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Transforming Maritime Logistics through Integrated Emerging Technologies: A Comprehensive Framework for Smart Port Operations and Sustainable Shipping

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ABSTRACT

The maritime industry facilitates over 90 percent of global trade through sea routes; however, it is facing soaring operational inefficiencies, fragmented data systems, and compulsory decarbonisation policies by the International Maritime Organisation (IMO). This study investigates and empirically supports an overarching technological infrastructure that analyses the convergence of artificial intelligence (AI), Blockchain Application, Internet of Things (IoT), Digital Twins (DT), and Autonomous Systems in maritime logistics. The assessment of technology adoption patterns, operational and implementation barriers within the framework of Indian smart ports is conducted using a Systematic Literature Review (SLR) comprising 55 peer-reviewed publications and supported by semi-structured interviews with industry practitioners. This paper is based on the Technology Acceptance Model (TAM), the Unified Theory of Acceptance and Use of Technology (UTAUT) and the Technology Organisation-Environment (TOE) model, and, as a result, nine-construct readiness model is developed. According to Structural equation modelling through partial least squares (PLS-SEM), Organisational Readiness ($\beta = 0.498$) and Perceived Barriers ($\beta = -0.441$) are the most salient predictors of overall transformation. The research provides practical suggestions to port authorities, shipping companies, and policymakers involved in the quest for sustainable digital transformation, drawing on knowledge of technological convergence, the international law of the sea, and Indian regulatory standards.

1. Introduction.

The global maritime sector underpins international commerce, handling approximately 90% of cross-border cargo by volume (UNCTAD, 2023). Ports, as nodal infrastructures, function not merely as cargo transhipment facilities but as complex regulatory, commercial, and logistical interfaces that directly determine national trade competitiveness (Notteboom et al., 2021). According to the International Maritime Organisation (IMO) 2050 decarbonization strategy (IMO 2023, Serra and Fancello, 2020), the maritime logistics industry is increasingly shaped by a combination of operational, infrastructural, and environmental pressures. These include rising vessel traffic, yard congestion, fragmented data flows across multi-stakeholder supply chains, ageing port infrastructure, and stricter environmental oversight (Heilig et al., 2017). India, as a rapidly expanding maritime economy possessing 13 major ports, 200-plus non-major ports, and 11098.81 km (kilometres) coastline, occupies a strategic inflexion point in this technological transition.

Despite the proliferation of individual technologies, two critical lacunae persist. First, the literature largely examines AI, blockchain, IoT, and digital twins as discrete analytical domains, rarely investigating their integrative potential within a unified governance and regulatory architecture (Mukherjee, 2020; Kou-

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hizadeh et al., 2021, Manisha et al., 2025, González-Cancelas et al., 2025, Zhou et al., 2024). Systems-level interdependencies where, for instance, IoT sensor streams feed AI predictive models, which are subsequently recorded on immutable blockchain ledgers and visualised through digital twins, remain substantially under-theorised. Second, empirical and legal aspects primarily originate in European, East Asian, or North American port contexts. Despite the Sagarmala Programme's USD 82 billion investment commitment and Maritime India Vision 2030's ambitious digitalisation targets, minimal research interrogates how these technologies interact with India's distinctive regulatory landscape, characterised by the Major Port Authorities Act 2021, the Indian Ports Act 1908, SOLAS, MARPOL, and IMO cybersecurity guidelines (Pradhan et. al., 2022, Government of India, 2021). In light of these gaps, the article can be positioned around the following overarching research question:

a. How do integrated emerging technologies, organisational readiness, and the legal–regulatory environment jointly influence the transition towards smart and sustainable maritime logistics, with particular reference to Indian ports?
b. What are the main technologies, application areas, and adoption patterns of emerging digital solutions in maritime logistics and port operations identified in recent literature?
c. Which organisational, environmental, and regulatory factors enable or hinder integrated technology deployment in port ecosystems?

