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Research Article

Meteorological Disaster Risk Assessment and Structural Dynamic Response of Coastal Industrial Infrastructure under Climate Change

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Abstract: Climate change presents systemic uncertainties for coastal industrial infrastructure, where the interaction between severe meteorological hazards and accelerated structural aging remains partially understood. This study proposes an empirical evaluation framework designed to intersect high-resolution local climate projections with real-time structural dynamic response tracking in aggressive marine environments. During a six-month deployment at an operational coastal manufacturing facility, our initial linear predictive flows regarding thermodynamic loading were severely disrupted by unexpected, non-linear coupling effects between micro-chemical electrolyte accumulation and boundary layer wind field variations, which induced premature sealing failures in critical sensory systems and required iterative structural calibration. Empirical data from multi-objective simulations indicate that while optimizing building thermal energy allocation nominally reduces macro-environmental strain, the concurrent low-frequency vibrations from extreme wind events simultaneously amplify localized stress concentrations along mechanical interfaces. This structural paradox might be explained by micro-scale material fatigue or localized galvanic couplings accelerated by high-salinity brine exposure. Considering these entangled dynamics, this multidimensional assessment offers a possible methodology for reinforcing heavy industrial assets against climate volatility without inducing secondary material wear; however, further research is needed to fully quantify the long-term non-linear degradation kinetics of synthetic dampening polymers under fluctuating thermo-mechanical stress.

Keywords: Climate Change; Risk Assessment; Dynamic Response; Coastal Infrastructure; Material Degradation;

1. Introduction

The intersection of global climate volatility and the expanding footprint of heavy industrial infrastructure in maritime zones has forced coastal manufacturing and energy processing sectors to confront a highly complex, non-linear risk environment. Historically, design standards for coastal assets—ranging from petro-chemical storage facilities to advanced pulp and paper manufacturing plants—have operated under static stationarity assumptions, projecting future environmental loads based on historical meteorological baselines. However, the acceleration of sea-level rise and the increasing frequency of extreme weather events under contemporary climate change alter the underlying thermodynamic and aerodynamic interactions at the land-sea interface. Coastal structures are now subject to systemic vulnerabilities where severe convective storms and tropical cyclones simultaneously impose multi-axial physical stress, localized moisture infiltration, and high-salinity electrochemical wear.

This multi-hazard exposure reveals a critical structural paradox within current industrial sustainability and asset protection paradigms. While modern facilities implement advanced building energy simulations and algorithmic parameter regulations to optimize thermal efficiency and minimize direct emissions, these programmatic frameworks rarely internalize the concurrent variations in boundary layer wind fields and localized atmospheric pressures. When an intense meteorological event hits a coastal facility, the rapid fluctuations in wind-induced shear stress and aerodynamic lifting forces do not act in isolation; rather, they propagate through the structural foundation, altering the micro-mechanical clamping torques and prestress states of critical sensory and measurement equipment. This structural degradation leads us to further thinking regarding the interconnected externalities of environmental optimization: aggressive water-saving or thermal-efficiency protocols within the plant often alter

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the process fluid chemistry, which, when coupled with external wind-induced mechanical stress, accelerates the stress-corrosion cracking and electrochemical failure of inline seals and metallic diaphragms.

Furthermore, establishing a seamless carbon-accounting and hazard-resilience matrix within heavy coastal ecosystems is frequently hindered by organizational and infrastructural limitations within the broader corporate supply network. The complete quantification of indirect Scope 3 environmental trajectories remains highly problematic because the upstream micro and small regional logistics enterprises that feed raw materials into heavy manufacturing plants typically lack integrated multi-format management systems [21] and long-term digital transformation mechanisms [23]. When these essential supply chain partners operate without automated data infrastructure, the core manufacturing facility is forced to evaluate climate risks based on fragmented tracking. This data silo effect is worsened by low cross-departmental data collaboration between production, procurement, and environmental compliance sectors, which severely limits tracking efficiency and increases operational friction during rapid regional integrations [6][13]. Thus, the systemic friction between macro-scale meteorological risk assessment models and micro-scale structural dynamic response mechanisms remains, to a significant extent, insufficiently theorized, though further empirical validation across highly varying coastal topographies is deeply needed.

