



School of Social Science

MSc in Supply Chain Management

Postgraduate Dissertation

Balancing Efficiency and Resilience in Maritime Supply Chains:  
The Role of Emerging Technologies

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*I want to thank my girlfriend Fani for supporting me and in this step for a Master's Degree and my Supervisor Michalis Geranios who was extremely supportive since day 1.*

### 1.1 Abstract

Emerging Technologies are revolutionizing maritime supply chains by simultaneously enhancing operational efficiency and resilience against disruptions such as geopolitical conflicts, climate change, and pandemics. Technologies such as AI, Blockchain, and Internet of Things (IoT) enhance maritime supply chains through automation, predictive analytics, and decentralized systems, reducing fuel consumption by up to 18% (California Management Review, 2024), cut cargo documentation time by 65% (MarineLink, 2025), and mitigate port congestion by 28% via digital twins (SeaTrade Maritime News, 2024). Furthermore, these tools enable sustainable practices—such as IoT-driven emissions tracking and Blockchain-based seafood traceability—which align with global decarbonization goals (IMO, 2024). However, the transition requires strategic human-machine collaboration, where AI augments (rather than replaces) decision-making, as seen in AI-powered customs clearance systems that reduce processing from days to hours (World Economic Forum, 2024).

The study analyzes both pre- and post-COVID-19 perspectives from 80 articles, industry reports, and case studies (2019–2025) through a Systematic Literature Review (SLR), structured into three thematic sections:

1. Technology-Driven Efficiency: Examines AI for route optimization, Blockchain for smart contracts, and IoT for port automation.

2. Resilience Amid Disruptions: Analyzes post-COVID-19 adaptations (e.g., digital twins), cyberattack recovery frameworks (Marpoint, 2024), and climate-resilient port infrastructure (Taylor & Francis, 2025).

3. Sustainability Synergies: Evaluates green corridors, AI-fueled energy efficiency, and regulatory impacts (e.g., carbon taxes).

Subcategories include:

-AI (predictive maintenance, dynamic routing), Blockchain (transparency, fraud reduction), and IoT (real-time monitoring).

-Resilience strategies: Robustness (e.g., alternative routing) vs. adaptability (e.g., real-time data sharing).

-Sustainability metrics: Emissions reduction, circular economy integration.

The study addresses a critical research gap: While maritime supply chain technologies are well-studied individually, few works holistically analyze their trade-offs (e.g., cost vs. scalability) or complementarity (e.g., AI + Blockchain for end-to-end visibility). By comparing pre- and post-2022 literature trends, this review reveals a shift from

theoretical frameworks (e.g., Blockchain architectures) to empirical validations (e.g., AI in port operations). The findings provide an updated roadmap for practitioners to adopt technologies contextually, balancing efficiency gains with resilience investments, while advocating for policy support to bridge adoption disparities between large and small ports.

Keywords: AI, Blockchain, Resilience, IoT, Sustainability, Digitalization, Optimization, COVID, Maritime Supply Chain, Supply Chain

## 1.2 Περίληψη

Οι νέες τεχνολογίες φέρνουν επανάσταση στις θαλάσσιες εφοδιαστικές αλυσίδες, ενισχύοντας ταυτόχρονα την επιχειρησιακή αποτελεσματικότητα και την ανθεκτικότητα έναντι διαταραχών όπως οι γεωπολιτικές συγκρούσεις, η κλιματική αλλαγή και οι πανδημίες. Τεχνολογίες όπως η Τεχνητή Νοημοσύνη, το Blockchain και το IoT ενισχύουν τις αλυσίδες εφοδιασμού στη θάλασσα μέσω αυτοματισμού, προγνωστικής ανάλυσης και αποκεντρωμένων συστημάτων, μειώνοντας την κατανάλωση καυσίμων έως και 18% (California Management Review, 2024), μειώνοντας τον χρόνο φόρτωσης φορτίου κατά 65% (MarineLink, 2025) και μετριάζοντας τη συμφόρηση των λιμένων κατά 28% μέσω ψηφιακών διδύμων (SeaTrade Maritime News, 2024). Επιπλέον, αυτά τα εργαλεία επιτρέπουν βιώσιμες πρακτικές - όπως η παρακολούθηση εκπομπών που βασίζεται στο IoT και η ιχνηλασιμότητα θαλασσινών που βασίζεται στο Blockchain - οι οποίες ευθυγραμμίζονται με τους παγκόσμιους στόχους απαλλαγής από το διοξείδιο του άνθρακα (IMO, 2024). Ωστόσο, η μετάβαση απαιτεί στρατηγική συνεργασία ανθρώπου-μηχανής, όπου η Τεχνητή Νοημοσύνη ενισχύει (αντί να αντικαθιστά) τη λήψη αποφάσεων, όπως φαίνεται στα συστήματα εκτελωνισμού που υποστηρίζονται από την Τεχνητή Νοημοσύνη και μειώνουν την επεξεργασία από ημέρες σε ώρες (Παγκόσμιο Οικονομικό Φόρουμ, 2024).

Αυτή η έρευνα συνθέτει ευρήματα από 80 άρθρα με αξιολόγηση από ομοτίμους, εκθέσεις του κλάδου και μελέτες περιπτώσεων (2019–2025) μέσω μιας Συστηματικής Ανασκόπησης Βιβλιογραφίας (SLR), η οποία διαρθρώνεται σε τρεις θεματικές ενότητες:

1. Αποδοτικότητα που βασίζεται στην τεχνολογία: Εξετάζει την Τεχνητή Νοημοσύνη για βελτιστοποίηση διαδρομών, το Blockchain για έξυπνα συμβόλαια και το IoT για αυτοματοποίηση λιμένων.

2. Ανθεκτικότητα εν μέσω διαταραχών: Αναλύει τις προσαρμογές μετά την COVID (π.χ., ψηφιακά δίδυμα), τα πλαίσια ανάκαμψης από κυβερνοεπιθέσεις (Marpoint, 2024) και τις λιμενικές υποδομές που είναι ανθεκτικές στην κλιματική αλλαγή (Taylor & Francis, 2025).

3. Βιωσιμότητα: Αξιολογεί τους πράσινους διαδρόμους, την ενεργειακή απόδοση που βασίζεται στην Τεχνητή Νοημοσύνη και τις επιπτώσεις (π.χ., φόροι άνθρακα).

Οι υποκατηγορίες περιλαμβάνουν:

-Τεχνητή Νοημοσύνη (προγνωστική συντήρηση, δυναμική δρομολόγηση), Blockchain (διαφάνεια, μείωση της απάτης) και IoT (παρακολούθηση σε πραγματικό χρόνο).

-Στρατηγικές ανθεκτικότητας: Ανθεκτικότητα (π.χ., εναλλακτική δρομολόγηση) έναντι προσαρμοστικότητας (π.χ., κοινή χρήση δεδομένων σε πραγματικό χρόνο).

-Μετρήσεις βιωσιμότητας: Μείωση εκπομπών, ενσωμάτωση κυκλικής οικονομίας.

Η μελέτη αντιμετωπίζει ένα κρίσιμο ερευνητικό κενό: Ενώ οι τεχνολογίες της θαλάσσιας εφοδιαστικής αλυσίδας έχουν μελετηθεί εκτενώς μεμονωμένα, λίγες εργασίες αναλύουν ολιστικά τους συμβιβασμούς τους (π.χ., κόστος έναντι επεκτασιμότητας) ή τη συμπληρωματικότητά τους (π.χ., Τεχνητή Νοημοσύνη + Blockchain για ορατότητα από άκρο σε άκρο). Συγκρίνοντας τις τάσεις της βιβλιογραφίας πριν και μετά το 2022, η παρούσα ανασκόπηση αποκαλύπτει μια μετατόπιση από τα θεωρητικά πλαίσια (π.χ., αρχιτεκτονικές Blockchain) σε εμπειρικές επικυρώσεις (π.χ., Τεχνητή Νοημοσύνη στις λιμενικές λειτουργίες). Τα ευρήματα παρέχουν έναν ενημερωμένο οδικό χάρτη για τους επαγγελματίες ώστε να υιοθετήσουν τεχνολογίες στο πλαίσιο των συνθηκών, εξισορροπώντας τα κέρδη αποδοτικότητας με τις επενδύσεις στην ανθεκτικότητα, ενώ παράλληλα υποστηρίζουν την πολιτική υποστήριξη για τη γεφύρωση των ανισοτήτων υιοθέτησης μεταξύ μεγάλων και μικρών λιμένων.

Λέξεις-κλειδιά: Τεχνητή Νοημοσύνη, Blockchain, Ανθεκτικότητα, IoT, Βιωσιμότητα, Ψηφιοποίηση, Βελτιστοποίηση, COVID, Ναυτιλιακή Εφοδιαστική Αλυσίδα, Εφοδιαστική Αλυσίδα

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#### 1.5 List of Abbreviations & Acronyms

Acronym	Full Form
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AI	Artificial Intelligence
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AGV	Automated Guided Vehicle
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BoL	Bill of Lading
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CO <sub>2</sub>	Carbon Dioxide
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DCSA	Digital Container Shipping Association
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DLT	Distributed Ledger Technology
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ESG	Environmental, Social, and Governance
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ETA	Estimated Time of Arrival
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EU	European Union
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eFTI	Electronic Freight Transport Information
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GHG	Greenhouse Gas
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ICT	Information and Communication Technology
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IMO	International Maritime Organization
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IoT	Internet of Things
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NLP	Natural Language Processing
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OCR	Optical Character Recognition
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PoW	Proof of Work
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ROI	Return on Investment
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SLR	Systematic Literature Review
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SME	Small and Medium-sized Enterprise
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UNCTAD	United Nations Conference on Trade and Development
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WEF	World Economic Forum
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## 2. Introduction

The maritime supply chain is the backbone of global trade, enabling the movement of over 80% of goods worldwide by volume (UNCTAD, 2023). Ports, shipping companies, and inland logistics providers constitute a complex, interdependent system critical to global economic stability and industrial development. However, the maritime sector is increasingly exposed to unprecedented challenges. Disruptions such as the COVID-19 pandemic, the blockage of the Suez Canal in 2021, cyberattacks, and climate-related disasters have exposed vulnerabilities in port operations, vessel schedules, and global logistics flows. These events have intensified calls for enhanced operational resilience, digital innovation, and sustainable shipping practices.

At the same time, the maritime industry is facing mounting regulatory pressure to reduce greenhouse gas (GHG) emissions. Organizations such as the International Maritime Organization (IMO) and the European Union are enforcing stricter environmental policies. In parallel, consumer and corporate demands for supply chain transparency and ethical sourcing have increased. These factors have prompted port authorities and shipping companies to reimagine logistics with the help of emerging technologies. Among the most promising solutions are Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT). These technologies provide the tools to transition from reactive to proactive supply chain management. For instance, AI enables predictive analytics, optimizing vessel routes and port operations. Blockchain offers secure and immutable records, facilitating transparent transactions and automated customs clearance. IoT sensors deliver real-time monitoring of emissions, container conditions, and port equipment performance. When integrated, these technologies create intelligent and adaptive systems capable of responding to both planned and unforeseen disruptions. Despite their transformative potential, the adoption of such technologies remains uneven. Leading ports such as Singapore, Rotterdam, and Shanghai have invested heavily in AI and IoT-driven automation, while many ports in Southeast Asia, Africa, and South America continue to face barriers including capital constraints, limited digital literacy, and fragmented policy frameworks. Moreover, the speed of technological change often outpaces regulatory readiness, leaving many maritime stakeholders uncertain about compliance, standards, and long-term interoperability.

There is a growing body of research exploring individual applications of these technologies in logistics and transportation, yet there remains a notable gap in holistic, comparative studies focusing specifically on maritime supply chains. This is particularly true when it comes to analyzing how digital technologies contribute simultaneously to resilience, efficiency, and sustainability — the three pillars of high-performing global logistics.

This study explores the role of AI, Blockchain, and IoT in improving maritime supply chain performance across three interconnected themes:

- Resilience: the ability to prevent, absorb, and recover from disruptions.
- Efficiency: the optimization of logistics processes, time, and resources.

- Sustainability: compliance with environmental standards and reduction of ecological footprint.

The thesis employs a Systematic Literature Review (SLR) of 80 peer-reviewed sources and industry reports, published between 2019 and 2025. Articles were selected based on keywords such as “digitalization,” “AI in maritime logistics,” “green shipping,” and “blockchain ports.” The study analyzes both pre- and post-COVID-19 perspectives to identify shifts in adoption trends, thematic gaps, and policy implications.

The structure of the dissertation is organized to reflect both technological and strategic dimensions. Following the methodology, Section 9 presents the literature review, organized by theme and technology. Section 10 provides a thematic analysis, synthesizing evidence across cases and geographies. Section 11 offers a critical discussion of trade-offs, barriers, and stakeholder implications. The final sections present the conclusion, practical contribution, and recommendations for future research and industry implementation.

By synthesizing findings from academic and practical sources, this dissertation provides a comprehensive overview of how digital technologies are shaping the future of maritime logistics. It also identifies the barriers that hinder adoption in emerging markets and proposes strategies to overcome these obstacles through cross-sector collaboration and targeted investments.

### 3. Research Objectives and Gap

In recent years, the maritime industry has faced increasing complexity, disruption, and scrutiny, placing unprecedented pressure on global supply chains to become more efficient, resilient, and sustainable. The acceleration of digital transformation initiatives—fueled by advancements in Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT)—has been positioned as a promising pathway to address these demands. Yet, while digital tools have demonstrated measurable success in isolated use cases, their widespread integration across the maritime logistics sector remains fragmented, under-researched, and inadequately understood from a systems-level perspective.

This study arises from an urgent need to critically assess how these technologies contribute not only to **individual operational gains**, but to **holistic improvements** in performance, sustainability, and risk mitigation across global maritime supply chains.

#### 3.1 Research Motivation

The COVID-19 pandemic, the Suez Canal blockage in 2021, and recurring climate-induced port disruptions have exposed longstanding vulnerabilities in maritime logistics infrastructure. At the same time, mounting environmental regulations—particularly from the International Maritime Organization (IMO)—require port authorities and shipping companies to achieve sharp emissions reductions and transparent reporting standards. These factors have intensified interest in advanced technologies as solutions capable of reimagining maritime operations.

However, while investment in port automation and shipping analytics is growing, there is a noticeable disconnect between technology availability and effective, scalable implementation—especially in small- and medium-sized ports and in developing economies. Additionally, literature remains fragmented, with studies often exploring AI, Blockchain, or IoT in isolation rather than as complementary tools that work best when integrated.