This paper proceeds as follows. Section 2 synthesizes extant literature, presenting a conceptual evolution table and the proposed integrated framework with hypotheses. Section 3 delineates the mixed-methods research design, including the SLR protocol and expert interview methodology. Section 3.1 presents empirical results, including PLS-SEM path coefficients. Section 4 discusses the findings in relation to theoretical frameworks and managerial implications. Section 5 concludes with limitations and future research directions.

2. Literature Review.

2.1. Technology in Maritime Logistics.

Scholarly attention to digital technologies in maritime contexts has evolved through four broad phases. The earliest phase, spanning the 1980s and 1990s, centred on Electronic Data Interchange (EDI) systems enabling transactional data exchange between ports, shipping lines, and customs authorities (Heilig et al., 2017). The second phase, contemporaneous with the widespread adoption of enterprise resource planning systems in the 2000s, saw the integration of operational databases with berth scheduling and cargo-tracking capabilities. The third phase, emerging post-2010, shows the proliferation of big data analytics, GPS tracking, and early machine-learning applications for vessel arrival prediction and terminal resource allocation (Tsou, 2019, Dalaklis at al., 2023, Fernández, et al., 2016). The fourth and current phase is characterised by the convergence of AI, blockchain, IoT, digital twins, and autonomous systems as part of a broader Industry 4.0 transition (Notteboom et al., 2021; Upadhyay, 2024; Huang et. al., 2023; Kuo et al., 2022).

The available literature represents this evolutionary arc, revealing persistent silos in technology research. The systematic review of 94 studies on blockchain in supply chains shows that transparency and traceability benefits were well evidenced, and integration with complementary technologies such as IoT and AI was addressed in fewer of the studies (Kouhizadeh et al., 2021). The parallel conclusion from a legal standpoint is that maritime jurisprudence has yet to develop coherent frameworks for electronic bills of lading, autonomous vessel liability, and cross-jurisdictional data governance, fundamental prerequisites for technology convergence (Mukherjee 2020).

Table 1: Summary of Selected Prior Studies on Maritime Digital Transformation.

Author (s) & Year	Focus / Topic	Domain	Method	Finding
Heilig et al. (2017)	Digital transformation history	Port technology	Descriptive	Technology evolution in ports; limited integration lens
Mukherjee (2020)	Maritime law & technology	Legal-regulatory	Doctrinal analysis	Legal documentation & autonomous vessels
Kouhizadeh et al. (2021)	Blockchain & supply chain sustainability	Logistics-sustainability	SLR + case study	Blockchain enhances transparency; implementation barriers remain
Notteboom et al. (2021)	Port economics & management	Port operations	Comprehensive review	Broad port economics; limited digital integration focus
UNCTAD (2023)	Maritime transport review	Global shipping	Statistical-analytical	Trade data; technology policy implications underexplored
IMO (2023)	GHG emission reduction strategy	Environmental policy	Policy document	Targets set; technology pathways not operationalised
Serra & Fancello (2020)	IMO decarbonisation logistics	Decarbonisation	Empirical analysis	Policy compliance; technology convergence not addressed
Davis (1989)	Technology Acceptance Model	Behavioural IS	Quantitative survey	Foundational TAM; requires contextual adaptation for maritime
Venkatesh et al. (2003)	UTAUT model	IS adoption	Multi-organisational survey	UTAUT validated; maritime application absent
Tornatzky & Fleischer (1990)	TOE framework	IT adoption	Conceptual-empirical	TOE widely applied; under-utilised in port digitalization

Source: Authors.

