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INTEGRATED PORT ENVIRONMENTAL PROCESS MATURITY MODEL – THEORETICAL FRAMEWORK

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Abstract: This paper introduces the Integrated Port Environmental Process Maturity Model (IPEPMM), a theoretical framework aligning environmental process maturity with measurable performance outcomes in maritime ports. The model synthesizes two previously independent approaches: the Environmental Process Maturity (EPM) ladder, which structures environmental capability development, and the Port Environmental Index (PEI), which quantifies environmental outcomes through standardized indicators. By embedding IoT-enabled data governance and stakeholder legitimization into one cohesive system, IPEPMM bridges the gap between process--based maturity and evidence-based performance. The framework redefines maturity stages as verifiable managerial commitments, linking capability progression to quantitative environmental improvements. This conceptual integration offers both theoretical advancement and practical guidance for achieving accountable, data-driven environmental management in smart ports while outlining directions for empirical validation and model refinement.

Keywords: environmental process maturity, port environmental index, smart port, sustainability management.

1. INTRODUCTION

Seaports are under intensifying pressure to demonstrate measurable progress on decarbonization and environmental quality while maintaining reliability and competitiveness. Two influential but largely parallel approaches dominate the assessment landscape.

First, environmental maturity models describe how organizations institutionalize environmental routines and governance across staged levels, thereby capturing the capability side of sustainability [Jabbour, 2015; Ormazabal et al., 2017b]. Evidence further links higher environmental management maturity to stronger green performance and supply-chain practices, underscoring the strategic importance of maturity [Jabbour, 2015]. Within ports specifically, emerging maturity schemes seek to structure environmental sustainability planning yet remain heterogeneous and survey-dependent [Housni et al., 2022].

Second, composite environmental indices quantify outcomes via indicators spanning air emissions, wastewater, noise, waste, light, and odor, often partitioned by source (ship, terminal, port authority) [Molavi et al., 2020; Oloruntobi et al., 2023]. The Port Environmental Index (PEI) exemplifies this trajectory and explicitly envisages IoT-enabled, near real-time analytics for benchmarking and management [Molavi et al., 2020; Siroka et al., 2021].

Literature reviews concur that ports need rigorous performance tools while also acknowledging gaps in standardization and accountability across indicator systems [Rodrigues & Ensslin, 2024]. Despite their complementary logics, capability-oriented maturity and performance-oriented indices are not integrated into a single, theoretically grounded construct. This separation generates two problems: first, maturity models may lack externally verifiable evidence of realized environmental effects, and second, indices may over-interpret transient improvements where the underlying processes are weak. The digitalization of ports reinforces this integration imperative: IoT data quality, lifecycle control, and governance are prerequisites for credible, continuous environmental metrics and for auditable claims concerning process maturity [Gao et al., 2024]. At the same time, smart-port maturity frameworks highlight staged advances in digital infrastructure and environmental awareness, offering conceptual anchors for capability-performance alignment [Boullauazan et al., 2023; Charłampowicz & Karaś, 2024].

The purpose of this research is to address these gaps by proposing an integrated system that couples a five-level Environmental Process Maturity (EPM), in which each process is appraised by its environmental impact, with PEI within a single coherent architecture.

2. LITERATURE REVIEW

Research into environmental management in ports must be perceived within a two--part approach. The first is dedicated to the process-oriented maturity models and therefore addresses the answers to questions of how far ports have progressed in institutionalizing environmental routines [Boullauazan et al., 2023; Charłampowicz & Karaś, 2024]. The second focuses on outcome-oriented indications, which can be seen as the state of environmental performance through measurable indicators [Safuan et al., 2025; Siroka et al., 2021]. Bridging these aspects requires clarity on their theoretical logics and measurement architectures.

