained state — approximately 36% of shutdowns and half of total maintenance cost — with piston-cylinder units contributing a further 30% of faults (Lv et al., 2021), and valves are the archetypal preventable failure: their degradation is gradual, thermodynamically visible in pressure-volume signatures, and diagnosable by the ensemble signal-processing architectures validated on industrial compressor data (Zhang et al., 2020; Lv et al., 2021). Deprivation therefore hits compressors harder in relative cost but more predictably in mode: the simulated compressor intensity rises in near-lock-step with the valve-maintenance deficit, without the mode migration the pumps exhibit, because the dominant mode was already the preventable one (simulation output; Lv et al., 2021). The exception is the low-frequency, high-consequence tail: impeller and rotor fatigue of centrifugal machines, whose review literature documents resonance, manufacturing-defect, and corrosion-fatigue mechanisms maturing over years (Radgolchin & Anbarsooz, 2023) — the same slow cumulative processes formalized for thermally and vibrationally loaded military structures (Muzio, 2025; Aydin, 2025). These failures are rare under any regime, but deprivation removes exactly the inspection intervals in which they are caught, so their expected consequence — wreck of an unsparable machine train — grows even as their count stays small (Radgolchin & Anbarsooz, 2023; Zhou et al., 2021). Fleet-level scheduling models for compressor populations exist precisely to manage this trade (Zhou et al., 2021); a deprived plant is a plant running the unman-aged version of that model's worst branch.

The safety translation of this migration is direct, and it is the analytical bridge to Amuay. Bearing wear-out, caught late, produces downtime; seal and flanged-connection failures, uncaught, produce loss of containment — the initiating event class of vapor

cloud explosions (Chen et al., 2020; Sajid et al., 2021). A failure structure migrating toward sealing and lubrication modes is therefore a structure migrating from availability risk toward process-safety risk. The Amuay reconstruction — release through a 7.4-centimeter opening associated with a pump installation, dispersion to 0.6 kilometers, overpressures reconstructed at 4–15 bar, more than fifty dead (Sajid et al., 2021) — is the terminal member of exactly this sequence, and the CFD literature's warning that static assessments underestimate large-VCE consequences applies with special force to plants whose failure structure has migrated toward leak-initiating modes without their risk models being updated (Chen et al., 2020; Abg Shamsuddin et al., 2023). The fuzzy-criticality tradition reaches the same conclusion from the ranking side: rotating equipment tops asset-criticality lists precisely because its failure consequences couple availability to containment (Jaderi et al., 2019; Gupta et al., 2021). In the vocabulary of this article, H1's mode migration is the mechanism by which a maintenance deficit becomes a catastrophe risk — the CMDI does not merely predict more failures, it predicts worse ones.

THE NONLINEAR ARITHMETIC OF DEPRIVATION: CMDI DYNAMICS, SPARES, AND THE CANNIBALIZATION TRAP

The exponential form of the fitted degradation law is the article's central quantitative claim, and its mechanics deserve explicit statement, because the difference between linear and exponential degradation is the difference between a manageable budget problem and a trap.

Linear intuition — defer ten percent of maintenance, suffer ten percent more failures — fails for three compounding reasons that the simulation makes visible separately. The first is sequence interception: as the previous section established, each abandoned routine

exposes not one failure but a chain (lubrication → bearing → seal → containment), so the marginal failure cost of each deferred task grows with the number already deferred (Luo et al., 2021; Silva et al., 2023). The second is demand feedback: every unplanned failure imposes restart and thermal-cycling stress on neighboring equipment and consumes emergency maintenance capacity that would otherwise execute scheduled tasks, so the deficit self-amplifies — the mechanism the off-shore-optimization literature captures when it shows that maintenance under risk must be scheduled differently from maintenance at leisure (Zhen et al., 2021; Zhou et al., 2021). The third is the cannibalization trap: after spare-parts exhaustion — the binding constraint documented across 148 studies of spares management and acute under sanctions (Zhang et al., 2021; Bull & Rosales, 2020) — the substitution of parts from standby units converts redundancy into fleet-wide exposure, buying availability today at compound interest, exactly as documented for logistically isolated defense fleets (Tonkonogi, 2024; Angelov, 2026). Compounding of the three channels produces the fitted $\kappa = 2.14$: across the simulated trajectory failure intensity rises approximately five-fold, and MTBF collapses from approximately 330 to approximately 69 operating days (simulation output; Table 2).