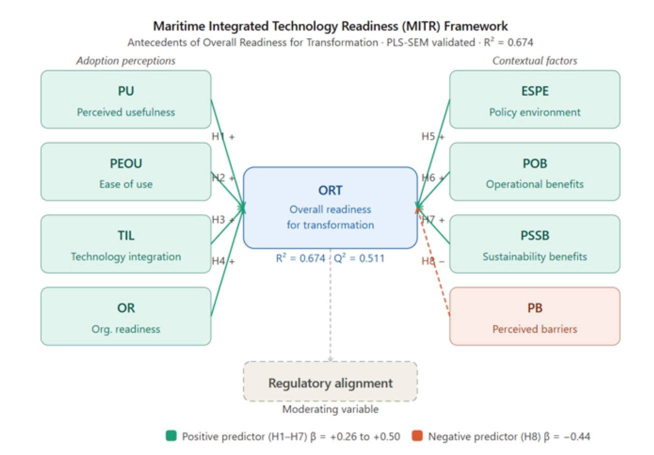
Table 1 reveals consistent evidence of three patterns: (a) technological investigations are domain-specific rather than integrative; (b) legal and regulatory dimensions receive scant empirical attention despite their acknowledged operational significance; and (c) the Indian maritime context remains underrepresented, notwithstanding India's growing strategic importance as a maritime nation. These patterns collectively constitute the research gap.

2.2. *Theoretical Frameworks.*

This paper is based on three theoretical complementary lenses. The Technology Acceptance Model (TAM) (Davis (1989), posits that perceived usefulness and perceived ease of use are the key factors influencing technology adoption intentions. TAM is widely accepted in the information systems field, and some authors have already applied it to logistics and supply chain technology (Venkatesh et al., 2003, Upadhyay et al., 2021, 2024). But its use in the multi-stakeholder, regulatory-rich, maritime port environment needs theoretical enhancements.

The Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003) extends TAM by introducing social influence, facilitating conditions, performance expectancy, and effort expectancy as determinants of adoption, which are particularly relevant in institutional contexts such as port governance. The Technology-Organisation-Environment (TOE) framework of adoption (Tornatzky and Fleischer, 1990) further contextualises adoption by situating organisational and environmental factors, such as firm size, top-management support, regulatory environment, and competitive pressure, as equally important mediators alongside technological characteristics. Combining TAM, UTAUT, and TOE provides a holistic theoretical framework for studying the adoption of technology in complex, controlled, multi-actor maritime contexts. Figure 1 of the MITR framework indicates that all eight antecedent constructs flow into the central node of ORT (Overall Readiness to Transformation).

Figure 1: Maritime Integrated Technology Readiness Framework (MITR framework).



Source: Authors.

2.3. *Proposed Integrated Framework.*

This paper presents a proposal based on the theoretical synthesis, which is the Maritime Integrated Technology Readiness (MITR). The conceptualisation of smart ports technology adoption in the MITR framework is that technology adoption depends on eight major constructs, Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Technology Integration Level (TIL), Organisational Readiness (OR), External Support and Policy Environment (ESPE), Perceived Operational Benefits - (POB), Perceived Sustainability and Safety Benefits (PSSB) and one inhibitory construct, Perceived Barriers (PB). These eight constructs in combination forecast the dependent variable, Overall Readiness for Transformation (ORT). The framework does include regulatory alignment explicitly as a moderating variable because the use of technology in maritime settings cannot be examined outside of its legal-institutional framework

3. Research Methodology.

3.1. *Research Design.*

This study adopts mixed-methods approach integrating Systematic Literature Review (SLR) with structured expert interviews. The methodological triangulation is a novelty in integrated technology adoption research in Indian maritime contexts, where both theoretical development and empirical grounding are required simultaneously. The SLR provides a theoretically informed synthesis of extant knowledge, the expert interviews generate practitioner insights that refine and contextualise the theoretical constructs, and the quantitative survey instrument enables statistical hypothesis testing.

3.2. *Systematic Literature Review.*

The systematic literature review followed by the PRISMA model for identification, screening, and selection of the available literature (Upadhyay et. al,2023). The search strings capture three broader aspects: the maritime sector, emerging technologies, and specific technology applications. These strings / keywords were applied across Web of Science, Scopus, Google Scholar, and IEEE Xplore using Boolean operators such as AND and OR as discussed in Table 2. The time frame was applied to publications between 2010 and 2025, with exceptions for seminal theoretical works predating this period (Davis, 1989; Tornatzky & Fleischer, 1990).