Ports have recently attracted models that retain the staged logic of process maturity while tailoring constructs to maritime specificities [Boullauazan et al., 2023]. A five-level ladder has been articulated for smart ports, embedding environmental sustainability as a core dimension alongside digital infrastructure, operations, stakeholder engagement, and security [Charłampowicz & Karaś, 2024]. Building on that ladder, level 1 (foundational) denotes ad hoc, compliance-driven practices with siloed responsibilities and limited evidence. Level 2 (coordinated) introduces standardized procedures, basic cross-functional coordination, and periodic reporting of core environmental KPIs. Level 3 (integrated) embeds measurement and feedback in daily operations, aligns targets across ship, terminal, and authority functions, and connects systems for traceability. Level 4 (sustainable) shifts to proactive management with tightened targets, continuous (often IoT-enabled) monitoring, formal improvement cycles, and explicit stakeholder commitments. Finally, level 5, the highest level (collaborative network), extends governance beyond the port itself, co-managing data and interventions with supply chain partners under transparent disclosure and external assurance [Charłampowicz & Karaś, 2024].

This line of work positions process maturity as the consistency, measurability, and continuous improvement of processes over time [Charłampowicz, 2024]. Complementarily, an environmental process maturity framework for ports specifies five levels and operationalizes three interlinked constructs: environmental performance, stakeholder engagement, and regulatory alignment [Charłampowicz & Mańkowski, 2024]. Moving beyond static certification, this framework treats maturity as a developmental pathway, as evidenced by structured indicators and benchmarking logic.

Parallel to process maturity, the set of indicators has converged on the PEI as a unifying, quantitative metric capable of real-time assessment [Molavi et al., 2020]. PEI aggregates environmental KPIs across significant environmental aspects (air emissions, wastewater, noise, waste, light, and odor) into three source-based sub-indices (ship, terminal, and port authority) and a composite score using standard steps of normalization, weighting, and aggregation [Siroka et al., 2021]. The methodology argues for transparent weighting choices given the trade-offs among environmental KPIs [Siroka et al., 2021]. The same architecture is detailed in a companion exposition emphasizing the selection of significant environmental aspects and IoT-enabled data capture to support comparability and near-real-time control actions [Gao et al., 2024; Siroka et al., 2021].

A recent review of environmental performance in ports underscores the growing reliance on indicator systems, the need for decision-useful transparency, and the complementarity of MCDA-style structuring with monitoring cultures that fit local contexts [Chlomoudis et al., 2024; Rodrigues & Ensslin, 2024]. Another aspect concerns the digital data substrate required by both EPM and PEI. Evidence from smart-port studies indicates that expanding IoT without adequate governance of data lifecycle, quality, and architecture measurement means that validity suffers [Gao et al., 2024]. This gap is not merely technical; it directly affects how reliably environmental KPIs can be validated, integrated into indices, and how process maturity assessment can be evidenced across organizational boundaries [Charłampowicz & Karaś, 2024; Gao et al., 2024].

Taken together, the literature yields three gaps that motivate the integrating of EPM and the PEI in a single theoretical system. First, maturity models in ports specify staged capabilities and governance routines but typically stop short of prescribing how stage transitions should be evidenced by quantified, composite environmental outcomes [Charłampowicz & Karaś, 2024]. Second, PEI and related indicators are helpful as an outcome comparability and real-time control but are largely applied to the organizational process capabilities that generate those outcomes, leaving managers without a principled way to diagnose whether poor scores reflect immature routines, data issues, or exogenous conditions [Siroka et al., 2021]. Third, both approaches presuppose, but rarely internalize, the quality and governance of digital data flows as an integral maturity construct and a prerequisite for robust index construction [Gao et al., 2024].

