

## Article

# Adapting a Cluster-Based Framework for Digital Shipping Corridors: An Exploratory Case Study of the Helsinki–Tallinn Corridor

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## Abstract

European maritime transport is undergoing a profound transformation driven by the dual imperatives of decarbonisation and digitalisation. Although green and digital shipping corridors are increasingly promoted as mechanisms for supporting this transition, there remains limited understanding of how digitalisation and sustainability can develop in parallel in cross-border maritime systems. This study adapts an existing cluster-based smart port framework to the corridor level to examine digital shipping corridors as integrated socio-technical systems. The framework is structured around four dimensions: technological foundations, intelligent port systems, performance-focused digitalisation, and strategic governance and sustainability. A qualitative case study based on publicly available documents and secondary sources is used to illustrate the framework and examine how these dimensions are reflected in practice. The findings indicate that the corridor demonstrates significant progress towards digital integration at the port-terminal level, although full corridor-wide integration remains incomplete. At the same time, the analysis highlights ongoing challenges related to broader system integration and the transition towards zero-emission maritime transport. The study concludes that digital shipping corridors should be understood as evolving socio-technical systems whose development depends on the alignment of technological innovation, governance capacity, and sustainability objectives. The study demonstrates how cluster-based analysis can be operationalised through qualitative case-study research. The proposed framework contributes to adapting smart port research from individual ports to corridor-level systems and offers a basis for future comparative research on maritime transport transitions.

**Keywords:** digital shipping corridors; smart ports; sustainability transitions; maritime digitalisation; governance; socio-technical systems; cross-border governance; Baltic Sea region



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## 1. Introduction

The maritime sector is a cornerstone of global trade, handling more than 80% of world trade and remaining the dominant mode of international freight transport [1–3]. Growing trade volumes, expanding hinterland demand, and increasingly interconnected port–hinterland systems have intensified congestion and operational complexity [4]. Consequently, ports have evolved from traditional cargo handling sites into integrated logistics and service platforms that are embedded within wider transport ecosystems and value

creation networks [4,5]. In recent years, the maritime sector has experienced accelerated transformation driven by tightening environmental regulation, decarbonisation pressures, and operational disruptions caused by the COVID-19 pandemic [6]. These developments have intensified the need for low-emission operations, cleaner fuels, energy-efficient technologies, and operational measures that reduce fuel consumption and emissions across vessels and ports [6–11]. Port sustainability research further demonstrates that ports increasingly seek to balance economic performance with environmental and social objectives, while reducing the externalities generated by maritime supply chains [10,12–14]. Digital transformation has emerged as a central mechanism supporting sustainability and operational transitions in maritime transport and port logistics. Existing research emphasises that digitalisation extends beyond process automation and involves broader organisational and ecosystem-level restructuring enabled by data-driven management and intelligent decision-making systems [3,9,15]. Recent studies of Northern European RoPax ports further demonstrate that digitalisation increasingly supports logistics integration, information sharing, and coordination among multiple stakeholders across maritime transport systems [15,16]. Technologies such as blockchain, IoT, cloud computing, artificial intelligence, digital twins, and predictive analytics support information sharing, operational coordination, cargo visibility, and environmental monitoring across maritime logistics networks [3,17–19]. These developments have accelerated the emergence of smart ports characterised by interconnected digital infrastructures, automation, and collaborative digital ecosystems [12,19,20]. However, maritime digitalisation continues to face challenges related to interoperability, cybersecurity, implementation costs, organisational readiness, and stakeholder coordination [3,5,17]. Recent research also draws attention to the growing importance of digitally integrated shipping corridors and collaborative maritime ecosystems, where technological infrastructure, regulatory alignment, logistical efficiency, environmental sustainability, and stakeholder cooperation must evolve simultaneously to support resilient and sustainable maritime logistics systems [21,22].

Within this broader sustainability transition, green shipping corridors have emerged as an important mechanism for accelerating maritime decarbonisation and digital transformation. Green shipping corridors refer to maritime routes where zero- or low-emission fuels, technologies, and operational practices are implemented through coordinated collaboration among ports, shipping companies, regulators, energy providers, and other stakeholders [11]. These corridors facilitate the adoption of sustainable maritime solutions by addressing infrastructure, investment, technological, and governance barriers. Recent studies further emphasise that successful corridor development depends on the integration of digital technologies, environmental strategies, operational coordination, and cross-border governance mechanisms across maritime ecosystems [9]. Several internationally recognised initiatives have since emerged, including the Singapore–Rotterdam Green and Digital Shipping Corridor, the Los Angeles–Shanghai corridor, and various North Sea and Nordic initiatives aimed at advancing low- and zero-carbon shipping through alternative fuels, digital trade corridors, operational optimisation, and coordinated emissions reduction strategies [11,21].

The increasing policy attention given to green and digital shipping corridors is also reflected in European transport policy. Through initiatives such as the Trans-European Transport Network (TEN-T) and related EU funding mechanisms, the European Union has supported investments in digital infrastructure, port modernisation, alternative fuels and cross-border transport integration. These initiatives position digital shipping corridors as notable instruments for achieving broader sustainability, connectivity and competitiveness objectives across European transport systems [23].

Within the Baltic Sea region, the Helsinki–Tallinn maritime corridor represents a significant regional example of cross-border green and digital maritime cooperation. Connecting two capital cities across the Gulf of Finland, the corridor forms part of the North Sea–Baltic TEN-T Core Network [23] and supports both high-volume passenger flows and RoPax cargo transport. Baltic cruise ferry systems have increasingly evolved into integrated transport and service platforms combining passenger mobility, vehicle transport, and onboard service functions [24]. In this context, the Helsinki–Tallinn corridor represents one of the most established examples of integrated RoPax operations in the Baltic Sea region. Previous research has shown that Ro-Ro shipping services are often unstable, with routes and port connections changing in response to market conditions, whereas long-term service stability is considered important for supporting investments and modal shifts. In contrast, the Helsinki–Tallinn corridor has demonstrated long-term service continuity and institutional cooperation, creating favourable conditions for sustained investments in digitalisation, interoperability and green transition initiatives [25].

Over the past decade, the corridor has been shaped by joint development initiatives between the Port of Helsinki, the Port of Tallinn, and major ferry operators, particularly through EU co-funded Twin-Port projects focusing on smart port development, digitalisation, environmental sustainability, alternative fuels and port infrastructure improvements [6]. The corridor is theoretically relevant because it combines high-frequency passenger and freight traffic, decades of institutional cooperation, substantial EU investment, and active sustainability experimentation, making it a particularly suitable case for examining corridor-level integration processes.

Despite the growing body of research on maritime digitalisation, smart ports, green shipping, and sustainable maritime logistics, existing studies remain fragmented across technological, operational, environmental, and governance perspectives. While individual studies examine smart port technologies, sustainability transitions, or governance separately, little attention has been given to how these dimensions interact within integrated digital shipping corridors and cross-border maritime ecosystems [3,9,15,17,19,21,24,26]. To our knowledge, no study has integrated these perspectives into a unified framework that captures their interactions across national boundaries and multiple stakeholders within a single corridor. This article addresses this gap by adapting a cluster-based analytical framework for digital shipping corridors, drawing on smart port research, sustainability transitions theory, and business ecosystem perspectives. Building on earlier smart port research, the framework is applied to the Helsinki–Tallinn corridor to examine how digital and green initiatives interact at the corridor level.