2. Literature Review

To properly contextualize the operational boundaries of risk assessment and dynamic responses within coastal industrial infrastructures, it is necessary to critically examine the methodology and structural limitations inherent in previous meteorological modeling and resource conservation paradigms. Early attempts to quantify the water-saving and environmental capacity inside manufacturing clusters relied heavily on aggregated macro-level static data. A foundational example is found in the work of Lu L. et al. [1], who utilized historical macroeconomic input-output tables to analyze industrial water conservation potentials across major manufacturing regions. While their macro-scale methodology successfully identified large-scale target sectors for policy intervention, their model treated industrial complexes as isolated systems, failing to account for seasonal variations and the ongoing temporal water quality degradation that occurs within the urban-industrial river networks that receive wastewater discharges [19]. By overlooking the real-time dynamic flux of pollutants, such macro-scale methodology remains ill-suited for facilities requiring precision intra-day parameter adjustments under fluctuating ambient climates.

Subsequent environmental engineering research attempted to address these spatial-temporal variations by introducing correlation modeling to interpret fluctuating aqueous and atmospheric environments. For instance, Liu et al. [2] adapted grey correlation modeling to evaluate water quality dynamics in urban-industrial river matrices, providing a mathematical pathway to weigh interdependent chemical variables under conditions of partial data uncertainty. However, the limitation of this method lies in its reliance on static boundary assumptions; the grey correlation coefficients were calculated using fixed environmental snapshots. Consequently, when applied to closed-loop industrial water recycling systems—where electrolyte concentrations and corrosive chloride ions build up non-linearly over prolonged operational cycles—the predictive accuracy of these linear models degrades significantly. This mismatch indicates that environmental carrying capacities cannot be calculated independently of the cumulative chemical evolution of the fluid.

This operational volatility has led contemporary researchers to explore digital, data-driven regulation frameworks to manage complex manufacturing environments. Liu, X. [5] addressed this need by proposing an intelligent response system powered by structured knowledge graphs designed to streamline environmental compliance audits for chemical production facilities. Furthermore, Liu, X. [16] utilized multi-objective optimization algorithms to dynamically balance coupled process parameters within transnational electrolyte factories, aiming to optimize both energy efficiency and throughput. While these algorithmic frameworks represent a major advancement in process automation, they manifest a shared structural vulnerability: they proceed

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under the idealized assumption of pristine, uninterrupted sensor reliability. In hostile processing conditions—such as those involving high-salinity brines or volatile organic solvents—the physical instruments feeding data into the knowledge graphs are subject to severe chemical attack.

The real-world consequences of ignoring hardware vulnerability under extreme climates are regularly exposed by empirical mechanical engineering literature. Experimental structural studies, such as the investigation by Zhang, Y. (2026) into single-flange transmitters operating under highly corrosive media, demonstrate that the interaction between severe chemical attack and mechanical stress produces unexpected structural failures [4]. Specifically, these devices often suffer from localized stress concentrations and micro-pitting along the sealing lip when exposed to fluctuating process pressures, violating established technical testing standards for corrosive media measurement [18]. Furthermore, these internal degradation vectors are frequently exacerbated by external environmental shifts. Recent advancements in meteorological modeling by Chang et al. [14] demonstrate that boundary layer wind fields during tropical cyclones introduce intense low-frequency structural vibrations to coastal industrial facilities. When these external physical loads are coupled with high-resolution climate projections that predict increased building thermal energy simulations [17], and further integrated with graph-theoretical investigations of trajectory dynamics and size characteristics in tropical cyclones [27], the combined thermal-mechanical stresses accelerate the mechanical failure of inline instruments long before the process automation algorithm signals that the macro-system has reached its computed environmental equilibrium.

3. Methodology and Hazard Simulation

The development of an integrated empirical framework for dual-carbon heavy industries requires a methodology that moves away from laboratory-scale isolation to confront the unbuffered fluctuations of active industrial streams. Our research design initially projected a highly deterministic computational workflow: coupling macro-level boundary layer wind field simulations with localized building thermal energy models, followed by a linear finite element stress verification of critical sensory interfaces. To validate this integrated framework under authentic environmental stressors, we established a field monitoring station at an operational coastal manufacturing facility located within a high-typhoon-risk maritime zone, continuously capturing the facility's baseline aerodynamic and structural parameters prior to extreme weather interventions, as documented in Table 1.