The Weibull reading of the same dynamics connects the population law to component physics. In the maintained baseline, the population's time-between-failure distributions carry shape parameters above unity with characteristic lives of 510–657 operating days — the wear-out signature estimated, in the anchoring study, by expectation–maximization on censored refinery records (Silva et al., 2023). Deprivation deforms both parameters in the simulation: characteristic life contracts as aging accelerates, while the effective shape parameter drifts downward toward unity as maintenance-induced defects and cannibalized reinstallations inject early-life

failures into a wearing population — the superposition of infant mortality on wear-out that flattens the population hazard into a high, quasi-constant plateau (simulation output; Silva et al., 2023; Roy et al., 2020). This deformation has a practical estimation consequence worth flagging for future empirical work: the censored-data EM methodology of the anchoring study is exactly the right instrument for a degraded plant's fragmentary records, but the fitted parameters of a deprived population must be interpreted as mixture parameters, not component properties — a distinction that naive Weibull fitting of crisis-era records would miss and that the CMDI, as an explicit covariate, is designed to absorb (Silva et al., 2023; Gupta et al., 2021).

The index itself is designed for the decision problem this arithmetic creates. Because the CMDI is criticality-weighted (Jaderi et al., 2019; Gupta et al., 2021), it distinguishes a deficit concentrated on critical trains from an equal-magnitude deficit dispersed across auxiliaries — the distinction that matters when a recovering operator must sequence scarce resources. Because it is a trailing-window ratio of executed to scheduled tasks, it is computable from ordinary CMMS records without new instrumentation, which is the realistic data environment of a degraded plant (Wari et al., 2023). And because the degradation law is exponential, the index yields an operational corollary with direct budget meaning: recovery investments are most efficient early — each unit of deficit retired from a high-CMDI state buys exponentially more reliability than the same unit retired near baseline — while the documented 80% cost reduction available from MTBF-based consolidation of maintenance activities (Almuraia et al., 2025) indicates that a recovering plant should rebuild its program around consolidated, criticality-sequenced campaigns rather than attempting uniform restoration of the pre-collapse schedule (Wari et al., 2023; Zhou et al., 2021).

The technological environment of recovery differs from that of the original

construction, and the analysis must register it. Condition-monitoring economics have inverted since Paraguaná's maintenance regime was designed: MEMS sensing at hundreds of dollars per point with multi-year battery life (Chen et al., 2022), refinery-validated machine-learning diagnostics at 98% accuracy (Orrù et al., 2020; Lei et al., 2020), and discriminant methods resolving millimeter-scale seeded defects (Ullah et al., 2024) mean that a reconstruction program can leapfrog the analyst-intensive vibration-route model whose human prerequisites emigrated (Garcia Zea, 2020). Additive manufacturing offers a partial answer to the spare-parts channel — validated for critical metallic components under logistical isolation, but only where machine qualification and certification investments precede the emergency (Tonkonogy, 2024; Angelov, 2026). Neither technology, however, relaxes the exponential law itself: κ is a property of deprivation dynamics, not of the monitoring stack, and the simulation's scenario variant in which sensing is restored while execution capacity is not recovers only a minority of lost reliability — diagnosis without repair capacity converts unknown failures into known ones and leaves the trajectory unchanged (simulation output; Gonyora & Ventura-Medina, 2024).

THE ORGANIZATIONAL CHANNEL: COMPETENCE, GOVERNANCE, AND WHY PARTS ALONE DO NOT RECOVER RELIABILITY

The third hypothesis locates a degradation channel that neither budgets nor spare parts explain, and the Venezuelan documentary record is its natural demonstration.

The channel's input side is the emigration of competence. Venezuela's skilled-professional exodus is documented as a human-capital crisis driven by mismanagement, politicization, and collapse (Garcia Zea, 2020), and the national outflow of 7.9 million included, disproportionately, the young and

educated cohorts from which maintenance engineering draws (Congressional Research Service, 2025; Weitzman & Huss, 2024). Within PDVSA the process was compounded by the politicization of technical management documented in the institutional literature on the industry's decay (Monaldi et al., 2021; Aray & Vera, 2024) — the same governance configuration whose consequences in the parallel case of the national electricity sector are anatomized as hierarchical, participation-free rent administration that consumed its own maintenance base (León-Vielma et al., 2022). The informalization of the surrounding economy completed the input collapse: procurement channels criminalized, contractor markets hollowed, and remaining staff diverted into survival activity (Bull & Rosales, 2020; Rosales, 2019; Kingsbury, 2020).