The study is guided by the following research questions:

1. How can existing smart port, sustainability-transition, and business ecosystem perspectives be integrated into a corridor-level analytical framework for digital shipping corridors?
2. In what ways does the Helsinki–Tallinn maritime corridor illustrate and deviate from the components of the proposed framework?

The remainder of the paper is structured as follows. Section 2 reviews the theoretical foundations of digital shipping corridors, drawing on smart port systems, sustainability transitions, and business ecosystem perspectives. Section 3 presents the cluster-based analytical framework. Section 4 describes the research methodology. Section 5 presents the empirical analysis of the Helsinki–Tallinn corridor. Section 6 discusses the findings in relation to existing literature. Finally, Section 7 concludes the study and outlines implications for research and practice.

## 2. Literature Review and Theoretical Foundations for Digital Shipping Corridors

### 2.1. Smart Port Systems and Digital Maritime Infrastructure

The maritime sector is undergoing rapid digital transformation driven by the complexity of global logistics systems, growing sustainability pressures, and the emergence of Industry 4.0 technologies. Within this transition, ports are evolving from traditional cargo handling locations into digitally interconnected logistics and service ecosystems that support operational coordination, supply chain integration, and sustainability objectives [27,28]. Existing research conceptualises ports as intelligent and data-driven nodes embedded within wider maritime and hinterland transport networks, where digital infrastructure, interoperability, and real-time information exchange have become critical elements of operational performance and competitiveness [12,20].

The concept of smart port has emerged as a central framework within this transformation. Smart ports are generally understood as ports that integrate advanced digital technologies, automation systems, and data-driven management practices to improve operational efficiency, resource allocation, environmental performance, and stakeholder coordination [28,29]. The evolution toward smart ports is closely associated with broader port development trajectories linked to Industry 4.0, where ports increasingly incorporate technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, blockchain, big data analytics, digital twins, and predictive management systems into port operations and logistics coordination [18,19,30].

Research demonstrates that digitalisation enables ports to automate operational processes, improve cargo visibility, optimise vessel and terminal operations, and support real-time decision-making across maritime logistics systems [3,17]. Smart port technologies facilitate more efficient coordination between shipping lines, terminal operators, customs authorities, freight forwarders, and hinterland transport actors, thereby improving information transparency and operational integration across supply chains [12]. In this context, Port Community Systems (PCSs) have become particularly important as digital platforms that support interoperability and data exchange among maritime stakeholders. Existing studies identify PCSs as foundational digital infrastructures that enable horizontal and vertical integration within port ecosystems, while supporting broader logistics coordination and operational synchronisation [12].

The increasing deployment of digital technologies has also transformed the operational logic of ports by enabling predictive, data-driven, and automated management practices. Technologies such as AI, IoT sensors, machine learning, and big data analytics support intelligent vessel scheduling, automated logistics operations, predictive maintenance, traffic optimisation, and continuous monitoring of cargo flows and infrastructure conditions [9,31]. Digital twins and Building Information Modelling (BIM)/Geographic Information System (GIS) integrated systems further extend these capabilities by enabling real-time simulation, asset monitoring, and lifecycle management of port infrastructure, supporting more resilient and adaptive port operations [31]. These developments illustrate how digital transformation extends beyond process digitalisation toward broader organisational and infrastructural restructuring within maritime transport systems [15,17].

In parallel, smart port development is linked to sustainability and green-transition objectives. Existing literature demonstrates that digital technologies can significantly contribute to emission reductions, improving energy efficiency and enhancing environmental governance in port operations [9,13]. Smart port systems support environmental monitoring, digital carbon accounting, predictive energy management and operational optimisation practices such as just-in-time arrivals and intelligent traffic coordination, all of which contribute to lower fuel consumption and reduced environmental externalities [13,32].

Research further suggests that smart port digitalisation can improve carbon-emission efficiency and support sustainable port governance through more intelligent resource allocation and automated operational management [13].

At the same time, literature emphasises that smart port performance and digital transformation outcomes depend on the interaction between technological, organisational and environmental factors [32]. The successful implementation of smart port systems requires organisational readiness, regulatory alignment, stakeholder collaboration, interoperability standards, cybersecurity capabilities, and integrated governance mechanisms across maritime ecosystems [3,17]. Consequently, digital transformation in ports is increasingly understood as a systemic and ecosystem-level process involving multiple interconnected actors, infrastructures, and governance arrangements [20,21].

Despite these advances, smart port research has been criticised for focusing predominantly on technological adoption and operational efficiency, while paying less attention to governance arrangements, social dimensions, and equity considerations associated with digital transformation and maritime development [20,21].

Within this broader evolution, digital shipping corridors can be interpreted as an extension of the smart port paradigm from individual ports towards integrated cross-border maritime ecosystems. Through interoperable digital infrastructures, shared data platforms, coordinated governance mechanisms, and collaborative operational systems, digital shipping corridors seek to enable more efficient, resilient, and sustainable maritime transport networks [16,21]. Existing research therefore positions smart ports and digital maritime infrastructures as foundational building blocks for the development of digitally integrated shipping corridors and future maritime logistics ecosystems [16,21].

In the Baltic Sea region, cruise-ferry systems have evolved into integrated transport and service platforms combining passenger mobility, vehicle transport, logistics functions, and onboard services within interconnected maritime corridors [6,24]. This development reflects a broader shift toward ecosystem-based transport systems in which value creation depends on interactions among ports, operators, logistics providers, public authorities and passengers rather than on individual organisations operating in isolation [6,20].

## 2.2. Sustainability Transitions in Transport and Logistics

Sustainability transitions theory provides a notable framework for understanding long-term transformations in socio-technical systems such as maritime transport, ports, and logistics networks. Sustainability transitions involve multidimensional changes through which existing systems evolve towards more sustainable configurations characterised by lower emissions, improved resource efficiency, technological innovation, and institutional change [33,34]. These transitions extend beyond isolated technological improvements and involve interconnected technological, organisational, economic, regulatory, and social transformations.

In the maritime sector, climate change mitigation pressures, environmental regulations, and changing global trade dynamics challenge conventional fossil fuel-dependent shipping systems and create pressures for structural transformation [33,34]. At the same time, maritime systems remain highly path-dependent due to long asset lifecycles, infrastructure investments, and established operational practices, making transitions gradual and complex [33,34].

Ports and maritime transport systems are central to global trade and supply chains, but they also generate substantial environmental externalities associated with shipping operations, cargo handling, industrial activities, and hinterland transport [14,35]. As sustainability pressures intensify, ports are increasingly expected to balance economic

competitiveness with environmental and social sustainability objectives through integrated sustainability strategies based on the triple bottom line perspective [14].

In response, the maritime sector has accelerated efforts toward decarbonisation, energy efficiency, and greener logistics systems. Existing research emphasises the growing importance of alternative fuels, operational optimisation, emissions monitoring and co-ordinated policy measures aimed at reducing greenhouse gas emissions from shipping activities [35,36]. However, these transitions remain challenging due to technological uncertainty, investment requirements, fragmented regulation, and the international nature of shipping operations [32,34].

Digitalisation has emerged as a key enabler supporting sustainability transitions across maritime transport and logistics systems. Technologies associated with Industry 4.0 and smart ports—including IoT, AI, blockchain, cloud computing, digital twins and big data analytics—support operational optimisation, real-time information exchange, predictive management, and environmental monitoring [27,28,31]. Smart ports are therefore characterised by interconnected digital infrastructures, intelligent management systems, automation, and integrated data-sharing platforms that improve both operational efficiency and sustainability performance [13].