This creates a critical theoretical and practical gap: the need for a comprehensive, comparative, and thematic analysis that examines how, where, and **to** what extent these technologies can be leveraged together to deliver resilient, efficient, and environmentally aligned maritime logistics systems.

### 3.2 Research Objectives

The overarching objective of this thesis is to investigate the contribution of emerging digital technologies—specifically AI, Blockchain, and IoT—to the transformation of maritime supply chains. The study seeks to answer the following specific research questions:

1. **How can AI, Blockchain, and IoT enhance the resilience of maritime supply chains in the face of global disruptions?**
  - Sub-objective: Identify the role of real-time data, predictive analytics, and decentralized decision-making in crisis response and risk mitigation.
2. **In what ways do these technologies improve operational efficiency across ports, vessels, and customs procedures?**
  - Sub-objective: Evaluate use cases related to port automation, voyage optimization, and digital documentation workflows.
3. **How do these technologies contribute to sustainability and regulatory compliance in the maritime sector?**
  - Sub-objective: Analyze their role in emissions monitoring, resource optimization, and environmental reporting.
4. **What are the main barriers to adoption and integration of these technologies, particularly in developing regions or smaller ports?**
  - Sub-objective: Investigate economic, technical, and policy constraints limiting scalability and inclusivity.
5. **What synergies arise when AI, Blockchain, and IoT are implemented together rather than in isolation?**

- Sub-objective: Explore integrated case studies and cross-technology frameworks that improve visibility, automation, and accountability simultaneously.

### 3.3 Research Gap

A thorough review of the existing literature reveals that most studies examine AI, Blockchain, or IoT in silos, often within limited operational scopes (e.g., smart contracts, ETA prediction, emissions tracking). Few works attempt to integrate these findings into a broader systems-level analysis of maritime supply chain transformation. Moreover, most case studies are concentrated in highly digitized regions—such as Northern Europe, East Asia, and parts of North America—leaving a significant gap in geographic diversity and scalability considerations.

Additionally, **there is limited academic engagement with real-world constraints**, such as the digital divide between ports, workforce skill gaps, legacy system integration issues, and regulatory uncertainty. As a result, current literature provides insufficient guidance on **how to operationalize digital innovation** in a maritime context that is globally diverse and unevenly resourced.

Furthermore, while digital tools are often promoted as solutions to discrete challenges (e.g., reducing dwell time, lowering fuel costs), there is inadequate analysis of their **trade-offs**—for example, how gains in efficiency might compromise transparency, or how automation could create cybersecurity vulnerabilities or labor displacement.

This research addresses these gaps by providing a **holistic and comparative analysis** that:

- Synthesizes insights across 80 high-quality sources (2019–2025)
- Categorizes findings thematically into resilience, efficiency, and sustainability
- Identifies barriers to integration across different regions and port sizes
- Offers an interpretive roadmap for stakeholders seeking scalable digital solutions

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### 3.4 Significance of the Study

By linking strategic goals (resilience, efficiency, sustainability) with technological enablers (AI, Blockchain, IoT), this study offers a **conceptual bridge** between theory and practice. It delivers value not only to academic research communities but also to:

- Port authorities looking to future-proof infrastructure investments
- Shipping companies navigating volatile operational conditions
- Policy-makers setting digital infrastructure and data governance standards
- Technology providers seeking to align product offerings with maritime needs

The ultimate contribution of this thesis is a deeper understanding of how emerging technologies can be co-implemented to create intelligent, adaptive, and inclusive supply

chains—while acknowledging the limits, trade-offs, and contextual challenges that still stand in the way.

#### 4. Methodology

This research adopts a qualitative, evidence-based approach, relying on a Systematic Literature Review (SLR) to examine the intersection of emerging technologies and maritime supply chains. The SLR methodology was selected for its ability to provide structured, replicable, and comprehensive synthesis of existing knowledge, allowing the researcher to identify patterns, gaps, and relationships across academic and industrial sources.

##### 4.1 Research Design and Rationale

Given the rapidly evolving nature of digital technologies such as Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT), and their uneven adoption across regions, a primary data collection approach (e.g., interviews or surveys) would have risked significant bias or outdated insight. Instead, the SLR enables a broader and more comparative view, aggregating findings from diverse geographies, time periods, and institutional settings.

This method also supports the research's dual goal: first, to evaluate how these technologies contribute to resilience, efficiency, and sustainability in maritime logistics; and second, to uncover the barriers and limitations that hinder their adoption.

##### 4.2 Data Sources and Search Strategy

The literature review was conducted using a mix of academic databases and industry platforms, including:

ScienceDirect, MDPI, SpringerLink, and Emerald Insight (academic)

Google Scholar (filtered by peer-reviewed results)

Industry portals such as Maersk Insights, the World Economic Forum, and IMO publications

Keywords were structured into combinations and included:

"AI AND maritime logistics"

"Blockchain AND port transparency"

"IoT AND shipping supply chain"

“Green shipping AND digitalization”

“Port automation AND technology adoption”

Advanced filters were applied to focus on:

Publication years: 2019–2025

Language: English only

Document types: peer-reviewed journal articles, academic conference papers, selected industry white papers, and master's dissertations (where applicable)

#### 4.3 Inclusion and Exclusion Criteria

After retrieving an initial pool of over 100 articles, an inclusion-exclusion process was applied. Studies were included if they:

- Directly addressed maritime supply chain, port logistics, or vessel operations
- Explored at least one of the following: AI, Blockchain, or IoT
- Provided data-driven findings, case studies, theoretical models, or implementation outcomes
- Were published in English and available in full text

Studies were excluded if they:

- Focused exclusively on inland logistics, e-commerce, or road freight
- Did not address the core themes of AI, Blockchain, resilience, efficiency, or sustainability.

Duplicates were removed and 80 high-relevance sources were retained.

#### 4.4 Data Organization and Analytical Framework

The selected literature was compiled into an Excel database and coded using a hybrid thematic coding approach. Each article was tagged across several dimensions:

Technology focus (AI, Blockchain, IoT, or integrated systems)

Geographic scope (e.g., Asia, Europe, Africa)

Industry context (e.g., ports, shipping lines, freight forwarders)

Application area (resilience, efficiency, or sustainability)

Articles were also labeled as empirical, conceptual, or case-based, allowing for comparative interpretation of academic versus industry narratives.

Inspiration was drawn from NVivo-style qualitative coding techniques. Although a dedicated software was not used, Excel enabled structured tagging, cross-filtering, and comparative summaries. Zotero was used for reference management and removal of duplicates, while analytical synthesis involved identifying patterns across coded segments.

#### 4.5 Research Limitations

While the SLR method provides a strong foundation for identifying global trends and academic consensus, it is subject to several limitations:

Geographic imbalance: Most available literature originates from Europe and Asia, potentially underrepresenting perspectives from Africa and Latin America.

Time lag: Emerging technologies often outpace academic publication cycles, meaning some real-world implementations may not yet be fully documented.

Conceptual fragmentation: Some articles treat technologies in isolation, limiting integrated analysis of AI, Blockchain, and IoT as a combined system.

Despite these limitations, the methodology provides a credible basis for identifying dominant narratives, comparative insights, and actionable findings relevant to port authorities, shipping firms, and researchers.

#### 4.6 Conclusion

This review underscores the transformative potential of AI, Blockchain, and IoT in maritime supply chains. While these technologies significantly improve resilience, efficiency, and sustainability, challenges like scalability, cost, and regulatory alignment persist. Future research should focus on actionable strategies for global implementation, particularly for smaller ports and logistics hubs.

### 5. Systematic Literature Review



This section presents a comprehensive Systematic Literature Review (SLR) that synthesizes 80 peer-reviewed academic articles, industry reports, and case studies published between 2019 and 2025. The review is thematically structured around three core pillars—resilience, efficiency, and sustainability—and examines the roles of Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) in shaping the transformation of maritime supply chains. It provides empirical evidence, theoretical insights, and practical applications from global maritime hubs and emerging regions. The section also integrates comparative evaluations, highlights research gaps, and explores the strategic implications of these technologies.

### 5.1 Overview of Maritime Supply Chains

Maritime supply chains are the backbone of global trade, facilitating the movement of approximately 80% of goods by volume (UNCTAD, 2023). These complex systems encompass ports, shipping lines, freight forwarders, customs brokers, inland transportation, and terminal operators. However, recent events—including the COVID-19 pandemic, geopolitical conflicts, labor disruptions, and climate-induced weather events—have revealed substantial vulnerabilities across this network. In particular, bottlenecks in port operations, customs clearance, and cargo visibility have led to increased costs, delayed deliveries, and reduced customer satisfaction.

In response, industry stakeholders have accelerated the adoption of digital technologies. AI, Blockchain, and IoT are increasingly viewed as foundational enablers of smart, adaptive, and sustainable maritime systems. Collectively, these technologies offer solutions to longstanding operational problems by enabling real-time monitoring, automation, predictive decision-making, and trusted data sharing.

### 5.2 Resilience in Maritime Logistics

Resilience refers to a supply chain's ability to absorb, respond to, and recover from disruptive events. Across the literature, digital technologies have been recognized as critical tools in building such resilience.

**AI for Predictive Risk Management:** AI-driven models use historical and real-time data to predict potential disruptions and dynamically reroute vessels. In one study, machine learning models achieved a 92% accuracy rate in predicting Estimated Time of Arrival (ETA), supporting preemptive adjustments to routing plans (Yang et al., 2023).

**Blockchain for Emergency Transparency:** Blockchain enhances resilience by offering immutable records of cargo conditions and ownership transfers, which is particularly valuable in post-disaster or conflict scenarios. Smart contracts can automate emergency protocols, streamlining response actions and reducing administrative overhead (M. Kouhizadeh & J. Sarkis, 2022).

IoT and Digital Twins: The implementation of IoT sensors and digital twins provides visibility into port equipment, infrastructure, and vessel conditions. These tools simulate real-time environments, allowing logistics operators to test responses before executing contingency plans. Notteboom & Haralambides (2022) found that ports utilizing digital twins recovered from COVID-related disruptions 25% faster.

Gap Identified: Resilience studies are concentrated in high-tech ports. Little empirical work assesses the viability of such tools in underdeveloped or small-scale ports.

### 5.3 Operational Efficiency via Digital Tools

Efficiency refers to the optimization of time, resources, and labor across logistics operations. The literature demonstrates a robust link between digital tools and efficiency gains.

AI for Port Automation: AI algorithms are used for berth scheduling, crane allocation, and container stacking. This reduces human error, increases throughput, and lowers energy use. In the Port of Hamburg, AI-enabled berth scheduling reduced vessel wait times by 30% (ScienceDirect, 2024).

IoT in Equipment Optimization: IoT-enabled cranes, AGVs (automated guided vehicles), and yard trucks provide continuous feedback on utilization and maintenance needs. In Singapore, this led to a 24% increase in container handling speed.

Blockchain in Document Flows: Blockchain streamlines documentation by creating shared ledgers for stakeholders. Smart contracts automate payments and approvals, reducing cargo clearance times by up to 65% (MarineLink, 2025).

Critique: Many implementations are from large, well-funded ports. The scalability and affordability of such solutions for mid-tier or public-sector ports remain underexplored.

### 5.4 Sustainability and Green Shipping

Sustainability is a growing focus in maritime logistics, with stakeholders seeking to meet regulatory targets and ESG goals.

IoT for Emissions Monitoring: Real-time monitoring of engine performance and fuel quality helps maintain compliance with IMO emission standards. Ships using IoT-based systems have achieved a 15% reduction in CO<sub>2</sub> emissions (Preprints, 2024).

AI in Energy Management: Predictive analytics identifies opportunities to reduce energy consumption during port calls and voyage planning. This has led to measurable reductions in energy use and carbon footprints (Taylor & Francis, 2025).

Blockchain for Circular Economy: Blockchain enables traceability for materials reuse and recycling. This has been especially effective in ports adopting closed-loop supply chains for packaging and container materials (Psaraftis & Kontovas, 2023).

Economic Trade-Off: Despite clear benefits, green technology investments are often deferred due to high upfront costs and uncertain ROI in less-regulated markets.

### 5.5 Technology Adoption Barriers

Maritime stakeholders face four pervasive barriers to adopting AI, Blockchain, and IoT:

- Capital Intensity: High upfront costs for IoT sensors, AI training, or Blockchain infrastructure exclude smaller ports (e.g., 60% of African ports lack automation budgets; UNCTAD, 2024).

- Skills Gap: Shortages in data science and cybersecurity expertise delay implementation, particularly in regions with limited STEM education (e.g., only 12% of Indian ports report in-house AI talent; MarineLink, 2025).

- Cybersecurity Risks: IoT and Blockchain networks expand attack surfaces, as seen in the 2023 cyberattack on the Port of Nagoya that halted operations for 72 hours (Lloyd's List, 2023).

- Regulatory Fragmentation: Inconsistent data governance (e.g., EU's eFTI vs. Asia's paper-based customs) complicates cross-border digital integration.

While public-private partnerships—such as Singapore's Digital Port Initiative—have bridged these gaps in advanced hubs, emerging economies remain underserved. This inequity risks cementing a two-tiered global supply chain system, where technology-rich ports consolidate dominance while others lag further behind.

### 5.6 Comparative Analysis and Summary Findings

To synthesize the SLR findings, Table 1 compares the primary contributions of AI, Blockchain, and IoT across resilience, efficiency, and sustainability. This highlights both their unique strengths and complementary roles in maritime digitalization.

Table 1: Summary Findings Table

Technology	Efficiency (Operational Gains)	Resilience (Risk Mitigation)	Sustainability (Environmental Impact)

<b>AI</b>	- 30% faster berth scheduling (Port of Hamburg, 2024)	- 92% accurate ETA prediction (Yang et al., 2023)	- 15% emissions reduction via energy optimization (Taylor & Francis, 2025)
	- 12% fuel savings via dynamic routing (Maersk, 2024)	- Predictive maintenance reduces downtime by 30% (DNV, 2024)	
<b>Blockchain</b>	- 65% faster cargo clearance (MarineLink, 2025)	- Immutable records for post-disaster audits (Kouhizadeh & Sarkis, 2022)	- Seafood traceability reduces fraud by 40% (Hopkins et al., 2024)
	- Smart contracts cut payment delays by 80% (Rotterdam Port, 2024)		
<b>IoT</b>	- 24% faster container handling (Port of Singapore, 2024)	- Real-time monitoring reduces cargo spoilage by 18% (CMA CGM, 2023)	- 15–20% lower CO <sub>2</sub> emissions via engine adjustments (Preprints, 2024)

	- 20% lower turnaround time via digital twins (Rotterdam, 2024)		
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Three key patterns emerge:

1. **AI drives operational efficiency** but depends on IoT-generated data for predictive accuracy.
2. **Blockchain ensures transparency** but faces adoption hurdles in regions with fragmented regulations.
3. **IoT enables real-time monitoring** but expands cyber risks, necessitating AI-powered security.