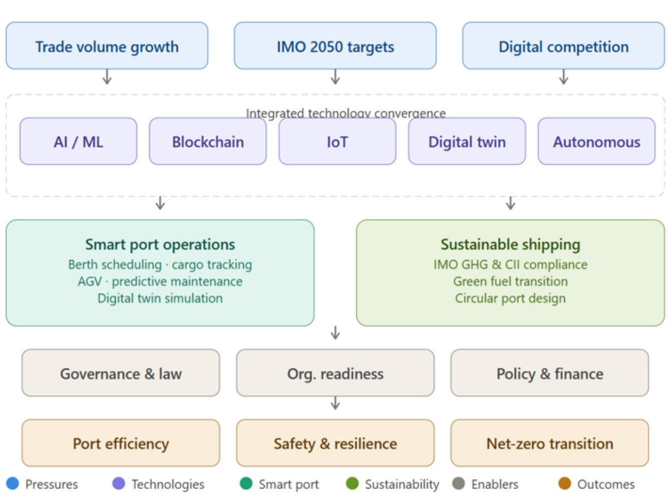
Following the combined database search, a three - stage screening process was applied. Title and abstract screening eliminated papers outside maritime, logistics, port, or shipping domains and those addressing technologies unrelated to the study scope. Furthermore, the full-text assessment applied four inclusion criteria: (i) empirical, conceptual, or legal focus on digital technology in maritime/port operations; (ii) English language; (iii) peer-reviewed, and (iv) availability of full text. The exclusion criteria applied were duplicates, conference abstracts, and papers that addressed logistics exclusively and lacked maritime relevance. Inter-rater reliability was assessed using Cohen's Kappa ($\kappa = 0.81$, indicating substantial record). After that, the final paper includes 55 peer-reviewed studies and 23 grey literature documents. Based on that, the five-layer architecture shown in Figure 2 illustrates how external pressures feed into the core technology, which then branches into the application pillars before breaking down through enablers to strategic outcomes.

Table 2: Keyword Search Strategy and Paper Selection Summary.

Search String	Keywords / Query	Database(s)	Results (N)
String 1 – Domain	"maritime logistics" OR "port logistics" OR "container terminals" OR "shipping logistics"	WoS, Scopus, Google Scholar	854
String 2 – Technology	"emerging technologies" OR "digital technologies" OR "Industry 4.0"	WoS, Scopus	612
String 3 – Specific Tech	"IoT" OR "blockchain" OR "artificial intelligence" OR "machine learning" OR "big data analytics" OR "digital twin" OR "autonomous vessels"	WoS, Scopus, IEEE Xplore	1,247
Combined (AND)	String 1 AND String 2 AND String 3	All databases	318
After deduplication	-	All databases	214
After title/abstract screening	-	All databases	122
After full-text assessment	-	All databases	55
Theme			**Articles**
Technological enablers (IoT, AI, blockchain)			47
Organizational enablers (training, strategy)			35
Environmental enablers (policy, standards)			28
Total covered (with overlaps)			110

Source: Authors.

Figure 2: Maritime Integrated Logistics five-layer architecture/framework.



Source: Authors.

3.3. *Expert Interviews.*

To extend the review findings, structured expert interviews were conducted with eight senior practitioners representing port authorities, terminal operators, maritime law scholarship, logistics IT consulting, sustainability management, government trade facilitation, autonomous systems research, and international shipping. Experts were purposively selected based on at least seven years of relevant industry or academic experience, institutional affiliation with a major Indian port, a regulatory body, or an international maritime organisation, and demonstrated engagement with technology adoption or regulatory compliance in their current role. The semi-structured interview guide comprised four thematic sections: (a) current technology deployment status; (b) perceived adoption barriers and enablers; (c) regulatory and legal challenges; and (d) recommendations for integrated framework design.

Table 3: Expert Interview Profile.