Within this context, digital shipping corridors can be understood as integrated transition mechanisms that combine digitalisation, sustainability, and cross-border maritime coordination into interconnected operational systems. Existing literature highlights the importance of coordinated ecosystems in which technological infrastructure, governance frameworks, environmental strategies, and stakeholder collaboration evolve simultaneously [3,21]. Corridor-based initiatives also function as experimental transition spaces, where digital technologies, cleaner fuels, operational optimisation measures, and collaborative governance models can be tested and implemented in real-world maritime environments.

Sustainability transitions theory has primarily developed through European empirical contexts and has been criticised for paying limited attention to power dynamics, politics, and unequal capacities for transition across regions and stakeholder groups [33,34,37].

### *2.3. Business Ecosystems and Value Co-Creation in Corridor Development*

Digital shipping corridors can be understood as business ecosystems in which multiple stakeholders collaborate through interconnected infrastructure, digital platforms, and coordinated operational processes. Ports function as integrated and value-adding nodes embedded within global supply chains and maritime logistics networks rather than isolated transport interfaces [38,39]. This ecosystem perspective emphasises interdependence, collaboration, and shared value creation among actors involved in corridor operations [39].

Within maritime logistics ecosystems, actors such as ports, terminal operators, shipping companies, logistics providers, customs authorities, technology firms, and energy suppliers depend on one another to coordinate activities and exchange resources effectively. From a service-dominant logic perspective, value is co-created through interactions and resource integration among multiple stakeholders [39]. Successful corridor development relies on collaborative relationships that improve operational efficiency, resilience, and service quality [38,39].

The transition toward smart ports and Port 4.0 has strengthened ecosystem connectivity through the adoption of Industry 4.0 technologies, including the Internet of Things, blockchain, artificial intelligence, cloud computing, and automation [38,40]. Digital platforms such as port community systems and integrated logistics networks facilitate real-time information exchange, operational synchronisation, and collaborative decision-making across organisational boundaries. Research also suggests that digitalisation reshapes value

structures within maritime ecosystems by enabling new forms of collaboration and network integration [20].

However, technological innovation alone is insufficient to ensure effective corridor development. Successful ecosystem transformation also depends on governance structures, organisational adaptation, stakeholder trust, and aligned incentives [39]. Value co-creation emerges through both vertical supply chain coordination and horizontal collaboration, including shared investments in digital infrastructure, sustainability initiatives and renewable energy systems [41]. Existing research on Baltic cruise-ferry operations further demonstrates that value creation within maritime corridors increasingly extends beyond transport functions towards integrated passenger and service experiences, where onboard services, hospitality functions, and mobility systems are closely interconnected [24]. These arrangements contribute to improved efficiency, reduced costs, enhanced resilience, and better environmental performance [40].

Overall, digital shipping corridors represent broader socio-technical ecosystems shaped by stakeholder interaction, governance mechanisms and shared value creation [39]. Their effectiveness depends on the ability of participating actors to integrate digital capabilities, coordinate logistics and energy systems, and collaboratively support sustainable maritime transport operations [38,39].

Business ecosystem perspectives have also been criticised for primarily emphasising value creation, competitiveness, and stakeholder coordination, while paying less attention to sustainability outcomes and environmental performance as explicit analytical objectives [38,39].

#### *2.4. Integration of Digitalisation, Sustainability, and Ecosystem Perspectives*

Although research on smart ports, sustainability transitions, and business ecosystems has expanded significantly, these perspectives are often examined separately [21,33,39]. This fragmentation limits understanding of digital shipping corridors as integrated socio-technical systems where technological, environmental, organisational, and governance dimensions interact simultaneously [21,33,39].

In this integrated perspective, sustainability transitions theory provides a temporal understanding of long-term system change, smart port research contributes to the technological and operational dimensions of digitalisation, and business ecosystem perspectives explain stakeholder coordination, value creation and inter-organisational relationships across maritime actors and jurisdictions [28,33,39].

Research on smart ports primarily focuses on digital technologies, automation, operational efficiency, and data-driven optimisation. Studies highlight the role of Industry 4.0 technologies, smart infrastructure, port-centric Information and Communication Technology (ICT) systems, microgrids, and digital platforms in improving port performance, resilience, and competitiveness [38,40,42,43]. Similarly, smart port and port integration strategies have been linked to congestion mitigation, improved Environmental, Social and Governance (ESG) performance, and enhanced operational coordination across maritime systems [5,44].

At the same time, sustainability-oriented research emphasises the environmental and societal dimensions of maritime and port development. Existing studies discuss decarbonisation pathways, renewable energy integration, sustainable port management and the transition toward low-emission maritime transport systems [14,36,41]. Smart ports are viewed as mechanisms for supporting sustainable development goals, energy efficiency and environmental governance.

Business ecosystem perspectives complement these approaches by focusing on stakeholder interdependence, value co-creation, and network coordination within maritime

logistics systems. Maritime transport and port systems rely on collaboration among ports, shipping lines, logistics providers, technology firms, and public authorities to create integrated service networks and shared value [39]. Digital platforms and information-sharing systems facilitate coordination across organisational boundaries and improve operational capabilities within port communities [42]. Recent studies also show that digitalisation reshapes value structures within port ecosystems by changing relationships between actors and enabling new business models and governance arrangements [20].

The shift from individual smart ports towards digital shipping corridors introduces additional complexity, because corridor performance depends on interoperability, institutional alignment, cross-border governance, and ecosystem coordination. Smart port-hinterland integration studies demonstrate that coordinated digital infrastructure and synchronised logistics processes are essential for improving corridor-level efficiency and resilience [45]. Likewise, research on coordinated port integration emphasises the importance of cooperation mechanisms, resilience strategies, and governance structures for managing congestion and maintaining system performance across interconnected ports [5].

Cross-border maritime corridors also face governance challenges related to regulatory harmonisation, data protection requirements, institutional trust, and interoperability between national systems. These challenges may constrain information sharing, hinder coordinated decision-making and slow the development of fully integrated digital shipping corridors [15,21].

Corridor development may also be understood as an evolutionary process progressing through phases of emergence, experimentation, scaling and stabilisation as technologies, governance mechanisms and stakeholder relationships gradually evolve and become more closely aligned [33,34].

Consequently, digital shipping corridors should not be understood solely as technological infrastructures, but rather as integrated socio-technical ecosystems in which digitalisation, sustainability objectives, and stakeholder coordination evolve together [15,33,39]. Existing literature increasingly suggests that successful corridor development requires simultaneous alignment of technological innovation, sustainability strategies, governance mechanisms and collaborative business ecosystems across multiple actors and jurisdictions [15,21,39].

The growing international interest in green and digital shipping corridors further illustrates the importance of ecosystem coordination and cross-border governance in maritime decarbonisation and digital transformation. Initiatives such as the Singapore–Rotterdam Green and Digital Shipping Corridor, the Los Angeles–Shanghai Green Shipping Corridor, and the Singapore–Los Angeles–Long Beach Green and Digital Shipping Corridor seek to accelerate the deployment of alternative fuels, digital solutions, and coordinated stakeholder action across major maritime trade routes [22,46,47]. Recent research on the Pacific Northwest–Alaska Green Shipping Corridor similarly demonstrates that successful corridor development depends on multi-stakeholder collaboration, infrastructure investments, and regulatory alignment, while implementation remains constrained by technological, financial, and governance barriers [48]. These initiatives suggest that digital shipping corridors should be understood as complex socio-technical ecosystems that require sustained institutional cooperation, shared governance arrangements and long-term strategic alignment among participating actors and jurisdictions.