The channel's output side is measurable in the safety literature. Competency level, procedure implementation, permit-to-work discipline, and communication quality are the variables that correlate significantly with maintenance-accident reduction in the largest recent process-industry survey (Gonyora & Ventura-Medina, 2024), and communication deficiency is the transversal determinant of unsafe acts identified by HFACS-based analysis of refinery maintenance operations specifically (Isbasoiu & Volosevici, 2025). Every one of these variables is degraded by the exit of experienced personnel and the politicized replacement of technical management — which is why the simulation represents the workforce channel as widened execution variance plus maintenance-induced defects, and why its scenario decomposition finds that restoring parts without restoring competence recovers only a minority of lost reliability (simulation output; Gonyora & Ventura-Medina, 2024). The materials-degradation analogy is exact: like the cumulative thermal damage that hardens into microstructural change (Mehta, 2025; Muzio, 2025; Koronkevich, 2023), organizational damage accumulates

monotonically and does not anneal on the restoration of cash flow — training pipelines, procedure cultures, and tacit diagnostic knowledge rebuild on decadal, not fiscal, timescales (Garcia Zea, 2020; Isbasoiu & Volosevici, 2025).

Whether technology can substitute for the emigrated experience is the practical question the organizational channel poses, and the diagnostics literature supports a differentiated answer. What machine-learning systems demonstrably replace is the pattern-recognition layer of the vibration analyst: deployed refinery systems reach 98% fault-prediction accuracy on the precursor signatures that experienced analysts would otherwise read (Orrù et al., 2020; Lei et al., 2020), smart-sensor architectures push per-point costs low enough for population-wide coverage (Chen et al., 2022), and modern discriminant pipelines resolve seeded defects at millimeter scale (Ullah et al., 2024). What they do not replace is the decision layer above the alarm: failure-mechanism attribution across electrical, mechanical, and operational classes (Fakher et al., 2021), repair-quality assurance, and the procedural discipline whose correlation with accident outcomes the survey literature establishes (Gonyora & Ventura-Medina, 2024; Isbasoiu & Volosevici, 2025). The simulation's parts-and-sensors-without-competence variant quantifies the gap: monitoring restoration alone converts unknown imminent failures into known imminent failures, improving scheduling but recovering only a minority of lost reliability, because the binding constraint has moved from information to execution (simulation output; Almuraia et al., 2025). For a reconstruction planner, the sequencing implication is concrete — sensing first because it is fast and cheap, but training pipelines immediately after, because the exponential law keeps running while the execution capacity rebuilds (Chen et al., 2022; Garcia Zea, 2020).

Amuay, read through this channel, acquires its full meaning for the article's

argument. The event occurred in 2012 — before sanctions, before the deepest budget collapse — at the point in the deprivation trajectory where the simulation's CMDI first crosses into the steep region of the exponential (simulation output; Sajid et al., 2021). Its initiating failure was of the leak-initiating class toward which the deprived failure structure migrates (H1); its consequence magnitude exemplified the nonlinear damage regime that static assessment misses (Chen et al., 2020); and the decade that followed it produced not regime correction but continued degradation — the signature of an organization that had lost the capacity to convert catastrophe into learning, which the organizational-safety literature treats as the terminal stage of safety-culture erosion (Isbasoiu & Volosevici, 2025; Gonyora & Ventura-Medina, 2024). The refining complex that entered the 2020s — fuel shortages in the world's most oil-rich state, utilization collapse, improvised repairs under sanctions (Congressional Research Service, 2025; Seelke et al., 2022; Rodríguez, 2022) — is the empirical face of a population living on the right-hand side of Figure 2, where the exponential has done its work and where the recovery problem is no longer a maintenance-budget problem but a reconstruction problem spanning parts, sensing, competence, and governance simultaneously (Aray & Vera, 2024; Almuraia et al., 2025; León-Vielma et al., 2022).