Code	Designation	Organisation Type	Exp. (yrs)	Mode	Thematic Domain
E1	Director (Port Operations)	PPP	18	In-person	Technology integration, regulatory compliance
E2	Head (ERP)	Container terminal operator	14	Video call	AI/IoT deployment, cybersecurity
E3	Maritime Law Scholar	Central university	22	In-person	IMO instruments, Indian shipping legislation
E4	Logistics IT Consultant	Tier-1 consulting firm	11	Video call	ERP/TOS integration, blockchain pilots
E5	Manager (Port Sustainable)	Private port developer	9	Phone	Decarbonisation strategy, ESG reporting
E6	Customs & Trade Facilitation Expert	Government agency	16	In-person	Single-window systems, digital documentation
E7	Researcher	National Universities	7	Video call	Autonomous vessels, drone surveillance
E8	Operations Manager (Shipping Line)	International carrier	13	Video call	Blockchain for BOL, predictive maintenance

Source: Authors.

All interviews were recorded, with the consent form circulated, and were subjected to thematic analysis using NVivo 14. An inductive coding approach was employed, derived from the MITR framework constructs and inductive codes emerging from the data.

3.4. *Quantitative Survey Instrument.*

The structured questionnaire was developed based on the MITR framework constructs, with items adapted from validated scales in the TAM, UTAUT, and TOE literatures and contextualised for maritime logistics. All items were measured on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The instrument was piloted with 20 maritime professionals and refined based on item-level feedback and initial reliability analysis. The survey was administered to 187 professionals across major Indian port authorities, container terminal operators, shipping agents, logistics consultants, and maritime regulatory bodies. A total of 162 responses were feasible for the study (response rate: 86.6%).

Table 4: MITR Framework Constructs, Items, and Theoretical Basis.

Construct	Items	Scale	Theoretical Basis / Source
Perceived Usefulness of Integrated Emerging Technologies (PU)	3	5-point Likert	TAM (Davis, 1989)
Perceived Ease of Use / Implementation (PEOU)	3	5-point Likert	TAM / UTAUT
Technology Integration Level (TIL)	4	5-point Likert	Industry 4.0 integration; logistics digitalization
Organisational Readiness (OR)	4	5-point Likert	TOE framework; logistics IT adoption
External Support & Policy Environment (ESPE)	3	5-point Likert	Policy/institutiona l environment; Indian maritime policy
Perceived Operational Benefits (POB)	4	5-point Likert	IT performance in the logistics sector
Perceived Sustainability & Safety Benefits (PSSB)	3	5-point Likert	Sustainability and safety in maritime logistics
Perceived Barriers (PB)	3	5-point Likert	Barriers in logistics, IT and Industry 4.0 adoption
Overall Readiness for Transformation (ORT)	3	5-point Likert	Dependent variable

Source: Authors.

Common method bias was assessed using Harman's single-factor test, which explained 26.3% of variance below the 50% threshold, indicating that common method variance is not a significant concern. Construct validity was established through confirmatory factor analysis (CFA), with all factor loadings exceeding 0.65. Composite reliability (CR) values ranged from 0.81 to 0.91, and average variance extracted (AVE) values exceeded 0.50 for all constructs, satisfying convergent validity criteria.

4. Results.

4.1. Descriptive Statistics.

The respondent's demographic data show that 64% were employed by public port authorities, 22% by private terminal operators, and 14% by logistics or regulatory consulting firms. Experience ranged from 5 to 32 years (M = 13.4, SD = 5.7). Furthermore, 71% of those with technology exposure reported direct involvement in at least one digital transformation initiative within their organisation in the preceding three years. Blockchain (38%), AI-based scheduling (52%), and IoT tracking (61%) were the most frequently cited deployed technologies, while digital twins (19%) and autonomous systems (8%) remained at early adoption or pilot stages.

Mean construct scores indicated that Perceived Operational Benefits (M = 3.91, SD = 0.64) and Perceived Usefulness (M = 3.74, SD = 0.71) elicited the strongest positive perceptions. Perceived Barriers received the highest mean on the inhibitory side (M = 3.88, SD = 0.69), confirming that implementation impediments, particularly interoperability constraints, cybersecurity risks, and skills deficits, are acutely perceived. Organisational Readiness recorded a moderate mean (M = 3.11, SD = 0.82), suggesting that institutional transformation capacity is a constraining variable despite positive technology perceptions.