### *2.5. Towards a Cluster-Based Framework for Digital Shipping Corridors*

The literature review demonstrates that digital shipping corridors emerge from the interaction of technological development, sustainability transitions, and ecosystem

coordination [21,33,39]. However, existing research remains fragmented and predominantly focused on individual ports rather than interconnected corridor systems [21,39].

To address this gap, this study adapts the cluster-based framework developed by Toomeoja et al. [49] as a starting point for analysing digital shipping corridors. The original framework identified four key dimensions of smart port development: technological foundations, intelligent port systems, performance-focused digitalisation and strategic governance and sustainability [49]. While originally developed at the port level, these clusters require adaptation to capture the cross-border interactions, governance arrangements and ecosystem dynamics that characterise digital shipping corridors.

In this study, the clusters are adapted to the context of digital shipping corridors and form the analytical basis for the framework presented in Section 3. This approach enables a more integrated understanding of how digitalisation and sustainability can develop in parallel across ports, stakeholders and national boundaries, while emphasising the importance of governance arrangements and ecosystem interactions in shaping corridor development.

### 3. Conceptual Framework for Digital Shipping Corridors

Building on the theoretical foundations outlined in Section 2, this study adapts the cluster-based framework developed by Toomeoja et al. [49] as a lens for examining digital shipping corridors as integrated socio-technical systems. The original framework was developed to synthesise smart port literature and explain smart port development at the individual port level [49]. However, it also identified critical research gaps related to cross-port digital interoperability, collaborative ecosystems and global coordination mechanisms [49]. The corridor perspective represents a logical extension of smart port research, because many of the challenges identified in the literature, including interoperability, cross-border coordination, and ecosystem integration, cannot be fully understood at the level of individual ports and instead require corridor-level analysis [49]. Unlike the original framework, which identified thematic clusters within smart port research, the present framework uses these clusters as interrelated analytical dimensions for examining corridor-level interactions and development processes.

The framework is organised around four interrelated clusters identified in prior research: smart port concepts and technological foundations, port development and intelligent systems, performance-focused digitalisation, and strategic governance and sustainability [49]. In the present study, these clusters are adapted to the corridor level, where digitalisation, sustainability, and governance processes unfold across multiple ports, stakeholders, and institutional environments.

Each cluster captures a distinct but complementary dimension of corridor development. Technological foundations provide the digital infrastructure required for connectivity and interoperability. Intelligent systems translate these capabilities into coordinated operational processes across ports and transport networks. Performance-focused digitalisation captures the observable outcomes of digital transformation, including efficiency and service improvements. Strategic governance and sustainability provide the institutional, regulatory, and environmental conditions necessary for coordinating activities across organisational and national boundaries. Together, these dimensions provide a more comprehensive analytical understanding of digital shipping corridors than any single theoretical perspective alone [21,33,39,49].

The four clusters should not be interpreted as independent dimensions. Instead, they represent interrelated components of digital shipping corridor development. Improvements in technological capabilities enable more advanced intelligent systems and operational integration, which may contribute to enhanced efficiency, reliability, and transparency. The extent to which these outcomes can be realised depends on governance

arrangements, institutional coordination, and sustainability strategies that shape investment decisions, regulatory alignment, and stakeholder collaboration. Thus, digital shipping corridor development can be understood as an iterative and mutually reinforcing process in which technological, operational, governance, and sustainability dimensions continuously interact [21,33,39,49].

The first cluster, smart port concepts and technological foundations, refers to the digital technologies and infrastructures underpinning smart port operations, including Port Community Systems, automation, Internet of Things applications, data-sharing platforms, and cybersecurity arrangements. At the corridor level, this cluster emphasises interoperability and standardisation across port systems to enable seamless data exchange and coordinated operations beyond individual port boundaries. The cluster therefore captures the enabling digital infrastructure of the corridor. Indicative evidence includes the presence of Port Community Systems, shared digital platforms, automation technologies, and interoperability arrangements.

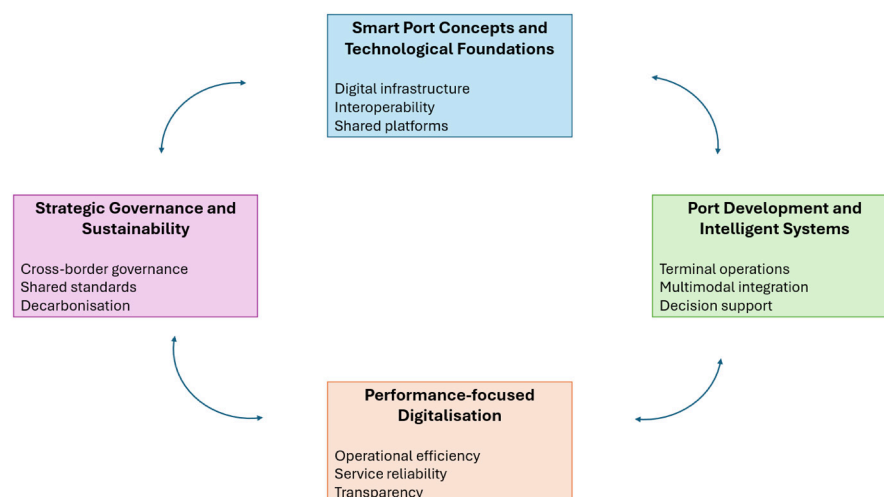
The second cluster, port development and intelligent systems, captures the evolution of ports into interconnected and intelligent logistics nodes within wider transport networks. In the context of digital shipping corridors, this includes coordinated terminal operations, real-time traffic management, multimodal integration, and the application of intelligent systems to support corridor-wide decision-making. This cluster focuses on how digital capabilities are applied within operational processes and coordinated decision-making. Indicative evidence includes intelligent traffic management systems, coordinated terminal operations, multimodal integration, and digital decision-support tools.

The third cluster, performance-focused digitalisation, addresses the operational and service-related outcomes of digital transformation. These outcomes include reduced waiting times, improved reliability, enhanced cargo and passenger flows, increased transparency, and more efficient coordination between ports, vessels, and hinterland transport systems. This cluster captures the observable outcomes of digital transformation rather than the technologies or governance arrangements that enable them. Indicative evidence includes improvements in waiting times, service reliability, throughput, transparency, and operational efficiency.

The fourth cluster, strategic governance and sustainability, encompasses the institutional, regulatory, and environmental dimensions of corridor development. It includes cross-border governance structures, shared standards, public–private partnerships, green infrastructure investments, and coordinated decarbonisation strategies. The cluster emphasises the importance of aligning digital innovation with sustainability objectives through collaborative governance mechanisms. Indicative evidence includes cross-border agreements, EU-supported initiatives, shared standards, and decarbonisation measures.

Although analytically distinct, the four clusters interact continuously and should therefore be understood as mutually reinforcing dimensions. The framework assumes that technological capabilities and intelligent systems may contribute to improved corridor performance, while governance arrangements and sustainability strategies create the institutional conditions necessary for corridor-wide coordination and long-term transition processes.