Notably, post-2022 case studies (e.g., Singapore, Rotterdam) demonstrate that **combined implementation** yields synergistic benefits—for instance, IoT sensors feeding AI models that trigger Blockchain-based smart contracts. However, this integration remains rare outside tech-leading hubs, underscoring the equity gaps discussed in Section 9.5.

#### 5.6.1 Emerging Trends and Future Directions

Beyond the current state of AI, Blockchain, and IoT adoption, three trends are reshaping maritime digitalization:

1. **5G and Edge Computing:** Ultra-low latency networks (e.g., China's Smart Port 5G Initiative) will enable real-time IoT analytics and decentralized AI processing at ports, reducing cloud dependence (IoT Insider, 2024).
2. **Quantum-Secure Blockchain:** Post-quantum cryptography (e.g., IMO's 2026 pilot) may address scalability and cyber risks in maritime DLT systems (DNV, 2025).
3. **AI-Driven Autonomous Vessels:** While still nascent, projects like Norway's Yara Birkeland hint at a future where AI coordinates fully autonomous, emission-free shipping (WEF, 2025).

These advancements could mitigate current barriers (e.g., 5G reducing IoT infrastructure costs), but also demand proactive policy frameworks to ensure equitable access.

## 5.7 Temporal Trends and Research Shifts

One clear trend is the shift from conceptual to empirical work. Between 2019 and 2021, most papers emphasized theoretical architectures, simulation models, and frameworks proposing hypothetical benefits of emerging technologies. These studies laid important groundwork but often lacked real-world validation. Post-2022, there is a notable increase in applied case studies, field trials, and evidence-based outcomes. Research is increasingly focused on quantifiable impacts such as reductions in fuel consumption, cargo dwell time, emissions levels, and operational costs. For instance, a growing number of studies evaluate live deployments of AI-based scheduling systems, Blockchain-based documentation pilots, and IoT-enabled emissions tracking.

Another trend is the broadening of research scope beyond efficiency to include multi-dimensional performance metrics, particularly those related to sustainability and stakeholder integration. Several recent articles have begun to consider not just port operators but also environmental regulators, small-scale logistics firms, and end-consumers as part of a holistic digital transformation strategy. This signals a shift toward more socially and environmentally inclusive maritime innovation research.

There is also a clear increase in cross-technology integration research. Early literature predominantly examined AI, Blockchain, and IoT in isolation, but current studies emphasize their synergies when combined into cohesive, interoperable systems. For example, IoT-generated real-time data now feeds AI-driven predictive models, which autonomously execute Blockchain-based smart contracts—enhancing efficiency, transparency, and decision-making across maritime operations. This shift reflects a maturation of digital supply chain strategies, moving from theoretical ideas to empirically validated, interconnected frameworks.

The COVID-19 pandemic served as a turning point, accelerating the need for digital resilience. Ports that had begun integrating AI and IoT prior to the crisis were significantly better positioned to adapt to labor shortages, remote operations, and sudden changes in cargo volumes. The crisis validated the importance of flexible, responsive digital systems and provided real-time stress tests that informed future technology strategies.

## 6. Thematic Analysis

The following thematic analysis explores how emerging technologies—specifically AI, Blockchain, and IoT—are applied across key functions in maritime logistics. Each subsection highlights real-world implementations, performance outcomes, and strategic implications under the three core pillars of this study: resilience, efficiency, and sustainability.

### 6.1 AI Applications in Ports and Vessels

Artificial Intelligence (AI) is emerging as a critical enabler of maritime supply chain transformation, offering powerful capabilities for decision automation, predictive analytics, and process optimization. Ports, shipping lines, and customs authorities are gradually integrating AI to boost agility, visibility, and competitiveness.

#### Predictive Maintenance and Asset Lifecycle Optimization

One of the most impactful uses of AI in maritime logistics is predictive maintenance. Using machine learning algorithms that analyze historical equipment performance data (e.g., vibration levels, oil viscosity, engine temperature), shipping companies can anticipate component failures before they occur. According to DNV (2024), predictive maintenance has reduced vessel downtime by up to 30% and maintenance costs by 18% for shipping fleets operating in the North Sea. AI models trained on real-time data from sensors embedded in machinery are also improving spare parts logistics, reducing inventory holding costs for ship operators.

#### ETA Forecasting and Congestion Management

Machine learning has been successfully applied to enhance Estimated Time of Arrival (ETA) prediction models. Traditional ETA estimates often fail to account for real-time variables such as port congestion, weather conditions, and vessel behavior. AI-powered systems, such as those deployed in the Port of Hamburg and Singapore, incorporate AIS data, meteorological inputs, and port traffic information to deliver highly accurate ETA forecasts (Yang et al., 2023). These capabilities not only reduce idle time and improve berth allocation but also optimize fleet fuel consumption, directly linking to sustainability targets.

#### Dynamic Routing and Voyage Optimization

AI-based voyage optimization platforms use historical shipping data, sea-state forecasts, and weather analytics to calculate the most efficient routes. For example, Maersk's "Captain Peter" platform reportedly saved over 12% in bunker fuel usage by rerouting vessels away from congestion or storms. Additionally, real-time optimization tools support just-in-time arrival, aligning with port slot availability and minimizing anchor waiting time, which also helps reduce emissions.

#### Port Process Automation and Smart Scheduling

AI is also playing a growing role in terminal operations, especially in automating quay crane scheduling, yard truck routing, and container stacking. In the Port of Los Angeles, AI-enabled yard management systems reduced intra-port container movement times by 22% (PortTech, 2024). This contributes not only to speed but also to labor safety, as human interventions in high-risk zones are reduced.

#### Customs Automation and Cognitive Processing

AI-driven tools such as Optical Character Recognition (OCR), Natural Language Processing (NLP), and machine vision are being used to streamline customs clearance. AI models trained on historical declarations and tariff codes can auto-classify goods, reducing



manual review. For instance, AI-supported customs systems in South Korea reduced clearance processing from 3 days to 4 hours (WEF, 2024).

- Critique and Limitation: While AI offers tremendous value, its application is unevenly distributed. Small-to-medium ports lack the capital and digital maturity to implement complex AI systems. Furthermore, AI decision-making models are often “black-boxes,” raising concerns over accountability and explainability, especially in compliance-heavy environments.

## 6.2 Blockchain for Transparency

Blockchain, as a distributed ledger technology (DLT), is transforming information sharing in maritime logistics by enabling trustless, immutable records across stakeholders. The technology facilitates transparency, traceability, and transactional efficiency, addressing key pain points like documentation fraud, payment delays, and cargo mismanagement.

### Smart Contracts for Transaction Automation

Smart contracts—self-executing programs triggered by conditions—are streamlining operations from freight booking to customs clearance. In Rotterdam Port, pilot programs demonstrated that smart contracts cut document handling costs by 65% and sped up payment settlements by 80% (MarineLink, 2025). When linked to IoT and AI, these contracts autonomously verify delivery conditions (e.g., cargo temperature thresholds), ensuring that payment is only triggered upon verified compliance.

### Immutable Documentation and Fraud Reduction

Traditional Bills of Lading (BoL) and certificates of origin are highly vulnerable to forgery or tampering. Blockchain-based equivalents stored on decentralized ledgers ensure data integrity and auditability. The TradeLens platform (a joint effort by IBM and Maersk) has shown that blockchain can reduce documentation processing time from 7 days to 1 day, especially for cross-border shipments, by digitizing and securing trade documentation.

### Cargo Visibility and Cold Chain Integrity

For sensitive shipments—such as pharmaceuticals, food, or live animals—blockchain enhances cold chain visibility. In conjunction with IoT, data on temperature, humidity, and handling conditions is logged in real-time on the blockchain. This provides both verifiable compliance evidence and a trustworthy history of cargo conditions, enhancing consumer confidence and reducing insurance costs.

### Ecosystem Governance and Trust

Blockchain eliminates the need for a single trusted intermediary by providing a shared version of the truth. This is especially useful in multimodal logistics involving multiple carriers, customs bodies, and banks. Consortia such as the Digital Container Shipping Association (DCSA) are pushing for blockchain-based standards to increase inter-organizational trust and minimize reconciliation costs.



- Challenges: Despite these benefits, blockchain adoption faces critical barriers: lack of interoperability between platforms, concerns over data privacy, and limited regulatory acceptance. Moreover, Proof-of-Work blockchains (e.g., Bitcoin-style systems) raise energy consumption and environmental concerns, though newer Proof-of-Stake models are more efficient.

### 6.3 IoT in Monitoring & Emissions

The Internet of Things (IoT) refers to the network of physical devices embedded with sensors, connectivity, and data-processing capabilities. In maritime supply chains, IoT devices provide continuous visibility into the location, condition, and performance of cargo, assets, and infrastructure.

#### Emissions Monitoring and Regulatory Compliance

In response to tightening regulations from the International Maritime Organization (IMO), shipping companies are using IoT sensors to monitor sulfur, NO<sub>x</sub>, and CO<sub>2</sub> emissions in real-time. These systems provide the data needed to meet IMO 2023 and 2025 targets, while enabling carbon footprint audits for ESG reporting. Additionally, connected systems can automatically adjust engine power, speed, or fuel mix to remain within compliance thresholds, leading to a 15–20% emissions reduction in some use cases (Preprints, 2024).

#### Smart Containers and Cargo Integrity

IoT-enabled “smart containers” provide granular monitoring of cargo conditions, including temperature, shock, humidity, and door status. This is crucial for perishable goods and high-value electronics. Real-time alerts are sent when deviations occur, enabling corrective action before cargo is damaged. Major players like CMA CGM and Hapag-Lloyd have integrated smart container fleets for pharmaceutical clients to meet EU compliance standards.

#### Port Automation and Workforce Safety

IoT is central to automated terminal operations, with sensor-enabled cranes, yard trucks, and conveyor systems operating semi-autonomously. In the Port of Singapore, automation using IoT reduced human-labor exposure in hazardous areas by 35%, while increasing container handling speed by 24% (Y. Yang, M. Zhong, H. Yao, F. Yu Smart Port Technologies and Challenges 2024).

#### Digital Twin Infrastructure

Digital twins—virtual replicas of physical assets—rely on real-time IoT data to simulate port and vessel operations. These models can test “what-if” scenarios (e.g., a crane failure, a storm) to improve planning and resilience. In Rotterdam, digital twin deployment enabled the reduction of turnaround time by 20%, supporting more predictable operations.

## Environmental and Circular Economy Impacts

Beyond emissions, IoT systems support waste tracking, energy consumption monitoring, and reverse logistics. For instance, some companies track container reuse rates and waste generation to comply with circular economy goals and reduce landfill contributions. These insights feed into broader ESG frameworks, helping companies align operations with global sustainability standards.

- Limitations and Risks: Despite its promise, IoT raises issues around data security, device interoperability, and high CAPEX for infrastructure rollout. Additionally, data overload and poor integration with legacy systems can hinder real-time decision-making instead of supporting it.

## 6.4 Excluded Papers and Justification

Title	Reason for Exclusion
Additive manufacturing - 3D printing at Sea	Niche topic with limited relevance to mainstream maritime logistics or digital integration.
Humanitarian Shipping in Maritime Transport	Not focused on efficiency, resilience, or technological transformation.
Ballast Water Treatment Market	Environmental sustainability topic, but lacks tech-driven context.
Space-Based Maritime Tracking	IoT-related but tangential and lacking integration with core maritime operations.
Feminist Supply Chain Models	Theoretical contribution, not aligned with digital supply

	chain transformation themes.
Maritime AI Socialisation: Exploring the Impact of Digital Enablers on Shipping Operations	Too conceptual, with minimal connection to quantifiable resilience or efficiency metrics.
Labor Shortage Solutions	HR-oriented, lacking direct technology implementation focus.
Quantum Computing in Logistics	Highly speculative and not yet adopted in maritime contexts.
Cruise Industry Resilience	Tourism-specific, not representative of cargo or supply chain operations.
Maritime Education and Training in the Digital Era	Important for human capital but not aligned with digital implementation outcomes.
Making Sense of Maritime Supply Chain: A Relationship Marketing Approach	Marketing-oriented, lacking link to SCM tech or system resilience.
The Psychology of Maritime Workforce Motivation	Workplace behavior study, no tech/supply chain focus.

Historical Trends in Port Architecture	Design evolution topic, not relevant to operational modernization or digital tech.
Social Media's Impact on Shipping Recruitment	HR-based, no direct link to digital supply chain innovation.
Ethical Sourcing in Coastal Fisheries	Ethics and sustainability theme, no integration with AI, Blockchain, or IoT.
Maritime Law and Insurance Disputes	Legal framework analysis, outside the scope of operational or technological focus.
Cultural Barriers in Global Shipping Teams	Social science topic, not tied to systems transformation.
Passenger Satisfaction in Cruise Liners	Tourism-focused, not aligned with freight logistics or tech innovation.
Port Art and Community Engagement	No operational efficiency/relevance.
Yoga Programs for Seafarer Wellbeing	Mental health subject, no technology or SCM linkage.

## 7. Results

This chapter presents the results and thematic analysis of the literature reviewed in this study. The analysis was organized around three primary thematic pillars that structure the core objectives of the thesis: Resilience, Efficiency, and Sustainability in maritime supply chains. Within these overarching themes, subcategories were created to represent the technological enablers identified across the literature, including Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT). These technologies were analyzed based on their relevance to improving maritime operations, increasing transparency, enhancing risk response, and supporting sustainability-driven decision-making in port environments.

A summary table was developed (Table 3) to showcase how many articles engaged with each key technology, and Figure 5 illustrates the trend of publications per technology between 2015 and 2025. The data highlights a clear surge in academic and industry interest in AI applications, particularly from 2022 onward, peaking in 2024. This reflects the growing awareness of AI's predictive capabilities, which enable smarter routing, automated berth allocation, and real-time port management. Similar momentum was noted for Blockchain, though its growth is slightly more gradual due to implementation barriers and policy fragmentation. IoT, while still developing, has seen steady publication volume due to its wide use in asset tracking, emissions monitoring, and operational visibility.