4.2. PLS-SEM Structural Model Results.

Hypotheses were tested using Partial Least Squares Structural Equation Modelling (PLS-SEM) in SmartPLS 4.0. PLS-SEM was selected due to its appropriateness for exploratory-confirmatory research with complex theoretical models and non-normal data distributions. The model explained 67.4% of the variance in Overall Readiness for Transformation ($R^2 = 0.674$), indicating strong explanatory power. Predictive relevance, assessed via Stone-Geisser's Q^2 (blindfolding procedure), yielded $Q^2 = 0.511$, confirming adequate predictive accuracy. Table 5 presents path coefficients (β), t-values (5,000 bootstrap iterations), and hypothesis decisions.

4.3. Qualitative Findings from Expert Interviews.

Thematic analysis of expert interview data yielded five overarching themes. First, technology silos persist; experts have independently observed that port systems operate in silos, with limited data interoperability between terminal operating systems (TOS), shipping line platforms, and customs single - window interfaces. Second, regulatory ambiguity was consistently cited as a barrier to blockchain-based documentation and autonomous vessel approvals (Mukherjee's (2020). Third, cybersecurity emerged as an acute concern, with some experts referencing. Fourth, workforce upskilling was identified as a critical enabler, particularly for AI-assisted berth planning and IoT-based predictive maintenance. Fifth, the Sagarmala Programme was regarded as a positive policy catalyst, though experts noted that implementation timelines frequently lagged commitments.

5. Discussion.

The independent construct Organisational Readiness (OR) in predicting ORT transformation outcomes strongly supports the TOE framework (Tornatzky & Fleischer, 1990), which positions organisational context, including management support, human capital, and change management, as a necessary condition for technology adoption, irrespective of the technology's inherent utility. In the maritime context, identified organisational inertia and legacy system dependencies as primary barriers to digital port transformation, consistent with the finding (Heilig et al., 2017). The significant negative effect of Perceived Barriers corroborates the finding that interoperability constraints and cybersecurity vulnerabilities represent the dominant inhibitors of blockchain adoption in supply chains, factors equally applicable to integrated technology deployment in ports (Kouhizadeh et. al., 2021).

The strong influence of external support and policy environment extends the institutional theory perspective that technology adoption in regulated industries is fundamentally contingent on the quality and coherence of the legal and regulatory environment. The Major Port Authorities Act 2021 represents a significant institutional reform, enabling port governance decentralisation and facilitating private investment; however, expert interviewees consistently noted that subordinate regulatory instruments have not kept pace with the Act's enabling provisions, creating implementation uncertainty (Nanyam and Jha, 2023).

5.1. Managerial Implications.

The findings suggest that technology adoption should be preceded by rigorous organisational readiness assessments that address the structural, human capital, and cultural dimensions of transformation capacity before committing capital expenditure to specific technology platforms. In different stages implementation roadmap commencing with IoT - enabled asset tracking and AI-assisted yard management, before advancing to blockchain documentation and digital twin simulation, allows organisations to build digital maturity progressively while managing implementation risk.

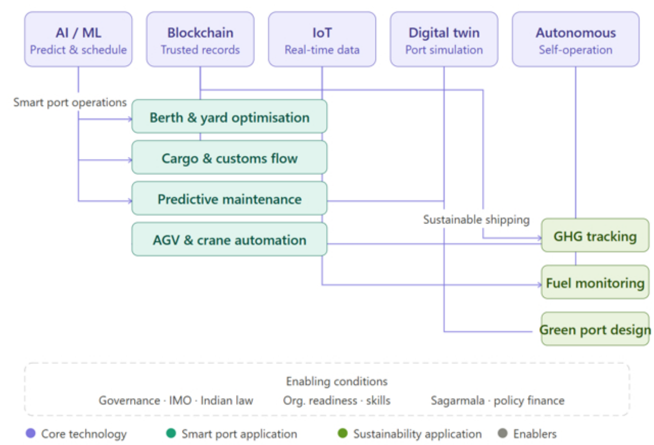
For shipping lines and logistics operators, the strong predictive power of Perceived Operational Benefits (H6) and Perceived Sustainability Benefits (H7) suggests that business cases for technology adoption should foreground quantifiable operational gains, berth productivity improvements, turnaround time reductions, fuel consumption optimization alongside emerging ESG metrics increasingly demanded by institutional investors and cargo owners. The convergence of commercial and sustainability imperatives represents a compelling dual mandate for digitalisation investment.