Together, these four clusters form an integrated analytical framework for analysing digital shipping corridors as socio-technical systems (Figure 1). The clusters capture mutually reinforcing dimensions that collectively shape corridor evolution and performance. In the following section, the framework is applied to the Helsinki–Tallinn corridor to examine how these dimensions are manifested in practice and to assess the extent to which the empirical case illustrates or deviates from the proposed framework.



**Figure 1.** Cluster-based conceptual framework for digital shipping corridors as cross-border socio-technical systems. The arrows indicate iterative and mutually reinforcing interactions among the four analytical dimensions. Source: Author’s adaptation based on Toomeoja et al. [49].

## 4. Materials and Methods

### 4.1. Research Design

This study adopts a qualitative single-case study approach to examine the Helsinki–Tallinn maritime corridor as a digital shipping corridor. Case study research is well suited to investigating contemporary phenomena within their real-world context, particularly when the boundaries between the phenomenon and its surrounding environment are difficult to distinguish [50]. The Helsinki–Tallinn corridor represents a complex socio-technical system involving ports, ferry operators, municipalities, EU institutions, digital infrastructures, sustainability initiatives, and cross-border governance arrangements. A case study design therefore provides an appropriate approach for examining how these interconnected dimensions interact in practice.

Following Yin (2014) [50], case studies are particularly valuable when the objective is to capture contextual complexity, examine dynamic processes over time, and explain how specific initiatives or systems function within operational environments. In the present study, the case study design enables examination of the technological development alongside governance arrangements, sustainability initiatives, interoperability mechanisms, and operational coordination processes that shape corridor development.

Given the study’s objective of examining institutional developments, governance arrangements, and publicly documented digital and sustainability initiatives, qualitative documentary analysis was considered the most appropriate methodological approach. Documentary sources provide access to strategic decisions, infrastructure investments, policy developments, and organisational practices that would be difficult to capture through other methods alone.

The study is explanatory and illustrative rather than statistically generalisable. In line with Eisenhardt [51], case-based research is particularly useful in emerging research areas, where conceptual categories and theoretical relationships remain underdeveloped. Eisenhardt argues that case studies enable close interaction between empirical evidence and conceptual development through iterative comparison between data and theory. Accordingly, this study uses the Helsinki–Tallinn corridor to refine and apply the cluster-based analytical framework for digital shipping corridors developed in Section 3.

The research further follows Yin’s [50] recommendation to combine multiple sources of evidence to strengthen credibility through triangulation. Documentary evidence from institutional publications, project documentation, policy documents, and academic litera-

ture was therefore analyzed to examine how technological, operational, governance, and sustainability dimensions contribute to the development of the corridor. The adapted analytical framework provided a structured basis for organising and interpreting the empirical material, while allowing the findings to refine the understanding of corridor-level digital shipping development.

#### 4.2. Case Selection: The Helsinki–Tallinn Maritime Corridor

The Helsinki–Tallinn corridor was selected as an information-rich and theoretically relevant case due to its advanced integration of digital and sustainability initiatives and its strategic role within the EU's North Sea–Baltic TEN-T Core Network. The corridor connects two capital cities and involves close cooperation between port authorities, ferry operators, municipalities, national governments, and EU-level institutions. Over the past decade, the corridor has benefited from substantial EU co-funding through TWIN-PORT and Connecting Europe Facility programmes supporting investments in digital infrastructure, automation, terminal modernisation, intelligent traffic systems, onshore power supply, and low-emission maritime technologies.

The case provides a theoretically relevant setting for examining the applicability of the proposed analytical framework, because it combines high-frequency passenger and RoPax traffic, advanced digital capabilities, long-standing institutional cooperation, and ongoing sustainability initiatives within a mature cross-border maritime system. The unit of analysis is the Helsinki–Tallinn maritime corridor as an integrated socio-technical system comprising ports, ferry operators, governance arrangements, digital infrastructure, sustainability initiatives, and institutional actors operating across national boundaries. Accordingly, the analysis focuses on cross-border interactions occurring within the Helsinki–Tallinn maritime corridor and the institutional, technological, and operational systems directly supporting its development.

The Helsinki–Tallinn corridor serves as an exploratory and illustrative case for examining how digital shipping corridors may evolve under comparatively favourable institutional, technological and economic conditions. Consequently, the findings should not be interpreted as statistically generalisable to all maritime corridors. The Helsinki–Tallinn corridor represents an advanced case characterised by long-standing institutional cooperation, substantial EU support and relatively mature digital infrastructure. Therefore, the findings are intended to provide illustrative insights into corridor development and should not be interpreted as representative of all maritime corridors, particularly those operating under less favourable institutional or resource conditions.

#### 4.3. Data Sources and Collection

This study is based on qualitative documentary analysis using publicly available institutional and industry documentation. The empirical material comprises official publications from the Port of Helsinki and the Port of Tallinn, Smart Port development publications, Green Corridor initiative documents, and TWIN-PORT project materials. Additional documentary sources include EU policy and project documentation related to the Connecting Europe Facility (CEF), the Trans-European Transport Network (TEN-T), and maritime sustainability initiatives, as well as publicly available information from industry stakeholders. Table 1 provides an overview of the documentary corpus and the analytical purpose of each document category.

The empirical documentary corpus consisted of 12 publicly available institutional and industry documents, including port documentation ( $n = 8$ ), EU and project documentation ( $n = 3$ ), and industry publications ( $n = 1$ ), as presented in Table 1. The corpus comprised webpages, project publications, policy documents, and industry reports. Because several

sources were web-based and continuously updated online materials, a meaningful total page count could not be established. The documentary sources were identified through a targeted search of publicly available materials from the Ports of Helsinki and Tallinn, EU institutions, project websites, and industry stakeholders directly involved in the corridor. The documentary sources were collected and accessed between May and June 2026. Documents were selected because they contained information directly relevant to digitalisation initiatives, governance arrangements, sustainability measures, infrastructure investments, or operational developments within the Helsinki–Tallinn corridor. Documents that were not directly related to the corridor or did not provide substantive information on these themes were excluded from the empirical analysis. The documentary evidence was further complemented by peer-reviewed academic literature to support the theoretical framing and interpretation of the findings.

**Table 1.** Overview of the documentary corpus and its analytical purpose.

| Document Category            | Examples                                                                 | Purpose in the Analysis                                                      | Number of Sources |
|------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------|-------------------|
| Port documentation           | Smart Port publications, digitalisation articles, project updates        | Digitalisation initiatives, governance arrangements, sustainability measures | 8                 |
| EU and project documentation | TEN-T documentation, TWIN-PORT publications, Green Corridor publications | Policy framework, infrastructure investments, cross-border cooperation       | 3                 |
| Industry publications        | Publicly available information from energy providers (e.g., Elengor)     | Alternative fuel adoption and operational sustainability initiatives         | 1                 |

The use of multiple documentary sources follows Yin’s [50] recommendation that case study research should combine several forms of evidence to strengthen triangulation and maintain a transparent chain of evidence. Information obtained from different document types was compared throughout the analysis to corroborate findings and reduce reliance on individual sources. Where possible, key observations were supported by multiple independent documents representing different stakeholder perspectives. Because several documentary sources originated from institutional and project publications, claims that could not be independently verified were treated as stakeholder-reported information and interpreted with appropriate caution.