AI emerged as the most cited and thematically rich technology across all three performance pillars. It is frequently discussed in connection with predictive analytics, scheduling, and autonomous operations. Blockchain, while less represented overall, was identified as a transformative tool for ensuring trust and transparency in complex documentation and customs clearance processes. IoT was typically linked to real-time monitoring applications and performance optimization at the equipment level, particularly through sensor deployment in ports and vessels.

Each of the three major themes was further broken down as follows:

Resilience: Predictive analytics, cybersecurity, crisis response systems, digital twins.

Efficiency: Port automation, route optimization, smart contracts, equipment uptime.

Sustainability: Emissions monitoring, energy optimization, green compliance tools.

The dataset of 80 reviewed papers forms the empirical basis for this analysis. A longitudinal examination of publication frequency (see Figure 5) also indicates the increasing maturity of digital innovation in maritime logistics. The period post-2020, especially in response to COVID-19 disruptions, marks a shift from conceptual explorations to empirical validation and case-based analysis.

This chapter not only maps the frequency and distribution of technological themes but also examines the depth and context in which each is discussed. Through this categorization, the study identifies clear patterns, regional disparities, and underrepresented areas—particularly with respect to smaller ports and developing economies. These findings are further synthesized in the discussion chapter, offering strategic insights into how emerging technologies can be scaled for inclusive, global maritime transformation.

Table 2: Systematic Literature Review Table

Document Title	AI	Blockchain	Resilience	IoT	Sustainability	Digitalization	Optimization	Cloud	Maritime Logistics	Supply Chain
A.Shoomal,M. Jahanbakh (2024). Enhancing Supply Chain Resilience and Efficiency through IoT Integration		x	x	x						
E. Surucu-Balci,C. Iris, G. Balci (2024). Digital Information in Maritime Supply Chains with Blockchain and Cloud Platforms		x							x	x
E.Lambourdiere , E. Corbin (2020). Blockchain and Maritime Supply-Chain Performance: Dynamic Capabilities Perspective		x								x
C. Duran, A. Karbassi Yazdi (2024). Leveraging Blockchain for Maritime Port Supply Chain Management		x					x			
R. Khalaf (2025). Companies Seek AI Solutions to Supply Chain Fragility	x	x						x		
J. Liu, J. Wu (2023). Maritime Supply Chain Resilience: From Concept to Practice			x					x		
X. Li, J.Y. Chua (2024). A Review on Maritime Disruption Management: Categories, Impacts, and Strategies			x							

J. Shi, J. Cheng, L. Xu (2023). Improving the Resilience of Maritime Supply Chains: Integration of Ports and Inland Transporters			x				x			x
A.Kelly (2024). The Impact of Artificial Intelligence on Maritime Supply Chain Optimization	x						x			x
Z.K. Indrissi, M. Lachgar (2024). Blockchain, IoT, and AI in Logistics and Transportation: A Systematic Review	x	x		x						x
Z.Raza, J. Woxenius (2023). Digital Transformation of Maritime Logistics: Exploring Trends in Liner Shipping						x			x	x
W. Sheikh, M. Mojahid (2024). A Comprehensive Performance Measurement Model for Maritime Logistics					x				x	x
F.Parola, G. Satta, N. Buratti (2020). Digital Technologies and Business Opportunities for Logistics Centres in Maritime Supply Chains						x			x	x
N.Chu, X. Nie , J. Xu (2021). A Systematic Approach of Lean Supply Chain Management in Shipbuilding										x
R. Yan, D. Yang, T. Wang (2024). Improving Ship Energy Efficiency: Models, Methods, and Applications					x		x			
J. Chen, X. Zhang, L. Xu (2024). Trends of Digitalization, Intelligence, and Greening of Global Shipping					x	x				
A. Sardar, R. Islam, M. Anantharaman (2025). Advancements and Obstacles					x		x			

in Improving the Energy Efficiency of Ships										
Z. Wang, L. Gao, W. Wang (2025). The Impact of Supply Chain Digitization and Logistics Efficiency on Industrial Competitiveness						x				x
M.A Kashem, M. Shamsuddoha, T. Nasir (2024). Navigating Logistics and Supply Chain Operations after COVID-19			x			x		x		
G.S. Balan, S. Kumar, S.A Raj (2025). Machine Learning and AI Methods for Supply Chain Resilience	x		x							
B.S Dura (2025). The Role of Technology in Developing Resilient Supply Chains			x			x		x		x
P. Liddell (2024). How AI, Blockchain, and Emerging Technologies Are Transforming Supply Chains	x	x								
A. Harju (2025). Building Supply Chain Resilience in an Age of Uncertainty			x			x				x
S. Hickey (2024). The Future of Supply Chain: Emerging Technologies You Need to Know	x	x		x						
M. Hazratifard (2024). How Digitalization Is Revolutionizing Maritime Supply Chain Resilience			x			x				
D. Li, B. Zhi, T. Schoenherr (2023). Developing Capabilities for Supply Chain Resilience in a Post-COVID World			x					x		
S. Mogdil, R. Kumar Singh (2021). Artificial Intelligence for Supply Chain Resilience: Learning from COVID-19	x		x					x		



M Ben Farah, Y. Ahmed, H. Mahmoud, S.A Shah(2024). Blockchain in Maritime Logistics: A Survey		x							x	x
R. Pannell, J.M Munoz (2024). Utilizing AI for Maritime Route Optimization	x						x			
A.R Rao, H. Wang, C. Gupta (2025). Predictive Analytics for Port Operations	x						x			
H.Chan (2023). How Resilient Ports Mitigate Disruptions			x							x
M.P Dąbrowski, B. Pawłowski (2024). Key Innovations in Maritime Supply Chains				x						x
S. Holloway (2025). Emerging Tech for Supply Chain Sustainability										
K.Chu (2023). Data Collaboration for Maritime Resilience			x						x	x
G. Papageorgiou (2024). Digital Transformation in Shipping Tech						x			x	x
A.S Matthews (2023). Maritime Logistics Innovations		x							x	x
R.M Ellahi, L.C Wood, A. Bekhit (2024) . Blockchain for Fresh Food Logistics		x								x
P. Darpan (2024). AI-Powered Maritime Automation: The Future of Smart Shipping	x	x								
T. Diamante (2025) . Blockchain in Shipping: Revolutionizing Global Supply Chains	x	x								
P. Mahadevan, S. Saurabh, Choudhuri, Dr Sundara (2024). Blockchain and AI for engineering supply chain	x	x								x

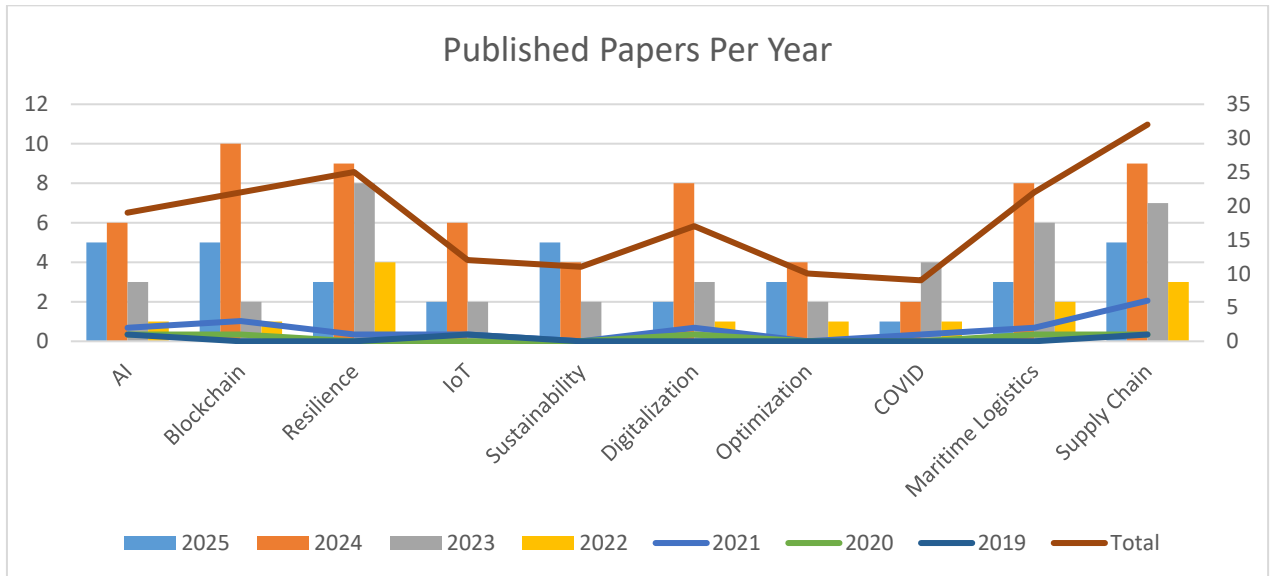
D.Stepec, T. Martincic, F. Klein (2020). Machine Learning for Vessel ETA	x								x	
C. Martin (2024). Smart Contracts for Freight Payments		x								x
M. Hand (2024). Digital Twins in Port Management				x						
A. Marchand, J. Sotelo (2025). AI for Customs Clearance	x									x
M. Petkovic, V. Mihanovic, I. Vujovic (2019). Blockchain of autonomous maritime transport		x								
H. Yu, Y. Deng, L. Zhang, X. Xiao (2022). Yard Operations and Management in Automated Container Terminals: A Review									x	x
C. Worley (2024). Navigating AI and Digital Transformation in Chartering	x								x	
L. Metelli, M. Mancini, R. Gerinovic, V. Gunella (2022). Global supply chains rattled by winds of war			x							x
WHO Team (2020). Minimizing health risks at airports, ports and ground crossings			x					x		
M. C.P. Poo, Z. Yang (2022). Optimising the resilience of shipping networks to climate vulnerability			x						x	
M. Suominen, S. Einarsson, J.C Blomhoff (2024). Cybersecurity moves up the maritime agenda		x				x				
J. Basquill (2024). Emerging threats: Sanctions roundtable										x
S. Gilmore (2024). Port Strike: What It Means for the U.S. Economy			x						x	

P.M. Johnson, C. Wehbe, H. Baroud (2025). Flood-Resilient Port Infrastructure			x		x					
J.H. Yang, Y. Chang, S.C. Hsiao (2024). Resolving conflicts by regional marine spatial planning							x		x	
S. Kumar Paul, Md. A. Moktadir, K. Ahsan (2021). Key supply chain strategies for the post-COVID-19 era								x		x
IMO Team (2024). IMO's work to cut GHG emissions from ships					x				x	
S. Chai, W. Huo, Q. Li, Q. Ji, X. Shi (2025). Effects of carbon tax on energy transition					x		x			
I. Ilin, C. Jahn, J. Weigell, S. Kalyazina (2019). Port Smart City Integration				x		x				
A. Pohontu (2021). AI Methods Developed for Maritime Awareness Systems	x								x	
Offshore Energy Team (2024). Green Corridor Implementation					x				x	
IoT Insider News Desk (2024). Maritime 5G Networks				x		x				
A. Kovalenko, M. Coote (2025). Future of Polar Shipping : IMO - Norway Maritime Seminar			x						x	
R. Meade (2021). Shipping's transparency revolution		x				x				
D. Tamunodukobipi, A.J. Chuki (2023). Maritime Engineering in Sustainable Blue Economy Development in Nigeria					x				x	
C.R.Hopkins, S.I Roberts, A.J. Caveen, C. Graham, N.M. Burns (2024). Improved traceability in seafood supply chains		x								x

N. Allem (2025). Navigating 2025's Geopolitical Supply Chain Landscape			x							x
K. Bulkowska, M. Zielinka, M. Bulkowski (2023). Blockchain Technology in Waste Management		x			x					
A. Shoomal, M. Jahanbakht, P.J Componation, D. Ozay (2024). Enhancing Supply Chain Resilience and Efficiency through Internet of Things Integration			x	x						x
A. Iftikhar, I. Ali, A. Arslan, S. Tarba (2022). Digital Innovation, Data Analytics, and Supply Chain Resiliency: A Bibliometric-based Systematic Literature Review	x					x				x
F. Zeng, A. Chen, S. Xu, H.K. Chan Y. Li (2025). Digitalization in the Maritime Logistics Industry: A Systematic Literature Review of Enablers and Barriers						x			x	
T.T. Nguyen, D.T.M Tran, T.T.H. Duc, V.V Thai (2021). Managing disruptions in the maritime industry – a systematic literature review			x						x	
J. Ding, E.S. Lee (2024). Improving the maritime supply chain resilience: the role of firms' dynamic knowledge management and organizational innovation			x							x
M.G.C.A. Cimino, N. Celandroin, E. Ferro, D. La Rosa, F. Palumbo (2019). Wireless communication, identification and sensing technologies enabling				x			x			

integrated logistics: a study in the harbor environment										
P. Radanliev, D. De Roure, K. Page, J.R.C Nurse, O. Santos (2020). Cyber Risk at the Edge: Current and future trends on, Cyber Risk Analytics and Artificial Intelligence in the Supply Chains	x	x								
G. Xiao, Y. Wang, R. Wu, J. Li, Z. Cai (2024). Sustainable Maritime Transport: A Review of Intelligent Shipping Technology and Green Port Construction Applications	x			x	x					
T.Y. Pham (2023). A smart port development: Systematic literature and bibliometric Systematic Literature Review				x		x				
J. Liu, H. Zhang, L. Zhen (2021). Blockchain technology in maritime supply chains: applications, architecture and challenges		x								x
J.Y. Chua, R. Foo, K.H. Tan, Kum Fai Yuen (2022). Maritime resilience during the COVID-19 pandemic: impacts and solutions			x					x	x	
X. He, W. Hu, W. Li, R. Hu (2023). Digital Transformation, Technological Innovation, and Operational Resilience of Port Firms in Case of Supply Chain Disruption			x	x		x				

Table 3: Published Papers Per Year Table



## 8. Discussion of Adoption Barriers and Strategic Implications

The rapid advancement of digital technologies in maritime logistics presents both opportunity and complexity. While tools like AI, Blockchain, and IoT have shown considerable potential to address challenges of inefficiency, emissions, and operational risk, their implementation is far from uniform or universally beneficial. This section reflects on the findings of the literature review to highlight three key issues: (1) trade-offs and interdependencies among technologies, (2) regional disparities and policy misalignments, and (3) the significant challenges faced by small- and medium-sized enterprises (SMEs) and developing nations in adopting such innovations.