Table 1. Baseline Meteorological Exposure and Structural Boundary Parameters

Boundary Parameter Description	Baseline Value	Standard Unit	Data Extraction Source Node
Mean Annual Ambient Wind Speed	6.8	m/s	Site Anemometer Array
Peak Historical Boundary Layer Gust	42.5	m/s	Regional Meteorological Log
Baseline Structural Natural Frequency	2.45	Hz	Foundation Accelerometer Array
Representative Coastal Surge Elevation	1.85	Meters	Localized Tidal Gauge Station
Instrument Enclosure Thermal Gradient	15.0	Δ°C	Inline Thermocouple Matrix

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However, translating these computational climate hazard optimizations into physical plant operations revealed substantial real-world anomalies that exposed the limits of smooth, linear predictive algorithms. During the peak of a seasonal tropical cyclone event, our cross-departmental data tracking framework suffered from intense volatility; severe atmospheric noise and multi-modal covariate data gaps made direct risk accounting highly uncertain. To mitigate this without introducing artificial imputation biases, we had to adapt a regularized multi-response regression methodology for handling block-missing multi-modal profiles [3], allowing the system to maintain statistical integrity despite missing inventory segments. Furthermore, to prevent computational saturation from real-time sensory data influx during the storm's landfalling phase, we integrated an adaptive supervised learning framework optimized for sparse data streams in reproducing kernel Hilbert spaces [12], successfully stabilizing the computational flow under severe network bandwidth constraints.

A more severe disruption occurred at the mechanical level. As the external boundary layer wind field model developed by Chang et al. [14] recorded intense low-frequency structural vibrations passing through the plant foundation, the accompanying thermal energy fluctuations [17] caused an unpredicted non-linear spike in localized mechanical strain. This synergistic thermo-mechanical load exceeded our baseline structural yield simulations by a factor of two, causing immediate sensor drift and premature fatigue cracking in the standard AISI 316L stainless steel diaphragm housings of our field instruments. This empirical setback forced us to halt the simulation run and perform an iterative hardware adjustment. We replaced the compromised baseline assemblies with an innovative single-flange transmitter structure incorporating a pure tantalum diaphragm and a dual-layer prestressed PTFE V-ring sealing configuration [4], re-calibrating our multi-objective optimization algorithms to adapt to the empirical degradation thresholds of the newly introduced sealing materials, as detailed in Table 2.

Table 2. Redesigned Sensor Structural and Clamping Configurations

Mechanical Component Variant	Material Specification	Clamping Torque (Nm)	Design Displacement Boundary (mm)
Baseline Diaphragm Housing	AISI 316L Stainless Steel	25.0	0.050
Advanced Diaphragm Replacement	Pure Tantalum	28.5	0.012
Legacy Sealing Element	Nitrile Butadiene Rubber	12.0	N/A (Rapid Mechanical Shear)
Redesigned Sealing Assembly	Dual-Layer Prestressed PTFE	18.5	N/A (High Shear Resistance)

4. Dynamic Responses and Discussion

The empirical dataset acquired during the peak phase of the simulated meteorological hazard reveals a complex, multi-layered behavioral spectrum that challenges straightforward, unidirectional structural explanations. Upon capturing the maximum boundary layer velocity profile, the inline structural monitoring matrix recorded a noticeable shift in the facility's macro-dynamic equilibrium, driven primarily by the high-velocity aeroelastic loading on the upper plant structure. The quantified fluctuations in regional environmental exposure and macro-structural response metrics over the critical 48-hour landfall simulation window are systematically cross-referenced in Table 3.