Peer-reviewed academic literature on smart ports, sustainability transitions, maritime digitalisation, and business ecosystems supported the theoretical framing and interpretation of the empirical findings. While the documentary corpus formed the empirical basis of the study, academic literature was used to contextualise and interpret the observed developments within the proposed analytical framework.

Generative artificial intelligence tools were used during the preparation of this manuscript to assist with manuscript structuring and language refinement. No artificial intelligence tools were used for data collection, data analysis, interpretation of findings, or the generation of scientific conclusions. All content generated with AI assistance was critically reviewed, verified, and edited by the authors, who take full responsibility for the content of the manuscript.

#### 4.4. Analytical Strategy

The analysis followed a theory-driven and deductive coding approach based on the four analytical clusters presented in Section 3: (1) smart port concept and technological foundations, (2) port development and intelligent systems, (3) performance-focused digital-

isation, and (4) strategic governance and sustainability. These clusters provided the initial analytical categories for organising and interpreting the empirical material. The purpose of the analysis was not to evaluate the maturity of the corridor against predefined thresholds or indicators, but rather to explore how the proposed analytical dimensions are reflected in the empirical case and where critical gaps and deviations remain. Due to the manageable size of the documentary corpus, the coding process was conducted manually. The unit of coding consisted of relevant text segments, statements, and descriptions referring to technologies, governance arrangements, sustainability initiatives, infrastructure investments, and operational developments within the corridor. Table 2 presents the analytical clusters, their definitions and examples of coded evidence.

**Table 2.** Analytical clusters and coding categories.

| Analytical Cluster                               | Definition                                                                | Examples of Coded Evidence                                                       |
|--------------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Smart port concept and technological foundations | Digital technologies and infrastructure enabling corridor operations      | PCS, digital platforms, automation technologies                                  |
| Port development and intelligent systems         | Smart systems supporting operational integration and information exchange | Traffic management systems, terminal technologies, intelligent transport systems |
| Performance-focused digitalisation               | Digital initiatives improving efficiency and sustainability performance   | Emissions monitoring, digital services, operational optimisation                 |
| Strategic governance and sustainability          | Collaborative governance arrangements and sustainability initiatives      | Green Corridor, TWIN-PORT, TEN-T cooperation                                     |

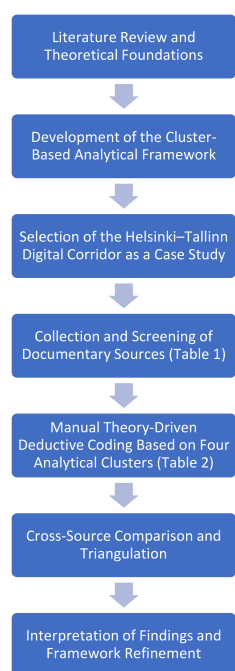
The documentary materials were first reviewed in full to identify information relevant to the study objectives. Relevant text segments were subsequently coded according to the four analytical clusters. Where empirical evidence related to multiple dimensions, the material was assigned to more than one category. This approach enabled the identification of interactions and interdependencies between technological, operational, governance and sustainability dimensions within the corridor.

The analysis focused on three objectives. First, it examined how the Helsinki–Tallinn corridor reflects the key components identified in the proposed analytical framework. The assessment of alignment was qualitative and based on the strength and consistency of documentary evidence. Second, it identified areas where the empirical case only partially aligns with theoretical expectations, such as incomplete corridor-wide integration or limited corridor-level sustainability indicators. Third, it examined how the four dimensions interact and collectively contribute to the development of a digital shipping corridor.

In line with Eisenhardt’s (1989) [51] approach to theory building from case studies, the analysis was iterative. Empirical observations were continuously compared with the conceptual framework, and the framework itself was refined through engagement with the empirical material. The case study demonstrates its applicability, identifies areas of alignment and deviation, and contributes to its further refinement in the context of digital shipping corridors. Following Yin’s [50] recommendations for case study research, evidence obtained from different documentary sources was continuously compared throughout the analysis. Cross-source comparison and triangulation were used to corroborate findings and reduce reliance on individual documents or stakeholder perspectives. Where documentary sources presented different perspectives or varying levels of detail, these differences were considered during the interpretation of findings.

The study also follows Yin's [50] emphasis on explanation-building within case study research. The analysis seeks to explain how digitalisation, governance coordination, sustainability initiatives, and operational integration collectively contribute to the emergence of a digital shipping corridor.

As with all qualitative research, the interpretation of documentary evidence involves a degree of researcher judgement. To enhance transparency and credibility, the analysis relied on multiple sources of evidence, explicit coding procedures and continuous comparison between empirical observations and the theoretical framework. The overall research process and analytical procedure adopted in this study are illustrated in Figure 2.

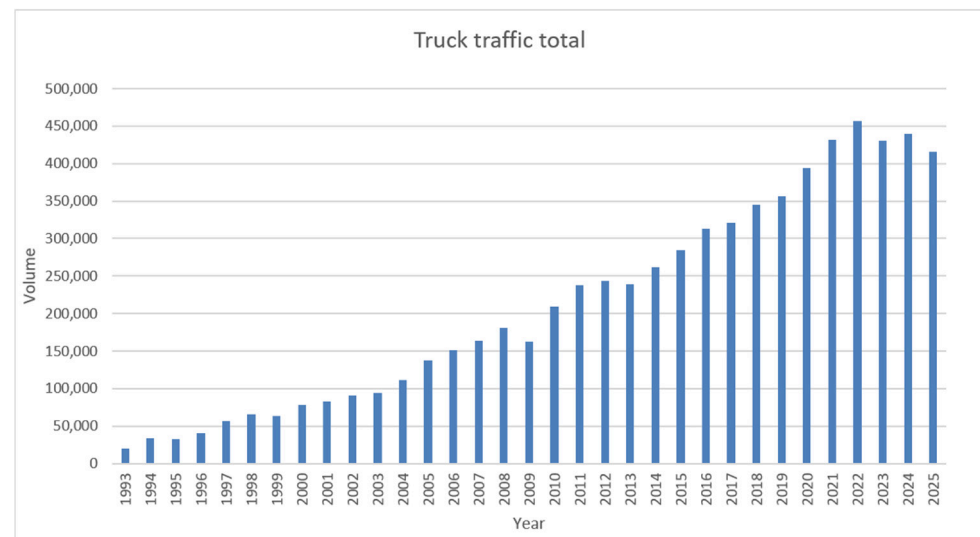


**Figure 2.** Research process and analytical procedure adopted in the study. Source: illustration is done by the author.