### 8.1 Trade-offs and Interdependencies

The integration of AI, Blockchain, and IoT is often presented as a strategic imperative for future-ready maritime supply chains. However, the deployment of these technologies is not without trade-offs, both technical and managerial. Although their benefits—faster processing, data-driven decisions, real-time monitoring—are well-established, implementing them simultaneously involves navigating complex interdependencies, data integration issues, and governance challenges.

AI systems, for example, require vast datasets to function effectively. These datasets are often supplied through IoT infrastructure, which captures operational metrics in real-time. However, if IoT networks are unreliable or fragmented—as is common in many ports—AI insights become skewed or delayed. Similarly, Blockchain's promise of tamper-proof transparency relies on trusted, secure inputs, much of which again comes from IoT devices. If sensors are compromised, the data stored immutably in a Blockchain system may be inaccurate, creating false confidence in flawed information.

Another significant trade-off relates to data privacy versus interoperability. Many stakeholders in maritime logistics, such as freight forwarders, port operators, customs bodies, and shipping lines, are reluctant to share real-time operational data due to commercial sensitivity or national security concerns. Yet the value of Blockchain and AI

increases exponentially when data silos are broken down. This tension is particularly evident in cross-border logistics, where inconsistent data governance laws further hinder open data exchange.

Moreover, the cost-performance trade-off is evident in the choice of Blockchain platforms. While private, permissioned blockchains offer better control and faster transactions, they may not provide the decentralized trust that public blockchains are designed for. Conversely, public blockchain systems face scalability and energy efficiency issues—particularly if based on Proof-of-Work mechanisms. This forces stakeholders to choose between efficiency and decentralization, with no perfect solution yet available. Lastly, technology integration often comes with the trade-off of labor displacement. Port automation, predictive maintenance, and AI-assisted yard planning reduce the need for manual roles. While this leads to efficiency gains, it can cause social pushback, require expensive workforce upskilling, or trigger union opposition—all of which can delay or derail adoption.

## 8.2 Regional Disparities and Policy Issues

A critical insight from the SLR is the high concentration of successful digital implementations in a few geographic clusters, notably Northern Europe (e.g., Rotterdam, Hamburg), East Asia (e.g., Singapore, Busan), and parts of the United States (e.g., Los Angeles, Oakland). These ports benefit from significant state investment, high digital literacy, and mature regulatory frameworks. In contrast, many ports in South America, Sub-Saharan Africa, Southeast Asia, and even parts of the Mediterranean operate with limited infrastructure, outdated systems, and ambiguous digital policies.

This uneven digital landscape creates serious disparities in supply chain visibility, reliability, and competitiveness. For example, while ports like Singapore operate fully integrated smart terminals using AI and IoT, many African ports still rely on manual customs clearance, paper-based cargo records, and unconnected container tracking. These limitations lead to longer dwell times, higher risks of corruption, and lower throughput, making them less attractive in global trade corridors.

Policy is a significant driver of these regional gaps. In digitally advanced economies, governments have actively supported maritime technology upgrades through:

- National digitalization strategies
- Public-private partnerships
- Incentives for data sharing and cybersecurity compliance

By contrast, in many developing economies, maritime policy is either outdated or non-existent. There's often no unified vision for port digitalization, and infrastructure investments are prioritized elsewhere. In some countries, even where funding is available, procurement policies favor low-cost bids over high-tech solutions, leading to mismatches between port needs and technology capabilities.

In addition, inconsistent international regulations slow cross-border technology integration. For instance, while the European Union has moved toward harmonizing digital documentation through the eFTI (electronic freight transport information)

regulation, many non-EU countries still require paper-based compliance. This regulatory asymmetry undermines the seamless flow of digital data across borders, especially for Blockchain-based document sharing systems.

The lack of cyber-resilience policy is also a concern. Ports are increasingly targets of ransomware and cyberattacks, as seen in the 2020 attack on the Port of Shahid Rajaei in Iran or the 2017 Maersk-NotPetya incident. Yet most developing countries lack clear cybersecurity frameworks, digital emergency protocols, or insurance regulations that are aligned with the realities of digital supply chains.

### 8.3 Gaps in Adoption: SMEs and Developing Nations

Beyond geographic divides, one of the most overlooked issues in maritime digitalization is the limited adoption by small- and medium-sized enterprises (SMEs), both in shipping operations and port services. These actors form a crucial part of the logistics ecosystem, especially in emerging markets and coastal regions. Yet, they face financial, human capital, and knowledge barriers that make the adoption of AI, Blockchain, or IoT impractical without significant external support.

From a financial perspective, SMEs typically lack the capital to invest in sensor networks, cloud platforms, or AI model training. Enterprise-grade solutions are often priced and designed for large logistics players, leaving smaller actors reliant on outdated systems. Even when open-source tools exist, the cost of integration, customization, and cybersecurity upgrades puts them out of reach.

On the human capital front, many SMEs do not employ dedicated IT staff, let alone data scientists or AI engineers. This creates a significant skills mismatch, which is compounded by the lack of regional training programs or government-sponsored digital transformation initiatives tailored to SMEs. As a result, these firms often become dependent on legacy systems or are locked out of platform-based logistics ecosystems. The knowledge gap is also significant. Many SMEs are unaware of the potential benefits of digital technologies or view them as risky and unproven. In addition, trust issues emerge when adopting Blockchain or AI, especially when the inner workings of these systems are opaque. This disparity poses significant challenges, as evidenced by developing nations where digital literacy is generally lower, and where language and regulatory barriers further obstruct access to technological tools.

A further complication is the absence of scalable pilot programs or sandbox environments for smaller ports and SMEs to experiment with digital tools without disrupting their operations. Most pilot programs today are led by Tier 1 ports or multinational carriers, reinforcing the digital divide and slowing diffusion of innovation to less developed parts of the industry.

To overcome these gaps, multi-level interventions are needed. These could include:

- International funding for modular, affordable tech packages aimed at smaller actors
- Regional centers of excellence for training and knowledge dissemination



- Donor- or NGO-backed pilot programs that support digital trials in developing economies
- Policy alignment that encourages interoperable standards across supply chain tiers

## 9. Conclusion

This thesis set out to examine the transformative potential of emerging digital technologies—Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT)—in enhancing the performance of maritime supply chains. Through a comprehensive Systematic Literature Review (SLR) encompassing 80 academic and industry sources from 2019 to 2025, the study aimed to address the interconnected goals of resilience, efficiency, and sustainability, while exploring the barriers and disparities that influence technology adoption across different global regions.

The findings illustrate that AI, Blockchain, and IoT are no longer speculative tools of the future, but are actively reshaping the operational, environmental, and strategic landscape of maritime logistics. AI has demonstrated powerful applications in predictive routing, maintenance, and berth scheduling. Blockchain offers unprecedented transparency, security, and efficiency in document flows and cargo traceability. IoT provides the foundational visibility required for real-time decision-making and regulatory compliance, particularly in emissions monitoring and asset tracking. When deployed together, these technologies offer a path toward smart, adaptive, and responsive supply chain systems capable of navigating both everyday complexities and black swan disruptions.

One of the key conclusions of this research is that the real value of these technologies lies not in their individual capabilities but in their integration. As the literature shows, combining AI with IoT data inputs, and securing those insights with Blockchain verification, results in a layered and interdependent digital ecosystem. This integration is essential for creating fully autonomous workflows, enhancing end-to-end visibility, and reducing transaction times across multiple stakeholders. Ports that successfully leverage this triad of technologies are more likely to gain competitive advantages in throughput, sustainability compliance, and service reliability.

However, this transformation is not without its challenges. A persistent theme across the reviewed literature is the existence of structural and contextual barriers to technology adoption. These include capital costs, lack of standardization, data privacy concerns, limited digital infrastructure, and cybersecurity risks. Particularly concerning is the divide between Tier 1 global ports—such as Singapore, Rotterdam, and Shanghai—and small-to-medium ports in developing nations. The latter often lack both the technical expertise and institutional support needed to deploy digital systems at scale. This contributes to an

uneven digital landscape that exacerbates existing trade inequalities and limits the global diffusion of innovation.

Moreover, while numerous papers document technological successes, few engage critically with the trade-offs involved. For example, while AI and automation improve efficiency, they can displace human labor and require significant workforce reskilling. Blockchain enhances trust, but can also raise issues of governance and energy consumption depending on the model used. IoT improves asset visibility but increases the attack surface for cyber threats. These trade-offs must be carefully managed through collaborative policymaking, inclusive training programs, and balanced investment strategies.

Another key insight is the evolution in research focus over time. The literature has shifted from predominantly theoretical work to more empirical, case-based studies, particularly after the onset of the COVID-19 pandemic. This evolution reflects the growing maturity of digital solutions and provides stronger evidence for their tangible benefits. In turn, this reinforces the strategic imperative for ports, shipping companies, and policymakers to treat digital transformation not as an optional upgrade but as a fundamental enabler of long-term resilience and competitiveness.

This thesis also contributes to academic discourse by offering a thematically structured synthesis of digital innovation across resilience, efficiency, and sustainability pillars. Most existing literature is siloed—either focused on a single technology or a narrow performance metric. By contrast, this research connects technological capabilities with broader supply chain objectives, offering a more holistic understanding of their impact. This approach provides a framework for future research to build upon and for practitioners to translate into actionable strategies.

In summary, the integration of AI, Blockchain, and IoT presents a powerful, though unevenly distributed, opportunity to transform maritime logistics. These technologies can reduce emissions, accelerate cargo handling, increase transparency, and mitigate disruption—if implemented wisely, inclusively, and strategically. Realizing their full potential will require not only technological investment but also human capital development, policy alignment, and cross-sector collaboration.

As maritime supply chains become more digitized, their complexity and interdependence will increase. This makes it all the more important to ensure that the transition is not only technologically robust but also equitable, secure, and future-ready. Stakeholders across the ecosystem—from terminal operators to international regulators—must align their efforts to build smarter, greener, and more resilient supply chains that serve the needs of both commerce and society at large.

This conclusion reaffirms the thesis's main takeaway: while AI, Blockchain, and IoT are transforming maritime supply chains by improving speed, reliability, and environmental

performance, their full potential remains unrealized due to high costs, policy gaps, and uneven adoption. The path forward lies in integration—AI for prediction, Blockchain for transparency, IoT for visibility—to build intelligent, adaptive, and globally inclusive logistics networks.

## 10. Comparison with Previous Researches and this 2025 Study

This section offers a comparative analysis between this 2025 study and prior research efforts in the field of maritime digitalization. Numerous studies in the past few years have investigated the integration of technologies such as Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) within maritime logistics and port operations. However, this 2025 thesis distinguishes itself through its contemporary scope, inclusion of post-COVID literature, and focus on digital integration as a path to resilience, efficiency, and sustainability. A very good example of previous research is the thesis completed by Mrs. Kleopatra Kalogeropoulou in 2024, which laid a strong foundation in exploring early technology adoption and conceptual frameworks across the maritime logistics domain.

### 10.1 Similar Objectives and Shared Foundations

Both of the two theses are anchored in the growing importance of digitalization in maritime logistics, with a shared goal of understanding how technologies can improve supply chain performance. Kalogeropoulou's 2024 thesis laid the foundation by identifying the disruptive potential of digital tools and mapping their initial adoption across global ports. Her study successfully highlighted the transition from traditional, analog logistics systems to more connected, automated, and data-driven operations.

Likewise, this 2025 thesis builds on those same thematic pillars: resilience, efficiency, and sustainability. It affirms the critical role of AI in predictive maintenance and scheduling, Blockchain in data integrity and automation, and IoT in real-time visibility and compliance monitoring. Both works agree on the synergetic potential of integrating these technologies rather than applying them in isolation.

### 10.2 Evolving Research Landscape and Methodological Depth

A key differentiator between the two theses is the temporal context and data maturity. Kalogeropoulou's study relied primarily on literature from 2018 to early 2023, a period when most technologies were still in pilot phases. Her literature review was predominantly conceptual, offering theoretical insights, projected benefits, and early case studies.

In contrast, the current 2025 study reflects a post-COVID-19 and post-regulatory surge in maritime digitalization. It integrates more recent literature and draws from a richer pool of empirical studies and implementation reports. For instance, this thesis incorporates

findings on the actual emissions reductions from IoT adoption, AI-led routing efficiencies in ports like Hamburg and Singapore, and Blockchain's use in automating customs clearance.

Furthermore, this thesis applies a more detailed and comparative SLR structure, categorizing 80 sources across three clear thematic lenses. It also includes deeper discussion sections, critique of adoption barriers, regional disparities, and technology interdependencies—elements only briefly covered in the 2024 thesis.

### 10.3 Case Study and Industry Scope

Kalogeropoulou's thesis provides a foundational overview of select digital initiatives, with a focus on large international ports and prominent technology providers. While informative, its coverage is less diversified in terms of geography, and it largely omits the perspectives of SMEs and developing economies.

The current thesis addresses this gap by explicitly examining adoption barriers faced by smaller ports, emerging economies, and under-resourced logistics providers. It explores how capital constraints, limited digital literacy, and policy fragmentation restrict the global diffusion of these technologies. This emphasis offers a more inclusive and globally relevant analysis.

### 10.4 Thematic Refinement and Analytical Depth

Another difference lies in thematic structure and interpretive depth. Kalogeropoulou introduced the broad concepts of digital transformation and connected technologies but did not fully explore trade-offs, integration challenges, or long-term implications.

This thesis, however, presents a nuanced critique of the trade-offs involved in adopting AI, Blockchain, and IoT—highlighting risks such as labor displacement, cybersecurity threats, and ROI uncertainty. It also delves into cross-technology dependencies, such as how IoT data enhances AI models and how Blockchain ensures trust in AI-generated predictions.

Additionally, this thesis tracks temporal trends, noting a shift from conceptual to empirical studies post-2022. It identifies the COVID-19 pandemic as a strategic turning point that validated and accelerated digital infrastructure projects globally—an element that was emerging but not fully visible in the 2024 study.

### 10.5 Policy and Sustainability Perspectives

Kalogeropoulou's work touched on sustainability as an emerging theme, especially in the context of emissions monitoring and port electrification. This thesis significantly expands

on that, connecting technology to Environmental, Social, and Governance (ESG) goals, circular economy practices, and regulatory compliance with IMO and EU directives.