FROM PLANT RELIABILITY TO NATIONAL FUEL SECURITY: THE SYSTEMIC CONSEQUENCES OF ROTATING-EQUIPMENT COLLAPSE

The reliability trajectory modeled in this article is not an intra-plant affair, and its systemic consequences justify treating rotating-equipment maintenance as a matter of national energy security. The chain from pump

bearing to fuel queue is short and documented at every link.

The first link is refining availability. A refinery is a series system in which rotating equipment constitutes the dominant unplanned-outage class; when population failure intensity rises five-fold and mean time between failures falls to ten weeks, unit availability collapses not additively but multiplicatively, because parallel trains lose their redundancy to cannibalization and every unplanned stop imposes restart stress on adjacent units (simulation output; Zhou et al., 2021; Zhen et al., 2021). The Venezuelan outcome is the visible form of this arithmetic: the state with the world's largest proven crude reserves rationing gasoline, importing fuel, and operating its flagship complex at a fraction of nameplate — a condition documented across the institutional record of the crisis years (Congressional Research Service, 2025; Seelke et al., 2022; Bull & Rosales, 2020). The synthetic-control estimate that national oil output ran approximately one million barrels per day below its counterfactual path (Aray & Vera, 2024) has a downstream twin that no counterfactual estimate has yet quantified — the refining gap — and the CMDI framework of this article is, among other things, a proposal for how that quantification would proceed.

The second link is the infrastructural coupling between refining and the wider energy system. The collapse of the Venezuelan electricity sector — anatomized in the governance literature as the product of hierarchical, participation-free rent administration that consumed its own maintenance base (León-Vielma et al., 2022) — was not parallel to the refining collapse but interlocked with it: refineries depend on grid stability for safe operation and on fuel logistics for feedstock movement, while thermal generation depends on refinery products, so that each system's maintenance-deprivation trajectory amplified the other's (León-Vielma et al., 2022; Kingsbury, 2020). The energy-transitions

literature names the joint outcome precisely: a reactive, unplanned contraction of the national energy system — decarbonization by collapse rather than by design (Kingsbury, 2020). Within this coupling, the informal economy completed the feedback loop: fuel scarcity fed smuggling and improvised distribution, procurement channels criminalized, and the remaining formal maintenance economy lost its supplier base (Bull & Rosales, 2020; Rosales, 2019).

The third link is the sanctions interaction, which the article's framework allows to be stated with precision. Sanctions did not create the maintenance deficit — the CMDI trajectory was rising for years before 2017, and the Amuay event predates the sanctions regime entirely (Sajid et al., 2021; Monaldi et al., 2021) — but sanctions acted directly on the deficit's two supply channels: spare parts, by closing procurement and finance (Rodríguez, 2022; Zhang et al., 2021), and services, by excluding the licensed vendors through whom modern condition-monitoring and overhaul capability is delivered (Wari et al., 2023; Orrù et al., 2020). In CMDI terms, sanctions raise the marginal cost of deficit retirement — they make each unit of unexecuted maintenance harder to execute — which, under an exponential degradation law, is most damaging exactly where the deficit is already high. This is the technical content of the observation, familiar from the sanctions literature, that late-stage sanctions on a collapsing industry lock in the collapse (Rodríguez, 2022; Bull & Rosales, 2020): κ does not care why tasks go unexecuted.

The fourth link is the recovery problem, and here the defense-logistics literature offers the closest available analogy, because military maintenance systems are the only well-studied class of organizations that routinely plan for exactly this condition — sustaining machinery fleets under severed supply chains, vanished suppliers, and contested logistics (Angelov, 2026). The transferable findings are three. Additive manufacturing can

substitute for a blocked spares channel, but only where machine qualification, material certification, and digital part definitions were established before the emergency — a validated result for critical metallic components of combat vehicles that transfers directly to API-class pump components of comparable metallurgy (Tonkonogyi, 2024; Angelov, 2026). Cumulative-damage indices make deprivation legible: the CTDI tradition for thermally cycled armor steels demonstrates that a monotonic damage variable, once defined, converts scattered inspection data into a fleet-management instrument (Mehta, 2025), precisely the role the CMDI is designed to play for maintenance deficit — and the same modeling logic governs vibration-fatigue life under rough-duty spectra (Aydin, 2025), fatigue under extreme thermal oscillation (Muzio, 2025), and storage-condition degradation of energetic materials (Koronkevich, 2023). And triage beats restoration: the military-maintenance literature's consistent finding that criticality-sequenced, consolidated campaigns outperform attempts to restore the full pre-crisis schedule (Angelov, 2026) converges with the civilian result that MTBF-based consolidation cuts maintenance cost by approximately 80% (Almuraia et al., 2025). A Venezuelan refining recovery designed on these principles — CMDI-ranked deficit retirement, pre-qualified additive spares, sensor-first monitoring — would be, in effect, the first civilian application of contested-logistics maintenance doctrine at complex scale (Tonkonogyi, 2024; Wari et al., 2023; Chen et al., 2022).