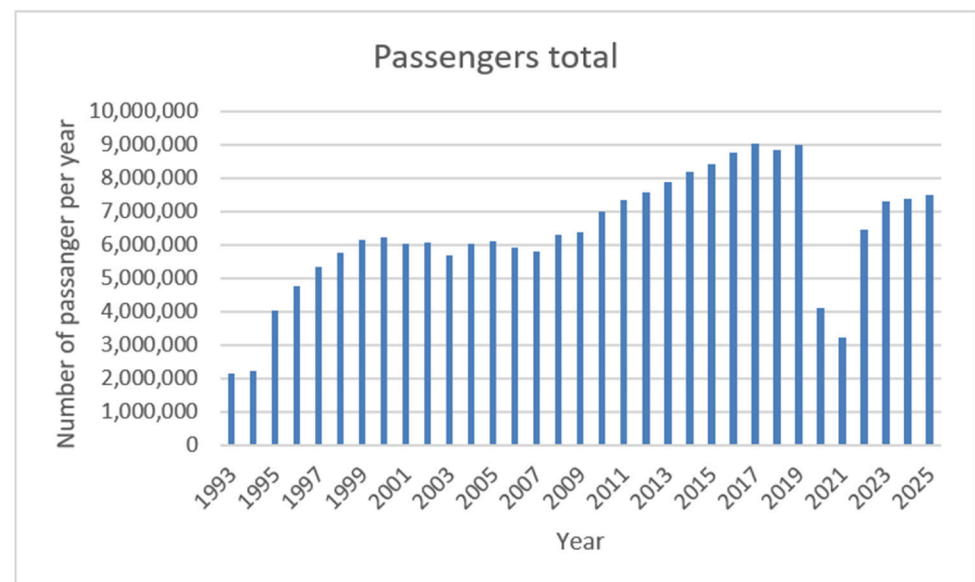
The study relied exclusively on publicly available information sources and no confidential or internal information was used in the analysis. Nevertheless, the interpretation of documentary evidence inevitably involves researcher judgement. To enhance transparency, the analysis relied on explicit coding procedures, multiple documentary sources, and continuous comparison between empirical observations and the theoretical framework.

## 5. Empirical Analysis: The Helsinki–Tallinn Digital Shipping Corridor

The Helsinki–Tallinn maritime corridor represents one of the most intensively operated ferry connections in the Baltic Sea region and forms part of the EU's North Sea–Baltic TEN-T Core Network. The corridor represents one of the busiest passenger and RoPax connections in Europe, handling approximately nine million passengers and two million vehicles annually [52,53]. Over the past decade, the corridor has evolved into a broader platform for digitalisation, sustainability experimentation, and cross-border maritime cooperation. Recent transport statistics further illustrate the continued importance of maritime passenger and ro-ro traffic in the Gulf of Finland (Figures 3 and 4), despite the long-term impacts of the COVID-19 pandemic and changing regulatory conditions affecting Baltic Sea shipping. This section applies the cluster-based analytical framework developed in Section 3 to examine how digital and green initiatives are implemented within the corridor.



**Figure 3.** Truck traffic between Helsinki and Tallinn 1993–2025. Source: Traficom—Finnish Transport and Communications Agency. Data were acquired in 2026.



**Figure 4.** Passenger traffic between Helsinki and Tallinn 1993–2025. Source: Traficom—Finnish Transport and Communications Agency. Data were acquired in 2026.

### 5.1. Smart Port Concepts and Technological Foundations

The Helsinki–Tallinn corridor exhibits significant progress in the adoption of digital technologies and smart port solutions within passenger and RoPax operations. One of the most significant developments has been implementing the Smart Port system at the Port of Tallinn’s Old City Harbour. Introduced initially in 2017, the system integrates automatic license plate recognition, automated gates, electronic traffic management, real-time vehicle guidance systems, and digital check-in procedures for passenger and freight traffic [54]. According to the Port of Tallinn, the system was developed to reduce congestion, improve terminal throughput, and decrease vehicle waiting times in an increasingly capacity-constrained port environment.

Subsequent development phases expanded Smart Port functionalities through automated traffic management and digital boarding procedures in both Terminal A and Terminal D [55]. The Port of Helsinki introduced similar SmartPort solutions in the West Harbour and Katajanokka terminals, including automated ticket gates, camera-based ve-

hicle identification, digital permit verification, and smart gate technologies supporting passenger and freight operations [56,57].

Importantly, the two ports coordinated the development of a shared SmartPort interoperability standard after ferry operators raised concerns regarding incompatible digital systems between Helsinki and Tallinn [56]. This standardised framework governs information exchange between port systems and ferry operators and illustrates that smart port development within the corridor depends on interoperability and coordinated digital infrastructure across organisational and national boundaries.

### *5.2. Port Development and Intelligent Systems*

The second cluster concerns the transformation of ports into intelligent logistics nodes integrated into wider transport and mobility systems. In the Helsinki–Tallinn corridor, this development is reflected in coordinated terminal modernisation, digital traffic management, automated boarding systems, and shared infrastructure investments between the two ports.

The TWIN-PORT cooperation programmes between Helsinki and Tallinn constitute one of the most significant institutional mechanisms supporting this transformation. Since 2012, multiple EU co-funded TWIN-PORT projects have supported the development of intelligent transport systems, automated mooring technologies, smart gate systems, digital traffic coordination, and RoPax infrastructure improvements across both ports [58]. The projects have aimed to improve the efficiency, sustainability, and interoperability of passenger and cargo transport along the Helsinki–Tallinn corridor.

The projects have included investments in automated mooring systems, onshore power infrastructure, digital traffic arrangements, dual ramps for RoPax operations, check-in automation, and intelligent gate technologies designed to optimise passenger and vehicle handling processes [58,59]. In parallel, the Port of Tallinn upgraded digital traffic management systems and terminal infrastructure within Old City Harbour and Muuga Harbour.

The Port of Helsinki has additionally implemented smart traffic management systems connected to surrounding urban infrastructure to reduce congestion around ferry terminals and improve traffic flows between the port and the city transport network [56]. These developments demonstrate that intelligent corridor systems extend beyond port boundaries and become integrated into wider urban and regional mobility systems.

More recently, the Port of Helsinki has also introduced digital quay reservation systems, real-time berth management tools, and automated vehicle monitoring solutions aimed at improving logistics coordination and operational visibility within the port environment [60].

The TWIN-PORT programmes have significantly improved digital infrastructure, terminal operations and cross-border cooperation between Helsinki and Tallinn through investments in intelligent transport systems, automated mooring technologies, digital traffic management and onshore power infrastructure [58,59]. However, publicly available evidence suggests that the projects have focused primarily on port-level infrastructure and operational improvements, while less progress has been achieved in developing corridor-wide performance indicators, integrated logistics platforms and broader stakeholder interoperability [58,59]. As a result, although TWIN-PORT has created notable foundations for digital shipping corridor development, several dimensions of corridor integration remain incomplete.

### *5.3. Performance-Focused Digitalisation*

Digitalisation within the Helsinki–Tallinn corridor has generated several operational and service-related improvements associated with traffic efficiency, terminal throughput, and coordination between maritime stakeholders. Automated check-in systems, digital

boarding management, automatic licence plate recognition, and harmonised SmartPort data standards have improved the efficiency of passenger and freight flows while reducing congestion within terminal areas [54,56].

The shared SmartPort interoperability framework between Helsinki and Tallinn is particularly critical from a performance perspective. By enabling information exchange between port systems and ferry operators, the corridor reduces operational friction associated with incompatible digital systems and supports more efficient boarding and traffic management procedures [56].

The Port of Helsinki has also expanded the use of real-time operational management systems within Vuosaari Harbour and passenger terminals. These include digital quay reservation systems, automated vehicle weighing and measurement technologies, camera-based monitoring systems, and digital situational awareness tools designed to optimise berth allocation and improve coordination between port operators and logistics stakeholders [57]. According to the Port of Helsinki, these systems support more efficient communication between operators, improve quay utilisation, and contribute to smoother cargo and vehicle handling operations.