3. INTEGRATED PORT ENVIRONMENTAL PROCESS MATURITY MODEL

The proposed Integrated Port Environmental Process Maturity Model (IPEPMM) framework combines a five-level EPM ladder with a composite PEI into one coherent management system. Its managerial goal is to align how environmental performance is achieved (capabilities, routines, and governance) with what is achieved (indicator results across ship, terminal, and port-authority domains). EPM provides staged capability development, while PEI provides transparent, comparable outcome metrics [Charłampowicz & Karaś, 2024; Siroka et al., 2021]

First, the process maturity should be perceived as the backbone of this system. Managers begin by delineating core environmental process families (e.g., vessel turnaround, cargo handling and yard equipment, energy management, waste and water, governance, and community) [Charłampowicz, 2024]. Each is appraised on a five-level maturity scale from "foundational" (the lowest level) to "collaborative network" (the highest level) in terms of the consistency of practices, evidence-based control, and continuous improvement [Charłampowicz & Karaś, 2024]. Crucially, every maturity level is defined relative to environmental impact so that higher levels reflect tighter controls, clearer accountability, and stronger integration with operational and stakeholder processes [Ormazabal et al., 2021].

In parallel, managers adopt the PEI architecture, which aggregates environmental KPIs into three source-based environmental sub-indices: SEI (ship), TEI (terminal), and PAEI (port authority), to create a single, intelligible composite for communication and benchmarking, yet remains fully decomposable for internal control [Siroka et al., 2021]. The indicator set typically covers air emissions, wastewater, noise, waste, light, and odor, aligned with ISO 14001, PERS, or any similar control systems, and good practice on indicator design and transparency [Rodrigues & Ensslin, 2024].

Because both maturity assessment and PEI evaluation rely on digital evidence, IoT data governance becomes an explicit enabling layer of the model [Utama et al., 2024]. Managers institute policies and roles for data standards, metadata, lifecycle, quality, and architecture to assure that measurements and audits are trustworthy and comparable across functions and partners [Gao et al., 2024]. Without this layer, ports risk fragmented systems and inconsistent metrics that undermine decision-making and external accountability [Gao et al., 2024].

IPEPMM links each maturity level to clear managerial expectations for outcomes: as processes progress from foundational to collaborative network, targets tighten (e.g., lower allowable emissions per call, higher renewable shares, and broader shore-power coverage), evidence requirements deepen (from periodic sampling to near-real-time monitoring), and integration requirements expand (from departmental initiatives to cross-terminal and community coordination). This prevents label inflation, which can be expressed in high process maturity with mediocre outcomes and turns maturity labels into managerial commitments [Charłampowicz & Karaś, 2024; Siroka et al., 2021].

Finally, to ensure the legitimated weighting and transparency, it is essential for managers to set weights for indicators and processes through structured stakeholder engagement (authorities, terminal operators, shipping lines, and community). The literature on port indicators emphasizes that feasible, context-appropriate metrics and transparent reporting sustain a culture of monitoring and learning, while multi-criteria decision approaches can support these design choices [Ha et al., 2017; Rodrigues & Ensslin, 2024].

Together, IPEPMM reframes environmental management from parallel tracks of capabilities and results into a single managerial system, where maturity defines the expected discipline and ambition of performance, while the index supplies continuous, transparent evidence that those expectations are being met, underpinned by robust data governance and stakeholder-aligned design [Charłampowicz & Karaś, 2024; Siroka et al., 2021].

Table 1. Proposed IPEPMM framework

Maturity Level	Process characteristics	Environmental Performance (PEI linkage)	Data governance requirements	Stakeholder integration
1. Foundational	Ad hoc, compliance--driven routines; fragmented responsibilities; reactive problem-solving	Minimal KPI coverage; irregular reporting; limited traceability	Manual data collection; low reliability; absence of data standards	Internal, operational-level awareness only
2. Coordinated	Basic formalization of procedures; early cross--department coordination; initiation of environmental KPIs	Periodic KPI monitoring for air, waste, and water; early normalization attempts	Partially digitized monitoring; limited data validation	Stakeholder engagement through compliance audits
3. Integrated	Process alignment across terminals and functions; feedback loops established; systematic environmental contro.	Regular KPI reporting across SEI, TEI, and PAEI domains; comparability achieved	IoT-enabled measurement; metadata and data quality controls	Internal and external consultations on KPI setting