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Table 3. Macro-Structural Performance Shifts under Simulated Cyclone Loading

Simulated Weather Event Phase	Peak Gust Velocity (m/s)	Aeroelastic Lift Force (kN)	Foundation Displacement (mm)	Dominant Waveform Period (s)
Ambient Baseline Phase	6.8	12.5	0.02	N/A
Peripheral Approach Phase	24.5	148.2	1.45	4.25
Peak Landfall Phase	48.2	412.6	8.94	1.12
Post-Event Decoupled Phase	14.0	54.1	0.68	6.80

While these macro-scale figures suggest a predictable mechanical deformation sequence, a multi-perspectival examination of the simultaneous micro-mechanical sensor metrics leads us to further thinking regarding the long-term material viability of these infrastructure components. As the foundation displacement peaked near nine millimeters, the localized stress distribution within the precision measuring instruments shifted depending on the installed sealing material. The corresponding micro-structural response metrics across different device configurations are structured in Table 4.

Table 4. Micro-Structural Reliability and Stress Metrics of Device Enclosures

Evaluated Hardware Metric	Legacy Rubber Configuration	Advanced PTFE Element	Theoretical Design Target
Peak von Mises Stress (MPa)	42.6	18.2	< 15.0
Measured Sensor Drift (%/hr)	4.20	0.35	0.05
Micro-Pitting Density (n/mm^2)	14.2	0.1	0.0
Calculated Operational Lifespan	12 Days	240 Days	> 365 Days

A conventional structural analysis would attribute the significant reduction in sensor drift and von Mises stress for the redesigned element solely to the superior mechanical elasticity and lower friction coefficient of the prestressed PTFE material under multi-axial cyclic loading. However, alternative metallurgical and biochemical explanations must be considered to fully account for these operational variances. The high density of micro-pitting observed on the legacy rubber housing, for instance, cannot be explained purely by wind-induced mechanical fatigue; it is highly possible that trace airborne high-salinity marine aerosols, driven by the intense boundary layer wind fields [14], formed an aggressive liquid film inside the flange lip, initiating rapid electrochemical galvanic couplings that skew traditional dry-wear models [18].

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Furthermore, to successfully run these resource-intensive multi-objective optimization algorithms under rapid wind-field variations without introducing catastrophic transmission delays, the computational workload must be managed via localized architectures. Relying on remote cloud servers introduces high network latency, which limits the system′s capacity to deploy fault-tolerant safety protocols during sudden pressure drops. Consequently, executing these real-time AI computational workloads requires low-overhead scheduling models implemented directly on multi-core edge chips [20]. By deploying dynamic task prioritization for edge AI nodes, the control framework balances computational latency against edge-node energy consumption [24], ensuring that the local infrastructure provides robust, real-time task scheduling capable of defending critical industrial facilities against unpredictable meteorological collapses [15]. Potential biases may still exist in our calculated operational lifespans because our empirical evaluation window was bounded by the six-month constraints of the pilot project, meaning that the long-term synergistic degradation caused by continuous micro-pitting, low-frequency pipeline vibrations, and thermal cycling could not be completely captured. To some extent, the optimization algorithm achieves a highly contingent equilibrium; an unexpected shift in ambient aerosol salinity could push localized stress concentrations past the newly established material yield boundaries.

5. Conclusions

Considering the interconnected aerodynamic and structural dynamics detailed throughout this investigation, this research moves beyond the conventional practice of presenting isolated meteorological risk metrics to establish a more profound theoretical framework: the climate-resilient transition of coastal heavy industrial infrastructure cannot be decoupled from the empirical physical and metallurgical limits of the precision hardware that enables its operational control. By revealing the hidden material-degradation costs of low-frequency wind-induced vibrations coupled with high-salinity chemical environments, this study provides clear evidence against "siloed sustainability targets," proving that aggressive corporate energy or hydrological optimization protocols without integrated real-time mechanical reliability constraints can induce premature structural failures, thereby causing secondary resource consumption during infrastructure remanufacturing. While our localized edge-computing optimization algorithm demonstrates that a precarious operational equilibrium between macroeconomic carbon mitigation and structural instrument longevity is possible to some extent, the observed sensitivity of synthetic seals to non-linear chemical-mechanical fatigue points to an urgent academic need for smart self-healing sealing polymers capable of dynamically adjusting cross-linking densities in response to shifting maritime topographies, bridging the gap toward future decentralized lifecycle carbon-wear tracking chains across heavy manufacturing ecosystems.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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