The significant effect of External Support and Policy Environment (H5) shows an urgent need for a coherent national maritime digital framework that harmonises the MPA (Major Port Authorities Act 2021) with IMO cybersecurity guidelines, SOLAS Chapter XI-2 security provisions, and emerging international standards for autonomous vessel operations. The establishment of a Maritime Digital Regulatory Sandbox, analogous to financial services regulatory sandboxes, would enable controlled piloting of autonomous systems and blockchain technology within a legally defined experimental perimeter, accelerating both innovation and regulatory learning.

5.2. Contribution to Theory.

This study contributes in three folds. First, it advances the integration of TAM, UTAUT, and TOE into a unified, maritime-specific adoption model, the MITR framework, that explicitly incorporates regulatory environment as both a moderating and enabling construct. Second, it provides, to the authors' knowledge, the first empirical validation of an integrated technology adoption model within the Indian maritime regulatory context, addressing a significant geographical gap in IS adoption literature. Third, the finding that Organisational Readiness constitutes the strongest positive predictor, surpassing technology-specific perceptions, challenges techno - centric perspectives dominant in maritime technology literature and reinforces the institutional turn in IS adoption research. Figure 3 shows the mapping of each technology to its specific port and sustainability applications

Figure 3: Mapping of Technology enabling sustainability.



Source: Authors.

Conclusions.

This study has developed and empirically validated the Maritime Integrated Technology Readiness (MITR) framework, demonstrating that the transformation of maritime logistics through integrated emerging technologies, AI, blockchain, IoT, digital twins, and autonomous systems is neither exclusively a technological challenge nor a regulatory one, but an institutional one requiring coordinated action across organisational, governance, and policy domains.

The study's findings are threefold. First, all eight hypothesised antecedent-to-ORT relationships were statistically supported, with Organisational Readiness and Perceived Barriers emerging as the dominant determinants of transformation readiness in Indian smart port contexts. Second, qualitative expert evidence reveals persistent technology silos, regulatory ambiguity, and cybersecurity exposure as the most critical systemic barriers (Mukherjee, 2020, Kouhizadeh et al., 2021). Third, the MITR framework provides a theoretically grounded, empirically validated instrument that port authorities, vendors, and policymakers can deploy for technology readiness assessment and strategic planning.

Limitations.

The survey sample, were collected from the Indian maritime sector and may not be fully generalized to other maritime economies with differing regulatory architectures. The cross-sectional design precludes longitudinal assessment of adoption trajectories. Self-reported survey data are subject to social desirability bias, which is partially mitigated by the anonymous administration protocol. The SLR, restricted to English - language publications, may have excluded relevant scholarship in other languages, particularly from East Asian and Arabic maritime jurisdictions.

Future Research Directions.

Future research may extend this work in four directions. First, longitudinal panel studies tracking technology adoption trajectories across Indian major ports would provide dynamic evidence on how readiness constructs evolve with institutional maturity. Second, comparative cross-national studies contrasting Indian, Singaporean, and European port adoption contexts would enhance theoretical generalized and identify context - specific regulatory design lessons. Third, simulation modelling of digital twin integration with AI-driven port management systems would provide quantitative operational impact estimates beyond the perceptual survey data. Fourth, legal scholarship specifically addressing the liability implications of algorithmic decision-making in autonomous port equipment operations represents a critical interdisciplinary frontier at the intersection of maritime law and IS research.

In summary, the Indian maritime sector stands at a significant technological threshold. The transformative potential of integrated emerging technologies demands not merely capital investment in hardware and software platforms, but a parallel investment in institutional architecture, regulatory clarity and regulatory cooperation. The MITR framework offers a structured starting point for this dual transformation.

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