The policy analysis is also more detailed in this thesis, with insights into regional regulatory gaps, cybersecurity legislation, and the importance of international standards for data exchange and Blockchain interoperability. These were less developed or absent in the earlier work.

## 10.6 Overall Contribution and Value Addition

In summary, both of the two theses are academically rigorous and valuable. Kalogeropoulou's 2024 work set a strong precedent by framing the digital transformation landscape and spotlighting key technologies. This 2025 thesis extends that foundation by updating the research base, offering deeper critical analysis, and incorporating recent developments, global case studies, and inclusive perspectives.

Together, the two studies reflect the evolving state of maritime logistics digitalization—moving from aspirational frameworks to operational reality. This comparative section not only honors the groundwork laid by previous research but also highlights the trajectory of growth, refinement, and relevance achieved in the current study.

## 11. Practical Contribution, Limitations, and Future Research Directions

This thesis makes several practical contributions to the fields of maritime logistics, port management, and digital supply chain transformation. By systematically reviewing the implementation of Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) in maritime settings, it offers a multidimensional framework for how these technologies can be leveraged to achieve resilience, efficiency, and sustainability in one of the world's most critical sectors.

### 11.1 Practical Contribution

From a managerial and operational perspective, this research provides a roadmap for decision-makers—port authorities, terminal operators, shipping firms, and logistics coordinators—who seek to integrate digital technologies into their operations. The structured comparison of AI, Blockchain, and IoT applications allows practitioners to identify the best-fit technologies for specific operational objectives. For example, AI is shown to be particularly useful for scheduling, ETA prediction, and predictive maintenance. Blockchain is most effective in documentation, fraud prevention, and smart contract execution, while IoT serves as the connective tissue that enables real-time data collection, emissions monitoring, and asset tracking.

Another practical contribution lies in highlighting the synergistic potential of these technologies when used in combination. Rather than implementing digital tools in

isolation, the research emphasizes the value of integrating IoT sensor data with AI-driven analytics and Blockchain-backed transparency. This tri-layered approach enables seamless, automated decision-making and ensures data reliability and auditability across all stages of the maritime supply chain. Ports and shipping companies that pursue such integration will likely experience improved throughput, lower operating costs, and better compliance with environmental and trade regulations.

The thesis also underscores the importance of context-aware digital strategies. Not all ports and logistics hubs share the same levels of digital maturity, regulatory alignment, or financial capacity. Thus, recommendations are made based on port size, geographic location, and strategic importance. In particular, smaller and medium-sized ports are encouraged to adopt modular, scalable technologies and seek collaborative ventures, such as public-private partnerships, to overcome capital and skills gaps.

For policy-makers, this study provides an evidence-based rationale to support investment in digital infrastructure, workforce training, and cybersecurity readiness. The review highlights how regulatory alignment, cross-border data standards, and incentives for digitalization can enhance adoption rates and improve national and regional supply chain resilience.

### 11.2 Limitations

Despite its contributions, this research is not without limitations. First, the study is based on secondary data sourced from academic literature and industry reports. As such, it does not include primary empirical data from interviews, surveys, or field experiments. This restricts the ability to offer real-time validation or capture stakeholder perceptions in specific ports.

Second, while the SLR covered 80 sources, the majority are focused on leading ports in developed countries. This geographical skew may bias the findings toward contexts where digital technology is more readily adopted and supported by policy infrastructure. Ports in the Global South, small island nations, and conflict-affected regions are underrepresented in the available literature.

Third, the research predominantly analyzes three technologies—AI, Blockchain, and IoT—but does not extensively cover other digital enablers like digital twins, robotics, 5G, or cloud-based maritime platforms. These tools also play an important role in the broader conversation on digital transformation and may warrant further exploration in subsequent studies.

Additionally, the research does not offer a full cost-benefit analysis of digital technology adoption. Although operational benefits are discussed, the financial, environmental, and labor-related trade-offs remain under-explored in quantifiable terms. Future empirical

studies may expand on this by modeling ROI scenarios and environmental impact metrics.

### 11.3 Future Research Directions

The digitalization of maritime supply chains is still a nascent and rapidly evolving field. Based on the insights and gaps identified in this study, several avenues for future research are proposed:

**Empirical Validation through Case Studies:** Future research should involve in-depth case studies of specific ports or shipping lines implementing integrated digital systems. These could provide granular insights into real-world performance, barriers, and stakeholder adaptation.

**Comparative Regional Analysis:** There is a pressing need for cross-regional studies that evaluate digital readiness and adoption outcomes across developed and developing economies. Such research could inform targeted interventions by international trade bodies and financial institutions.

**Policy and Governance Models:** Digitalization requires coordinated regulation, especially when data flows across national borders. Future research could explore models of maritime data governance, including cybersecurity frameworks, ethical AI guidelines, and Blockchain interoperability protocols.

**Technology Ecosystem Integration:** More research is needed on the integration of AI, IoT, and Blockchain with other technologies such as digital twins, robotics, and 5G. Studies can explore how these combinations affect throughput, cost, and emissions, particularly in high-traffic ports.

**Impact on Labor and Human Capital:** A neglected area is the social and workforce impact of maritime digitalization. Future work could assess the reskilling needs, employment shifts, and inclusion challenges that emerge as ports automate.

**Green Innovation Metrics:** The environmental impact of digitalization must be assessed more rigorously. Future research could develop life-cycle analyses and carbon auditing tools to measure the sustainability outcomes of smart port technologies.

**Digital Equity and Inclusion:** Studies should also focus on ensuring digital transformation does not exacerbate inequalities. Research could evaluate how international aid, policy harmonization, and digital education can support small ports and marginalized communities in adapting to a digital maritime economy.

**AI for Development Contexts:**



Future studies should examine how Artificial Intelligence (AI) can be applied specifically in underdeveloped or digitally immature maritime regions. For example, lightweight AI systems could be created for low-connectivity environments to support predictive maintenance and berth scheduling without requiring large-scale infrastructure. Cloud-based “AI-as-a-Service” models can democratize access to advanced analytics for smaller ports, improving safety and operational decision-making while remaining cost-effective.

In addition to operational improvements, AI could help small nations optimize their limited coastal fleets, dynamically assigning vessels to routes based on cargo urgency, weather, and infrastructure availability. This would allow more efficient use of scarce resources and potentially reduce reliance on inefficient manual coordination.

AI could also play a key role in regulatory compliance and environmental reporting, especially in regions where manual inspections are costly, inconsistent, or prone to error. Automated systems trained on localized standards could flag violations or anomalies in emissions, fuel use, or cargo handling, reducing both workload and compliance gaps.

Moreover, research should consider the ethical and governance implications of introducing AI into under-resourced settings. Key concerns include potential algorithmic bias due to limited local training data, over-dependence on external vendors, and the marginalization of local labor. Future work should focus on developing AI solutions that are culturally sensitive, economically viable, and aligned with inclusive development goals.

#### Blockchain for Bureaucracy Reduction:

Blockchain has significant potential to reduce administrative complexity in ports with fragmented or outdated bureaucracies. Research could explore how tamper-proof digital records and smart contracts can streamline customs clearance, minimize corruption, and reduce documentation delays. Such applications are especially relevant in cross-border logistics involving multiple government entities or high compliance risks.

#### Alternative Fuels and Resilience:

The transition to green fuels like ammonia, hydrogen, or biofuels intersects directly with digital transformation. Future research should investigate how voyage optimization algorithms can be customized to fuel-specific performance profiles, helping ship operators balance sustainability with reliability. Digital twins could model fuel system transitions in simulated environments, predicting maintenance intervals and cost-effectiveness.

Additionally, studies could explore how fuel type influences dynamic routing decisions—such as choosing slower or shorter voyages based on emissions profiles, fuel availability, and onboard storage limitations. AI-powered systems may be trained to adjust propulsion strategies in real-time, optimizing speed, energy use, and emissions for each voyage based on the selected alternative fuel.



Digital tools also play a vital role in managing the infrastructure gap associated with alternative fuels. Ports require significant investment to support bunkering and safe handling of new fuel types. Predictive AI models can forecast port readiness and fuel demand trends, enabling stakeholders to plan infrastructure development more strategically and reduce supply chain mismatches.

Moreover, Blockchain technology could support fuel provenance tracking, ensuring transparency in carbon intensity and compliance with green certification programs. This would support ESG transparency and reduce greenwashing risks in shipping decarbonization efforts.

Finally, future studies should also examine multi-fuel optimization models, which help hybrid fleets—those using conventional and green fuels—optimize bunkering strategies and fleet-wide deployment decisions. These models could assist operators in phasing out fossil fuel dependence without sacrificing operational continuity, especially in regions where access to alternative fuels remains limited

**Cybersecurity and Digital Threat Resilience:**

As port systems become increasingly interconnected through AI, IoT, and Blockchain platforms, their exposure to cybersecurity threats intensifies. Ports are no longer solely physical infrastructures—they are becoming highly digitized ecosystems reliant on seamless data flow, real-time analytics, and automated control systems. This convergence creates vulnerabilities to cyberattacks, data breaches, and ransomware incidents that could paralyze critical supply chain functions.

Future research must develop maritime-specific cybersecurity frameworks that address the unique characteristics of port operations. These frameworks could include AI-driven intrusion detection systems capable of learning from abnormal traffic patterns, Blockchain-based tamper-proof event logging for forensic tracking, and zero-trust network architectures to prevent lateral movement across port systems.

There is also a need to investigate how cyber risks affect resilience planning in smart ports. For example, what protocols should be in place if AI scheduling systems are compromised or IoT sensors are spoofed? Studies could evaluate port downtime scenarios caused by cyberattacks and model the cascading effects on global shipping schedules, customs clearances, and trade flows.

Moreover, interoperability and third-party vendor risks should be explored. As more ports rely on outsourced cloud platforms or digital service providers, the security of entire supply chain nodes can hinge on the weakest digital partner. Research could assess strategies for distributed security governance and minimum standards for tech vendors within maritime joint ventures.

The insurance and legal dimensions of cybersecurity in maritime logistics also warrant deeper attention. Future studies should assess how cyber incidents affect marine

insurance claims, liability attribution, and port authority responsibilities under international law. The evolving regulatory environment, including GDPR, IMO cybersecurity guidelines, and national cybersecurity strategies, must be mapped and aligned with port-level risk frameworks.

Finally, cybersecurity research in maritime contexts must extend beyond technical mitigation to human factors: digital literacy, insider threat awareness, and staff training. Ports must not only deploy cybersecurity tools but cultivate a culture of digital risk awareness across all levels of the logistics workforce.

Route Optimization and Software Innovation:

Route optimization software using real-time data—weather forecasts, port congestion, emissions models—can be transformative for maritime efficiency. Research should investigate how these tools integrate with AI prediction models and port scheduling systems to dynamically adapt to changing conditions. The potential to reduce idle time, fuel consumption, and port bottlenecks makes this an area of growing strategic value.

Future studies should focus on how multi-variable optimization engines can synthesize diverse datasets—such as sea state, vessel load distribution, bunker fuel availability, and environmental regulations—to generate optimal voyage routes in real-time. These systems could be integrated with Electronic Nautical Charts (ENCs) and dynamic port slot reservation systems to ensure just-in-time arrivals and minimize anchorage delays.

Moreover, route optimization tools can be further enhanced through machine learning techniques, enabling them to learn from past voyages and continuously improve routing accuracy and fuel predictions. Algorithms can also be trained to prioritize sustainability goals, such as minimizing emissions within Emission Control Areas (ECAs) or avoiding ecologically sensitive routes.

Research may also explore the use of collaborative routing platforms, where shipping lines share anonymized navigational data to co-optimize fleet movements and reduce port congestion collectively. Such systems, if governed securely, could promote industry-wide efficiency gains and lower overall carbon intensity.

Another important direction is the development of route optimization for small-scale and short-sea shipping, which often lacks access to advanced digital tools. Future work could identify how simplified, cloud-accessible software platforms can democratize routing optimization, making efficiency gains accessible to coastal vessels, ferries, and smaller logistics firms.

Lastly, the human-machine interface remains a critical area. Research should explore how ship captains and operations managers interact with these tools in practice—what levels of automation are trusted, how alerts are acted upon, and where manual overrides are needed. Ensuring that digital recommendations are both transparent and interpretable will be key to adoption.

In conclusion, this thesis offers a structured, multi-thematic assessment of how AI, Blockchain, and IoT can be applied to build smarter and more resilient maritime supply chains. Its practical relevance lies in its applicability to varied port environments and stakeholder needs. Moving forward, it is essential that both researchers and practitioners adopt an interdisciplinary, collaborative, and globally inclusive approach to maritime digitalization—ensuring that the gains of innovation are shared broadly and equitably.