cont. Table 1

4. Sustainable	Proactive management with quantified environmental targets; continuous improvement cycles; transparent monitoring	Advanced PEI integration; real-time analytics; improved outcome consistency	Data lifecycle governance; formal roles and accountability; standard metadata	Structured stakeholder dialogue and indicator co-design
5. Collaborative Network	Co-management of environmental governance with partners; open data exchange; integrated port-community model	Full PEI traceability and benchmarking across networked entities; verified performance	Interoperable data architectures; third-party assurance; open--access platform.	Formal stakeholder co-governance, transparent reporting, and joint accountability

Source: own study.

The framework presented above operationalizes the conceptual structure of the Integrated Port Environmental Process Maturity Model by articulating how capability advancement is inseparably tied to quantifiable outcomes and data assurance mechanisms. Each maturity level defines not only the procedural discipline of environmental management but also the scope and reliability of the performance evidence that must accompany it. By embedding PEI metrics within the maturity architecture, ports can translate abstract maturity labels into measurable progress trajectories and verifiable accountability standards.

At lower maturity levels, the model reflects a reactive, compliance-oriented posture where environmental data are sparse and fragmented. As organizations progress toward the integrated and sustainable stages, environmental information systems become increasingly digitized, standardized, and governed under formal data policies. This progression marks a critical transformation from procedural compliance toward evidence-based management, where digital traceability and metadata validation assure the credibility of reported outcomes.

At the collaborative network stage, the maturity construct evolves beyond the boundaries of a single port organization. Governance becomes participatory, incorporating terminal operators, shipping lines, and community actors into shared data ecosystems. The environmental index thus ceases to function solely as an internal performance tool and transforms into a transparency and trust mechanism within the wider maritime supply chain. This integrative logic positions IPEPMM as a system of accountability where capability development, environmental outcomes, and data integrity reinforce one another in a continuous feedback loop.

4. DISCUSSION

The proposed IPEPMM framework deliberately combines staged capabilities with composite outcomes, answering two long-standing critiques in the port sustainability literature. First, outcome-oriented approaches, such as the PEI, provide transparency and comparability, and remaining largely detached from the organizational routines that generate, or fail to generate, those results [Siroka et al., 2021]. Their architects explicitly acknowledge the limitations of qualitative self-assessments and advocate for quantitative, IoT-enabled, standardized metrics [Jiang et al., 2025; Siroka et al., 2021]. By linking performance expectations to defined maturity levels and mandating auditable evidence standards to strengthen data reliability, IPEPMM explicitly articulates the capability assumptions that PEI leaves unaddressed, while retaining PEI's decomposability across ship, terminal, and authority domains [Siroka et al., 2021].

Second, maturity-only schemes have been criticized for heuristic staging without explicit links to measurable environmental effects or to the digital data preconditions that underpin continuous monitoring [Charłampowicz & Mańkowski, 2024; Ormazabal et al., 2017b]. Reviews emphasize gaps in standardization, accountability, and tool development for decision-useful port metrics [Rodrigues & Ensslin, 2024]. IPEPMM addresses these by cross-walking each maturity level to concrete indicator expectations, elevating IoT data governance from an operational detail to an enabling construct, precisely where the smart-port literature finds the field most underdeveloped [Gao et al., 2024; Hsu et al., 2023; Yang & Hsieh, 2024].

Relative to environmental process maturity models tailored to smart ports, IPEPMM converges on the need for staged capability building but diverges on two points. Smart port maturity frameworks articulate five progressive stages spanning digital integration and sustainability but stop short of embedding environmental indicator behavior as testable commitments at each stage [Charłampowicz & Karaś, 2024]. IPEPMM instead binds stage labels to verifiable outcome targets and evidence thresholds, reducing the risk of label inflation, where high maturity coexists with mediocre environmental results. Moreover, by integrating PEI metrics, IPEPMM retains the managerial advantage of a core metric with the embedded capacity for granular examination [Siroka et al., 2021].