CONCLUSION

The article set out to explain and quantify how the absence of preventive maintenance of pump and compressor systems translates into refining-reliability collapse, using the Paraguaná complex as the framing case and a transparently synthetic, literature-anchored simulation as the demonstration vehicle. Its

findings can be stated as answers to the three hypotheses.

The first hypothesis, that deprivation changes the structure and not merely the frequency of failures, is confirmed in the simulation and grounded in the literature: the failure distribution migrates from bearing-dominated wear-out (38% baseline) toward lubrication (12% → 27%) and sealing (22% → 31%) modes — precisely the leak-initiating classes implicated in vapor-cloud-explosion initiation (Silva et al., 2023; Luo et al., 2021; Sajid et al., 2021; Chen et al., 2020). The migration converts availability risk into process-safety risk, which is the mechanism connecting maintenance deficit to catastrophe.

The second hypothesis, that degradation is nonlinear in accumulated deficit, is confirmed on the simulated dataset: the exponential law $\lambda = \lambda_0 \cdot \exp(\kappa \cdot \text{CMDI})$ with $\kappa = 2.14$ (95% CI: 1.87–2.41, $R^2 = 0.93$) outperforms linear specifications decisively, with failure intensity rising approximately five-fold and MTBF contracting from approximately 330 to 69 operating days across the deprivation trajectory (simulation outputs; anchors: Silva et al., 2023; Lv et al., 2021). The compounding channels — sequence interception, demand feedback, cannibalization — are each grounded in the maintenance-optimization literature (Zhen et al., 2021; Zhang et al., 2021; Tonkonogyi, 2024).

The third hypothesis, that workforce loss is an independent degradation channel, is supported by the conjunction of the documentary and organizational-safety records: the documented Venezuelan skilled-labor exodus (Garcia Zea, 2020; Weitzman & Huss, 2024) maps onto the competence, procedure, and communication variables that measurably govern maintenance-accident outcomes (Gonyora & Ventura-Medina, 2024; Isbasoiu & Volosevici, 2025), and the simulation's scenario decomposition shows parts-only recovery to be structurally insufficient. The hypothesis is supported rather than strictly confirmed, because the workforce channel's

magnitude in the real population cannot be estimated without plant data.

The principal original contribution of this article is the Cumulative Maintenance Deficit Index — a criticality-weighted, CMMS-compatible measure of accumulated unexecuted maintenance — together with the exponential degradation law linking it to population failure intensity, demonstrated end-to-end on a literature-anchored synthetic population. The instrument converts the maintenance-deprivation phenomenon from a narrative of decline into a measurable trajectory with decision-relevant properties: criticality weighting for sequencing, exponential dynamics for recovery prioritization, and explicit data requirements for empirical application.

The limitations of the research are stated without qualification. First and decisively, all equipment-level numerical results are Monte Carlo outputs of a synthetic population, not Paraguaná measurements; the fitted κ , the MTBF trajectory, and the mode-migration percentages are demonstrations of the instrument's behavior under a documented deprivation scenario, and they must be re-estimated on plant records — CMMS task histories, failure logs, and criticality registers — before any operational use. Second, the deprivation trajectory (90% $\rightarrow$ 15% execution) is calibrated qualitatively to the documentary record, not measured. Third, the simulation's aging-acceleration factors are proportional approximations; component-specific physics (seal tribology, valve dynamics) would refine them (Luo et al., 2021; Lv et al., 2021).

Fourth, the organizational channel is represented reduced-form; the survey instruments of the organizational-safety literature (Gonyora & Ventura-Medina, 2024; Isbasoiu & Volosevici, 2025) define what its direct measurement would require.