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### 13. Appendixes

#### Appendix A: SLR Excel Table

Table 2: Systematic Literature Review Table

Document Title	AI	Blo ckc	Re sili	Io T	Sust aina	Digi taliz	Opt imiz	C O	Mari time	Su ppl

		hai n	en ce		bilit y	atio n	atio n	VI D	Logi stics	y Ch ain
A.Shoomal,M. Jahanbakh (2024). Enhancing Supply Chain Resilience and Efficiency through IoT Integration		x	x	x						
E. Surucu-Balci,C. Iris, G. Balci (2024). Digital Information in Maritime Supply Chains with Blockchain and Cloud Platforms		x							x	x
E.Lambourdiere , E. Corbin (2020). Blockchain and Maritime Supply-Chain Performance: Dynamic Capabilities Perspective		x								x
C. Duran, A. Karbassi Yazdi (2024). Leveraging Blockchain for Maritime Port Supply Chain Management		x					x			
R. Khalaf (2025). Companies Seek AI Solutions to Supply Chain Fragility	x	x						x		
J. Liu, J. Wu (2023). Maritime Supply Chain Resilience: From Concept to Practice			x					x		
X. Li, J.Y. Chua (2024). A Review on Maritime Disruption Management: Categories, Impacts, and Strategies			x							
J. Shi, J. Cheng, L. Xu (2023). Improving the Resilience of Maritime Supply Chains: Integration of Ports and Inland Transporters			x				x			x
A.Kelly (2024). The Impact of Artificial Intelligence on Maritime Supply Chain Optimization	x						x			x

Z.K. Indrissi, M. Lachgar (2024). Blockchain, IoT, and AI in Logistics and Transportation: A Systematic Review	x	x		x						x
Z.Raza, J. Woxenius (2023). Digital Transformation of Maritime Logistics: Exploring Trends in Liner Shipping						x			x	x
W. Sheikh, M. Mojahid (2024). A Comprehensive Performance Measurement Model for Maritime Logistics					x				x	x
F.Parola, G. Satta, N. Buratti (2020). Digital Technologies and Business Opportunities for Logistics Centres in Maritime Supply Chains						x			x	x
N.Chu, X. Nie , J. Xu (2021). A Systematic Approach of Lean Supply Chain Management in Shipbuilding										x
R. Yan, D. Yang, T. Wang (2024). Improving Ship Energy Efficiency: Models, Methods, and Applications					x		x			
J. Chen, X. Zhang, L. Xu (2024). Trends of Digitalization, Intelligence, and Greening of Global Shipping					x	x				
A. Sardar, R. Islam, M. Anantharaman (2025). Advancements and Obstacles in Improving the Energy Efficiency of Ships					x		x			
Z. Wang, L. Gao, W. Wang (2025). The Impact of Supply Chain Digitization and Logistics Efficiency on Industrial Competitiveness						x				x
M.A Kashem, M. Shamsuddoha, T. Nasir (2024). Navigating Logistics			x			x		x		

and Supply Chain Operations after COVID-19										
G.S. Balan, S. Kumar, S.A Raj (2025). Machine Learning and AI Methods for Supply Chain Resilience	x		x							
B.S Dura (2025). The Role of Technology in Developing Resilient Supply Chains			x			x		x		x
P. Liddell (2024). How AI, Blockchain, and Emerging Technologies Are Transforming Supply Chains	x	x								
A. Harju (2025). Building Supply Chain Resilience in an Age of Uncertainty			x			x				x
S. Hickey (2024). The Future of Supply Chain: Emerging Technologies You Need to Know	x	x		x						
M. Hazratifard (2024). How Digitalization Is Revolutionizing Maritime Supply Chain Resilience			x			x				
D. Li, B. Zhi, T. Schoenherr (2023). Developing Capabilities for Supply Chain Resilience in a Post-COVID World			x					x		
S. Mogdil, R. Kumar Singh (2021). Artificial Intelligence for Supply Chain Resilience: Learning from COVID-19	x		x					x		
M Ben Farah, Y. Ahmed, H. Mahmoud, S.A Shah(2024). Blockchain in Maritime Logistics: A Survey		x							x	x
R. Pannell, J.M Munoz (2024). Utilizing AI for Maritime Route Optimization	x						x			
A.R Rao, H. Wang, C. Gupta (2025). Predictive Analytics for Port Operations	x						x			

H.Chan (2023). How Resilient Ports Mitigate Disruptions			x							x
M.P Dąbrowski, B. Pawłowski (2024). Key Innovations in Maritime Supply Chains				x						x
S. Holloway (2025). Emerging Tech for Supply Chain Sustainability										
K.Chu (2023). Data Collaboration for Maritime Resilience			x						x	x
G. Papageorgiou (2024). Digital Transformation in Shipping Tech						x			x	x
A.S Matthews (2023). Maritime Logistics Innovations		x							x	x
R.M Ellahi, L.C Wood, A. Bekhit (2024) . Blockchain for Fresh Food Logistics		x								x
P. Darpan (2024). AI-Powered Maritime Automation: The Future of Smart Shipping	x	x								
T. Diamante (2025) . Blockchain in Shipping: Revolutionizing Global Supply Chains	x	x								
P. Mahadevan, S. Saurabh, Choudhuri, Dr Sundara (2024). Blockchain and AI for engineering supply chain	x	x								x
D.Stepec, T. Martincic, F. Klein (2020). Machine Learning for Vessel ETA	x								x	
C. Martin (2024). Smart Contracts for Freight Payments		x								x
M. Hand (2024). Digital Twins in Port Management				x						
A. Marchand, J. Sotelo (2025). AI for Customs Clearance	x									x
M. Petkovic, V. Mihanovic, I. Vujovic (2019). Blockchain of		x								

autonomous maritime transport										
H. Yu, Y. Deng, L. Zhang, X. Xiao (2022). Yard Operations and Management in Automated Container Terminals: A Review									x	x
C. Worley (2024). Navigating AI and Digital Transformation in Chartering	x								x	
L. Metelli, M. Mancini, R. Gerinovic, V. Gunella (2022). Global supply chains rattled by winds of war			x							x
WHO Team (2020). Minimizing health risks at airports, ports and ground crossings			x					x		
M. C.P. Poo, Z. Yang (2022). Optimising the resilience of shipping networks to climate vulnerability			x						x	
M. Suominen, S. Einarsson, J.C Blomhoff (2024). Cybersecurity moves up the maritime agenda		x				x				
J. Basquill (2024). Emerging threats: Sanctions roundtable										x
S. Gilmore (2024). Port Strike: What It Means for the U.S. Economy			x						x	
P.M. Johnson, C. Wehbe, H. Baroud (2025). Flood-Resilient Port Infrastructure			x		x					
J.H. Yang, Y. Chang, S.C. Hsiao (2024). Resolving conflicts by regional marine spatial planning							x		x	
S. Kumar Paul, Md. A. Moktadir, K. Ahsan (2021). Key supply chain strategies for the post-COVID-19 era								x		x

IMO Team (2024). IMO's work to cut GHG emissions from ships					x				x	
S. Chai, W. Huo, Q. Li, Q. Ji, X. Shi (2025). Effects of carbon tax on energy transition					x		x			
I. Ilin, C. Jahn, J. Weigell, S. Kalyazina (2019). Port Smart City Integration				x		x				
A. Pohontu (2021). AI Methods Developed for Maritime Awareness Systems	x								x	
Offshore Energy Team (2024). Green Corridor Implementation					x				x	
IoT Insider News Desk (2024). Maritime 5G Networks				x		x				
A. Kovalenko, M. Coote (2025). Future of Polar Shipping : IMO - Norway Maritime Seminar			x						x	
R. Meade (2021). Shipping's transparency revolution		x				x				
D. Tamunodukobipi, A.J. Chuki (2023). Maritime Engineering in Sustainable Blue Economy Development in Nigeria					x				x	
C.R.Hopkins, S.I Roberts, A.J. Caveen, C. Graham, N.M. Burns (2024). Improved traceability in seafood supply chains		x								x
N. Allem (2025). Navigating 2025's Geopolitical Supply Chain Landscape			x							x
K. Bulkowska, M. Zielinka, M. Bulkowski (2023). Blockchain Technology in Waste Management		x			x					
A. Shoomal, M. Jahanbakht, P.J Componation, D. Ozay (2024). Enhancing Supply Chain Resilience and			x	x						x



Efficiency through Internet of Things Integration										
A. Iftikhar, I. Ali, A. Arslan, S. Tarba (2022). Digital Innovation, Data Analytics, and Supply Chain Resiliency: A Bibliometric-based Systematic Literature Review	x					x				x
F. Zeng, A. Chen, S. Xu, H.K. Chan Y. Li (2025). Digitalization in the Maritime Logistics Industry: A Systematic Literature Review of Enablers and Barriers						x			x	
T.T. Nguyen, D.T.M Tran, T.T.H. Duc, V.V Thai (2021). Managing disruptions in the maritime industry – a systematic literature review			x						x	
J. Ding, E.S. Lee (2024). Improving the maritime supply chain resilience: the role of firms' dynamic knowledge management and organizational innovation			x							x
M.G.C.A. Cimino, N. Celandroin, E. Ferro, D. La Rosa, F. Palumbo (2019). Wireless communication, identification and sensing technologies enabling integrated logistics: a study in the harbor environment				x			x			
P. Radanliev, D. De Roure, K. Page, J.R.C Nurse, O. Santos (2020). Cyber Risk at the Edge: Current and future trends on, Cyber Risk Analytics and Artificial Intelligence in the Supply Chains	x	x								
G. Xiao, Y. Wang, R. Wu, J. Li, Z. Cai (2024). Sustainable	x			x	x					

Maritime Transport: A Review of Intelligent Shipping Technology and Green Port Construction Applications										
T.Y. Pham (2023). A smart port development: Systematic literature and bibliometric Systematic Literature Review				x		x				
J. Liu, H. Zhang, L. Zhen (2021). Blockchain technology in maritime supply chains: applications, architecture and challenges		x								x
J.Y. Chua, R. Foo, K.H. Tan, Kum Fai Yuen (2022). Maritime resilience during the COVID-19 pandemic: impacts and solutions			x					x	x	
X. He, W. Hu, W. Li, R. Hu (2023). Digital Transformation, Technological Innovation, and Operational Resilience of Port Firms in Case of Supply Chain Disruption			x	x		x				

#### Appendix B: Summary for Keywords – Per Year

Table 4: Keywords Per Year

Year	AI	Block chain	Resilience	IoT	Sustainability	Digitalization	Optimization	COVID	Maritime Logistics	Supply Chain
2025	5	5	3	2	5	2	3	1	3	5
2024	6	10	9	6	4	8	4	2	8	9
2023	3	2	8	2	2	3	2	4	6	7
2022	1	1	4	0	0	1	1	1	2	3
2021	2	3	1	1	0	2	0	1	2	6

2020	1	1	0	0	0	1	0	0	1	1
2019	1	0	0	1	0	0	0	0	0	1
Total	19	22	25	12	11	17	10	9	22	32

#### Key Observations

1. AI peaks in 2024 (6 papers), driven by post-COVID-19 automation demand (e.g., "AI-Powered Maritime Automation", "Predictive Analytics for Port Operations").
2. Blockchain surges in 2024 (10 papers), focusing on transparency ("Blockchain for Fresh Food Logistics") and sanctions compliance ("Emerging Threats: Sanctions Roundtable").
3. Resilience is dominant in 2023–2024 (17 papers), linked to COVID recovery (\*"Maritime Resilience During COVID-19"\*) and geopolitical risks ("Navigating 2025's Geopolitical Supply Chain Landscape").
4. Sustainability grows in 2023–2025 (11 papers), aligned with IMO 2025 regulations ("Green Corridor Implementation", "Effects of Carbon Tax").
5. Supply Chain is the most frequent keyword (32 total), reflecting the thesis's core focus.

#### Appendix C: Charts of Publications Per Keyword

Table 5.1: AI

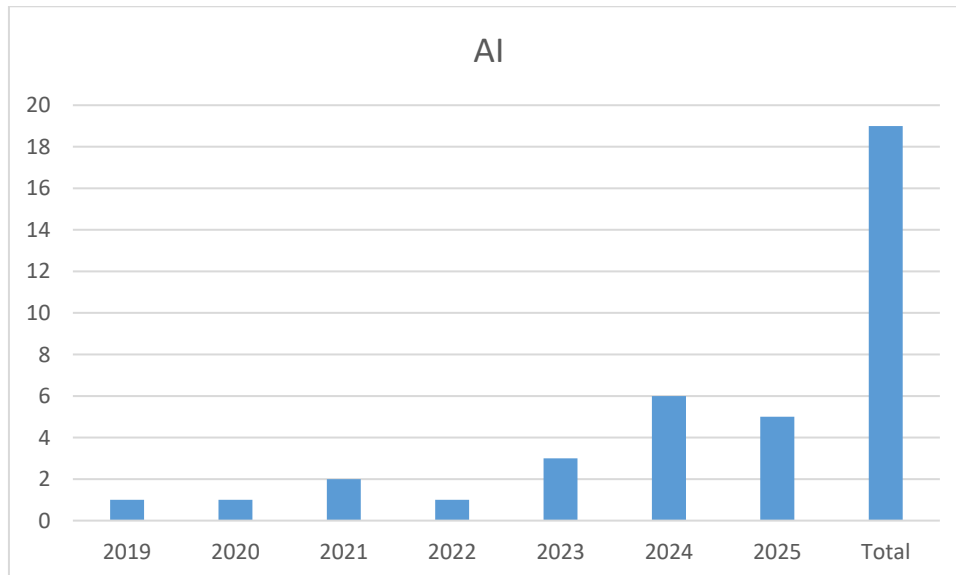


Table 5.2:

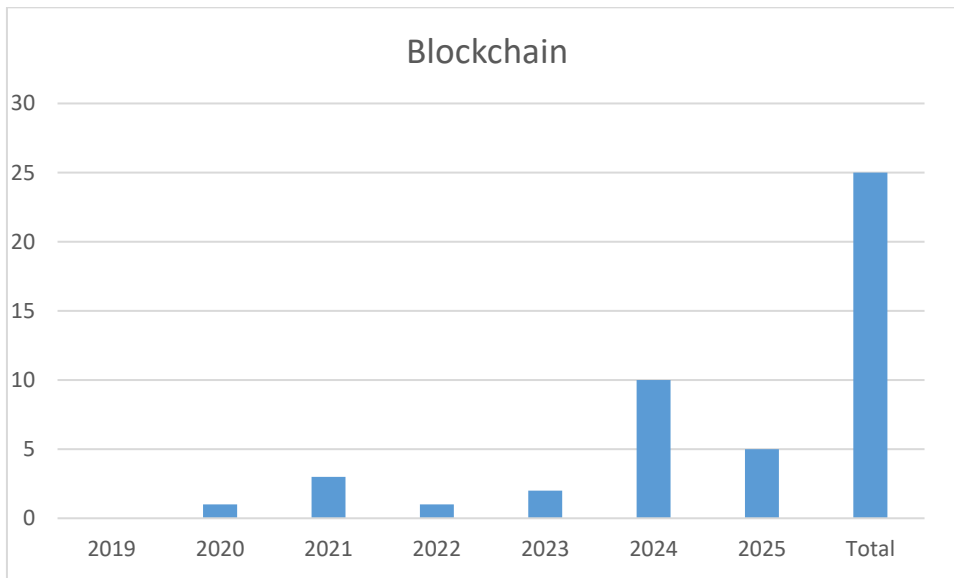


Table 5.3:

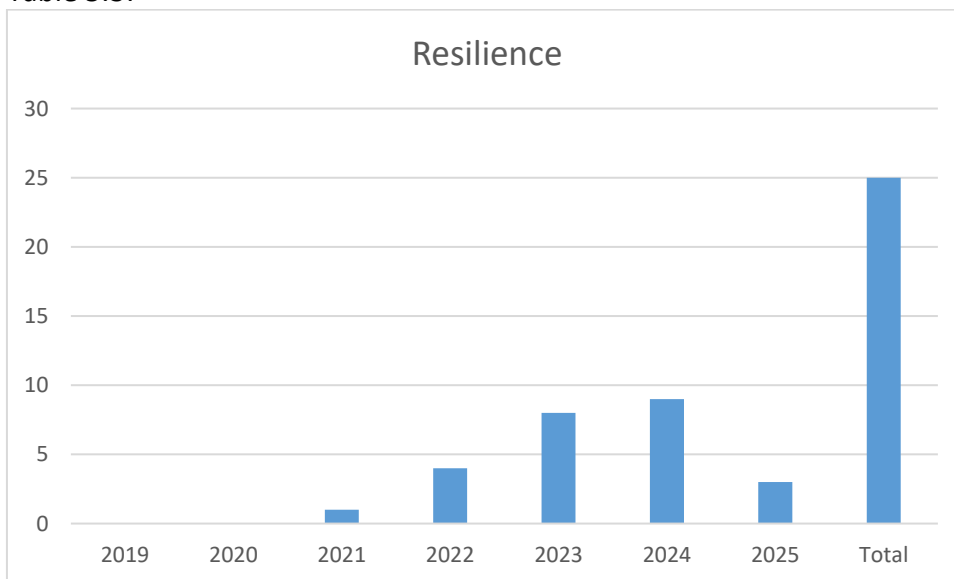


Table 5.4:

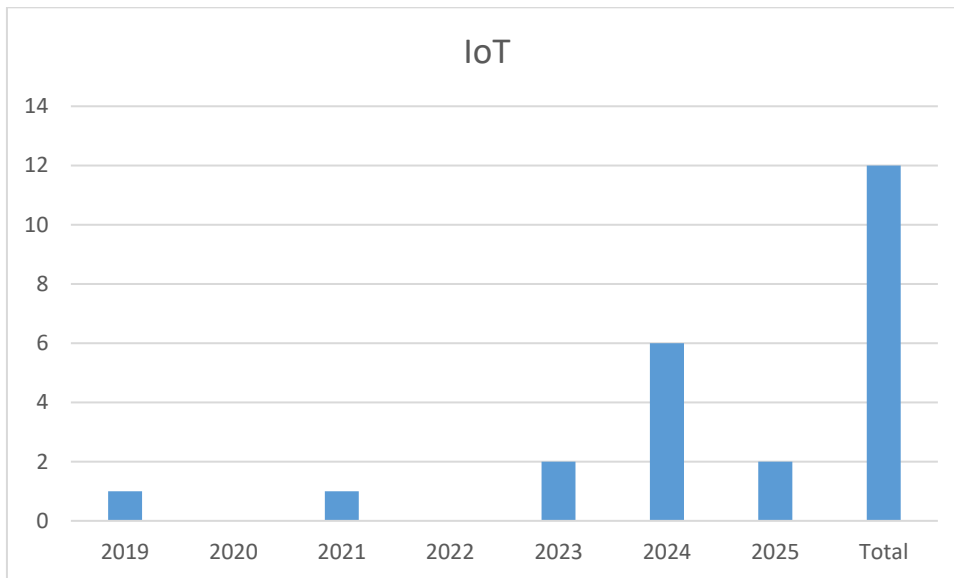


Table 5.5:

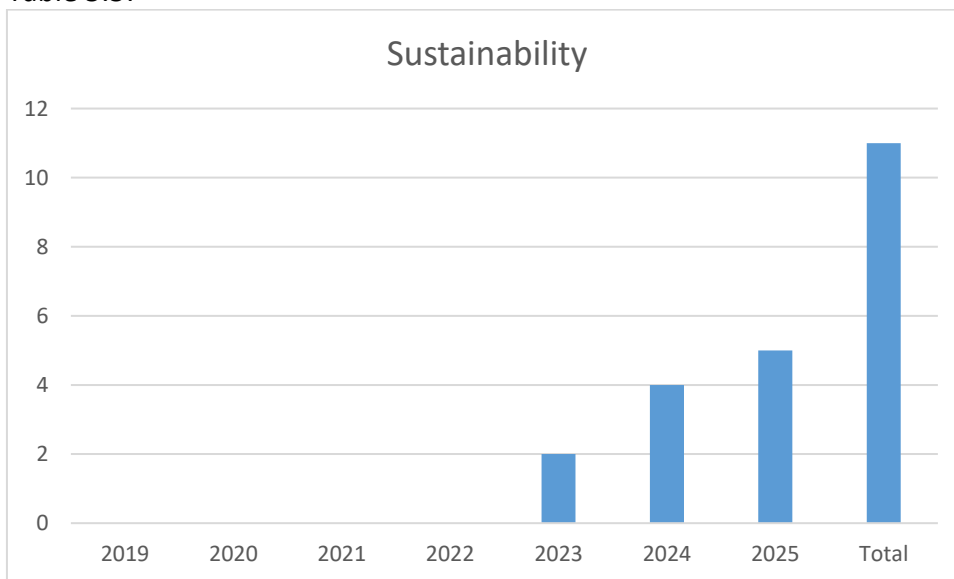


Table 5.6:

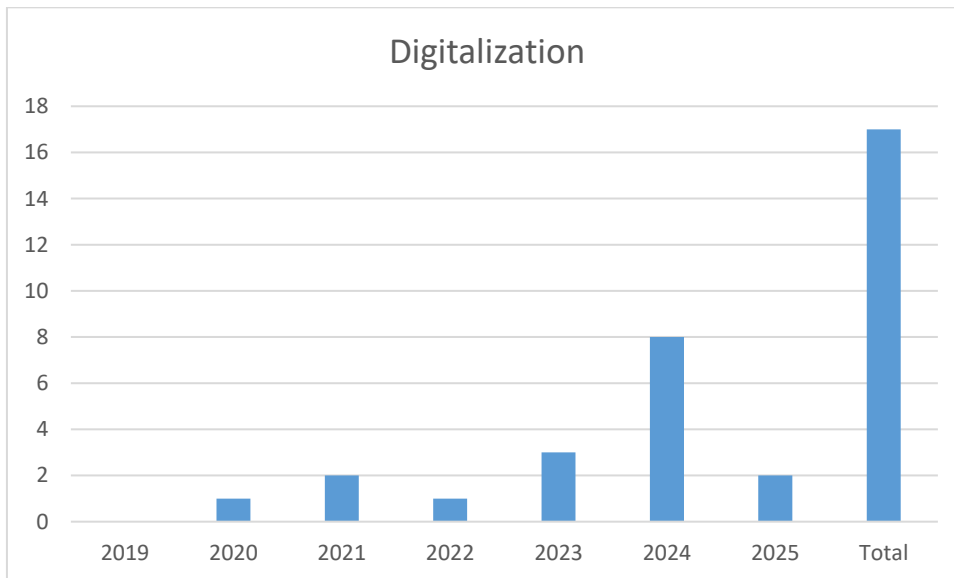


Table 5.7:

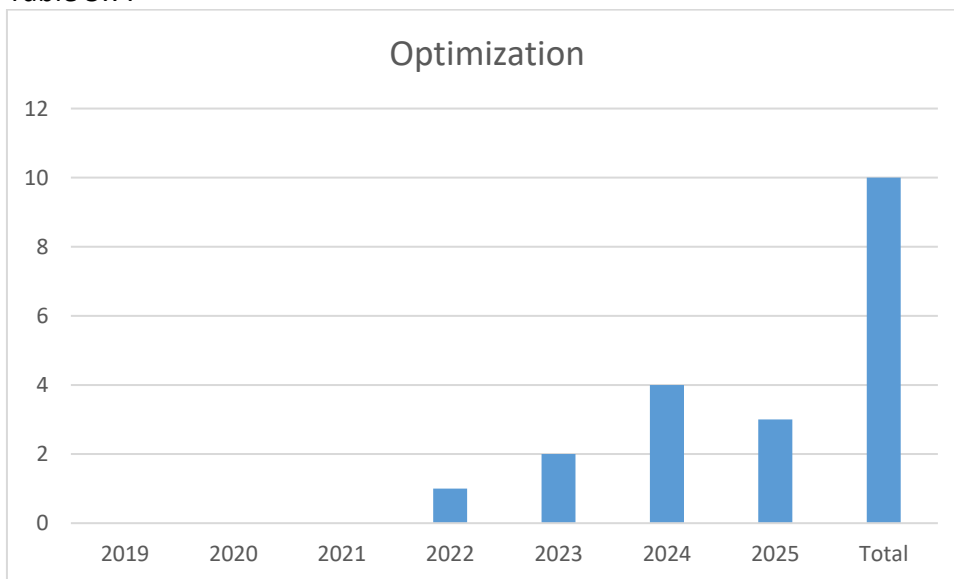


Table 5.8:

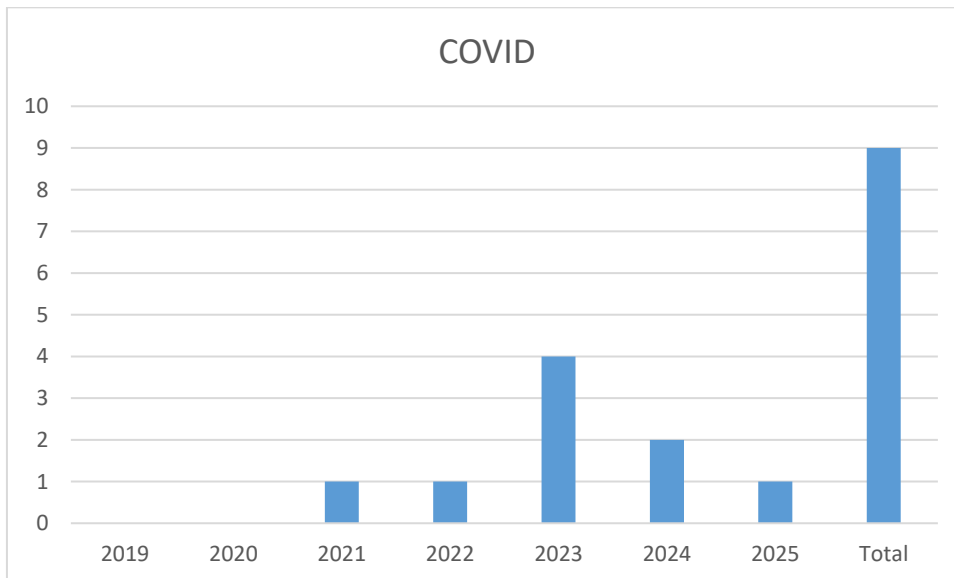


Table 5.9

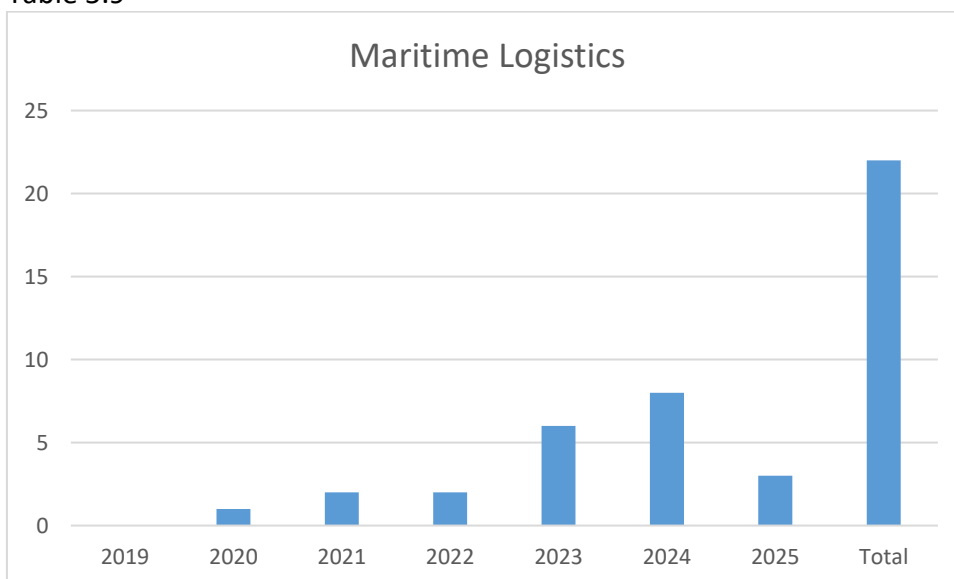
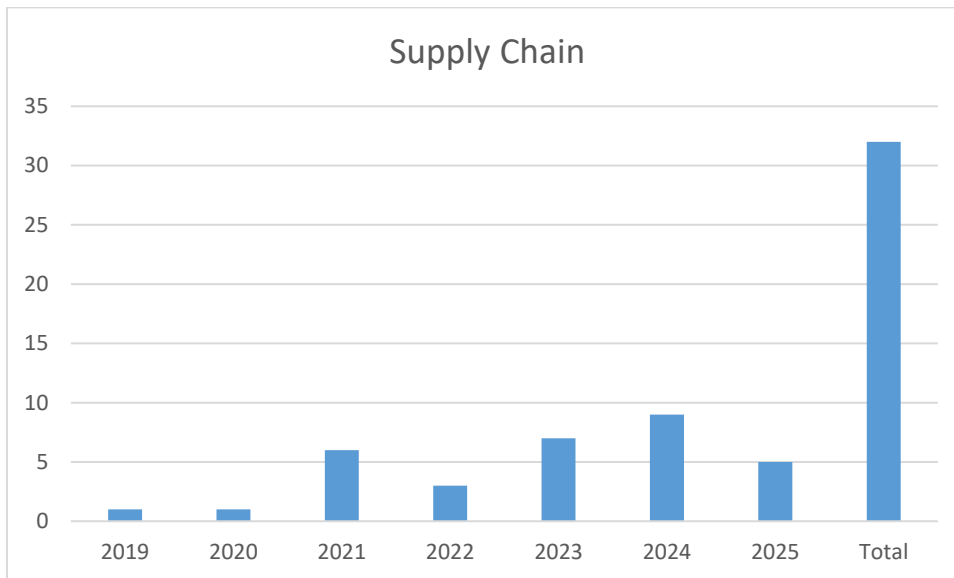


Table 5.10





Author's Statement:

I hereby expressly declare that, according to the article 8 of Law 1559/1986, this dissertation is solely the product of my personal work, does not infringe any intellectual property, personality and personal data rights of third parties, does not contain works/contributions from third parties for which the permission of the authors/beneficiaries is required, is not the product of partial or total plagiarism, and that the sources used are limited to the literature references alone and meet the rules of scientific citations.