Evidence from environmental process maturity outside ports strengthens IPEPMM assumptions about the capability performance link. Studies report that advancing environmental management maturity covaries with stronger green performance and is shaped by routines, such as training, systematization, and governance, elements that IPEPMM situates within process families and data-assurance requirements [Jabbour, 2015; Ormazabal et al., 2017b; Ormazabal et al., 2021; Ormazabal & Sarriegi, 2014]. These findings align with the view that organizations progress from legal compliance to systematization and eco-innovation, with each step introducing new factors (e.g., training, formalization, market requirements), a logic IPEPMM internalizes by tightening indicator targets and data-quality expectations at higher maturity [Ormazabal & Sarriegi, 2014].

At the same time, the smart port literature cautions that digitalization without governance produces fragmented systems and non-comparable metrics [Behdani, 2023]. Systematic review and case evidence highlight lifecycle and data quality management as especially weak in ports, implying that any index-driven oversight must embed governance roles and standards from the outset [Gao et al., 2024; Yang & Hsieh, 2024].

5. CONCLUSIONS

This paper developed a management-oriented integration of environmental capability and outcome assessment for ports. The proposed IPEPMM framework positions five--level EPM as the organizing backbone for environmental governance and continuous improvement and nests the PEI within this backbone to ensure that reported outcomes are interpreted through demonstrable process capability and auditable evidence. In doing so, it responds to two persistent asymmetries in the literature: capability models that lack falsifiable links to measured effects and composite indices that remain silent about the organizational routines and data conditions that generate their scores [Rodrigues & Ensslin, 2024; Siroka et al., 2021].

First, process maturity is tied to explicit expectations for outcomes and evidence. As ports progress through EPM levels, targets tighten, measurement becomes more continuous, and integration broadens to inter-organizational coordination. Second, data governance is elevated from a technical enabler to a constitutive element of environmental assurance, recognizing that IoT measurement is only as credible as the policies, roles, and quality controls that data lifecycles [Gao et al., 2024; Siroka et al., 2021]. Third, stakeholder-legitimated weighting ensures the composite retains managerial usability and societal legitimacy while remaining decomposable for diagnosis and accountability [Rodrigues & Ensslin, 2024].

The framework advances the theory in two ways. It formalizes a capability performance dependency that existing smart port maturity schemes articulate conceptually but do not embed as verifiable commitments at each stage [Charłampowicz & Karaś, 2024; Triska et al., 2024]. It also reframes indices as diagnostic instruments rather than ranking tools, deviations between maturity claims and outcome trajectories become signals for corrective action, learning, or reassessment of targets [Siroka et al., 2021]. Beyond ports, this alignment resonates with evidence from industrial settings where higher environmental management maturity co-evolves with superior environmental performance and more systematic routine design [Ormazabal et al., 2017a].

Being purely conceptual, the framework has limitations. It assumes that maturity stages can be operationalized through self-assessment and that indicator sets can be stably governed across diverse actors and technologies. It also presumes that stakeholder processes can reconcile materiality and comparability without diluting the index's decision power. Finally, while the framework guards against label inflation, it cannot by itself prevent strategic behavior absent external audit and transparency mechanisms [Rodrigues & Ensslin, 2024].

Future research should prioritize developing metrics and audit protocols for each EPM level, specifying data governance checklists and maturity-linked evidence requirements for PEI indicators. Moreover, this should include testing construct validity and measurement invariance across ports and conducting sensitivity analyses on weighting and target setting under alternative stakeholder configurations. Pilot studies and multi-port comparative studies would provide pathways to calibrate thresholds, learn boundary conditions, and evaluate the cost-benefit of maturity-driven investments [Charłampowicz & Karaś, 2024; Siroka et al., 2021]. In summary, IPEPMM offers a coherent theoretical lens to align how ports manage environmental impacts with what they demonstrably achieve and sets out a research agenda to test and refine that alignment in practice.

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