Future research should proceed on three lines: empirical estimation of the CMDI- λ relationship on real CMMS datasets from degraded plants, for which recovering operators in sanctioned or post-crisis environments are the natural (if difficult) partners; extension of the index to static equipment and instrumentation, whose deprivation dynamics differ; and integration of the CMDI into dynamic vulnerability assessment (Chen et al., 2020), so that process-safety models update as the failure structure migrates. For policy and practice, the implications are two. For operators, the exponential law inverts the usual austerity logic: maintenance is the last budget line whose cuts compound, and the CMDI provides the early-warning variable that budget shares do not. For any future reconstruction of Venezuelan refining, the analysis implies a sequenced program — criticality-ranked deficit retirement, sensor-based monitoring to substitute for emigrated analysts, additive-manufacturing qualification for the sanctioned spares channel, and competence rebuilding as a first-order investment rather than an afterthought (Almuraia et al., 2025; Chen et al., 2022; Tonkonogyi, 2024; Garcia Zea, 2020) — because the arithmetic of κ guarantees that a plant recovered in the wrong order will spend its budget re-living the right-hand side of the exponential.

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ANALIZA OTKAZA ROTACIONE OPREME U VENECUELANSKIM RAFINERIJAMA: UTICAJ IZOSTANKA PREVENTIVNOG ODRŽAVANJA PUMPNIH I KOMPRESORSKIH SISTEMA KOMPLEKSA PARAGUANÁ NA POUZDANOST PRERADE

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Sažetak: Rafinerijski centar Paraguaná, unija rafinerija Amuay i Cardón na venecuelanskom poluostrvu Paraguaná i istorijski jedan od najvećih rafinerijskih kompleksa na svijetu, doživio je kolaps pouzdanosti bez presedana u modernoj downstream industriji, kulminirajući događajima poput eksplozije oblaka pare u Amuayu 2012. godine — više od pedeset poginulih, šteta veća od milijardu američkih dolara, i uzrok sveden na curenje ugljovodonika nakon otkaza zaptivanja povezanog sa pumpnim sistemom. Cilj ovog članka je da objasni i kvantifikuje kako se sistematski izostanak preventivnog održavanja pumpnih i kompresorskih sistema pretvara u degradaciju pouzdanosti prerade. Istraživanje primjenjuje mješoviti metodološki pristup: strukturiranu sintezu literature o modovima otkaza i praćenju stanja rotacione opreme; dokumentarnu rekonstrukciju konteksta deprivacije održavanja u venecuelanskoj preradi poslije 2013; i simulaciju pouzdanosti reprezentativne populacije opreme razmjera Paraguaná, zasnovanu na modelu, čiji su parametri usidreni u objavljenim podacima o otkazima — raspodjela otkaza pumpi dominirana ležajevima od približno 38%, Weibullovi karakteristični vijekovi od 510–657 radnih dana, i struktura otkaza kompresora dominirana ventilima od približno 36%. Originalni doprinos članka je Indeks kumulativnog deficita održavanja (CMDI) — mjera neizvršenog planiranog održavanja ponderisana kritičnošću i akumulirana kroz vrijeme — zajedno sa empirijski fitovanim eksponencijalnim zakonom degradacije, $\lambda(t) = \lambda_0 \cdot \exp(\kappa \cdot \text{CMDI})$, koji na simuliranom skupu podataka daje $\kappa = 2,14$ (95% CI: 1,87–2,41) uz $R^2 = 0,93$, što implicira da svaki priraštaj deficita održavanja od 0,32 približno udvostručuje intenzitet otkaza populacije rotacione opreme. Ključni nalazi: pad pouzdanosti pod deprivacijom održavanja izrazito je nelinearan; struktura modova otkaza pomjera se od habanja praćenih komponenti ka sistemskim otkazima podmazivanja, zaptivanja i pomoćnih sistema; a emigracija radne snage djeluje kao nezavisan kanal degradacije koji sama dostupnost rezervnih dijelova ne može nadoknaditi. Svi simulacioni rezultati eksplicitno su označeni kao modelski generisani i namijenjeni su kao prenosivi analitički obrazac koji treba popuniti stvarnim pogonskim podacima.

Ključne riječi: rotaciona oprema, centrifugalne pumpe, kompresori, preventivno održavanje, pouzdanost, Paraguaná, rafinerija, CMDI, Weibullova analiza.