The empirical findings also suggest an asymmetry between passenger and freight digitalisation within the corridor. Passenger transport services appear to have achieved a higher level of digital integration through online booking systems, digital ticketing, automated boarding procedures and real-time passenger information services [54]. In contrast, publicly available evidence of fully integrated freight digitalisation remains more limited, particularly regarding interoperable logistics platforms, cross-border data sharing and end-to-end cargo visibility [56,57]. This imbalance indicates that digital transformation within the corridor has progressed more rapidly in passenger services than in freight operations and draws attention to the continued challenges associated with achieving comprehensive digital integration across multiple stakeholders and jurisdictions.

Digitalisation may additionally contribute indirectly to environmental performance through reduced vehicle idling, smoother boarding procedures, and more efficient traffic coordination in terminal areas [15]. However, publicly available information provides relatively limited systematic corridor-level indicators linking digital operational improvements directly to quantified emissions reductions or wider sustainability outcomes [35].

#### *5.4. Strategic Governance and Sustainability*

The development of the Helsinki–Tallinn corridor is influenced by governance arrangements, long-term institutional cooperation, and sustainability-oriented infrastructure investments involving ports, municipalities, ferry operators, EU institutions, and national governments.

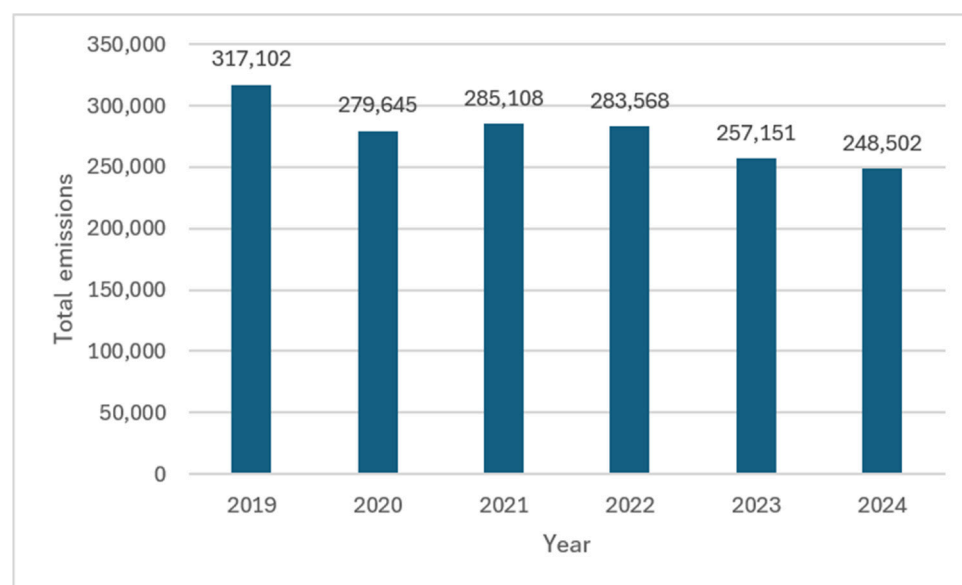
One of the most significant recent developments has been the establishment of the Helsinki–Tallinn Green Corridor initiative. In October 2023, the ports and cities of Helsinki and Tallinn, together with major ferry operators and governmental actors, signed a Memorandum of Understanding aimed at accelerating the transition toward climate-neutral passenger and cargo transport across the Gulf of Finland [52,53]. The initiative positions the corridor as a broader framework for sustainability projects related to maritime decarbonisation, operational efficiency, and low- and zero-emission transport solutions.

Environmental sustainability initiatives within the corridor are also reflected in fleet modernisation and the gradual adoption of lower-emission fuel technologies. Through the TWIN-PORT II programme, EU funding supported the introduction of Tallink's Liquefied Natural Gas (LNG) powered ferry M/S Megastar, which entered operation on the Helsinki–Tallinn route in 2017 [58]. More recently, Tallink introduced the LNG-fuelled M/S MyStar in 2022 and has begun incorporating bio-LNG into vessel operations in cooperation with

regional energy suppliers. According to Tallink and Elenger, bio-LNG has been supplied to MyStar during regular operations on the Helsinki–Tallinn route as part of the company’s broader objective to replace conventional LNG use with renewable alternatives in both MyStar and Megastar operations [61].

In parallel, the ports have invested extensively in onshore power supply systems, automated mooring technologies, traffic optimisation measures, and terminal modernisation projects through successive TWIN-PORT programmes and other EU-supported initiatives [58,59]. These investments align closely with wider European sustainability policies aimed at reducing emissions from maritime and port operations.

Publicly available emissions data from the Fin-Est Green Corridor initiative further illustrate the environmental dimension of corridor development. According to data published by the Port of Tallinn, total carbon dioxide (CO<sub>2</sub>) emissions associated with corridor operations decreased from 317,102 t CO<sub>2</sub> in 2019 to 248,502 t CO<sub>2</sub> in 2024, representing an overall reduction of approximately 21.6% (Figure 5). The observed decline appears to be associated with a combination of fleet modernisation, operational optimisation measures, investments in port infrastructure, and the gradual adoption of lower-emission fuels and technologies within the corridor.



**Figure 5.** Total emissions of the Fin-Est Green Corridor 2019–2024 (t CO<sub>2</sub>). Source: Author’s adaptation based on the data from the Port of Tallinn [62].

Although LNG-powered vessels can contribute to lower direct carbon dioxide emissions and improved local air quality, the long-term climate benefits of LNG remain uncertain due to methane slip and upstream emissions [63]. Thus, LNG is increasingly regarded as a transitional fuel that can support short- and medium-term emission reductions, but is unlikely to represent a fully decarbonised solution for maritime transport [63]. The gradual introduction of bio-LNG may further reduce lifecycle greenhouse gas emissions; however, the extent of the environmental benefits depends on feedstock characteristics, production pathways, and methane management across the supply chain [63].

From a governance perspective, the corridor demonstrates the importance of long-term institutional coordination and EU co-financing mechanisms in enabling corridor-level digital and sustainability transitions. The case shows that effective digital shipping corridor development depends on sustained cooperation between public authorities, port operators, shipping companies, and infrastructure stakeholders across national boundaries. At the same time, the case reveals several areas that remain underdeveloped. Despite significant

progress in decarbonisation initiatives and cross-border cooperation, the corridor still lacks fully integrated corridor-wide performance indicators, common environmental targets across all stakeholders and integrated energy system planning. These areas represent important opportunities for further corridor development and demonstrate that institutional coordination remains as critical as technological advancement.

### 5.5. Transition Challenges

Despite its significant progress status, the Helsinki–Tallinn corridor continues to face several transition challenges. High-frequency ferry operations create substantial energy demand and operational intensity, while tightening environmental regulation increases pressure for further decarbonisation and technological upgrades [6,36].

Although LNG-powered vessels and onshore electricity infrastructure contribute to certain emission reductions, these technologies do not yet represent fully zero-emission solutions [36,63]. Achieving deeper decarbonisation will likely require additional investments in alternative fuels, electrification, digital optimisation systems and supporting infrastructure. Such transitions involve considerable financial and technological uncertainty for both ports and shipping operators.

Despite significant progress in port digitalisation and maritime cooperation, integration with hinterland transport systems remains limited. Publicly available evidence suggests that digital initiatives within the corridor have primarily concentrated on port operations and maritime passenger services, while less attention has been given to end-to-end logistics integration beyond the port perimeter [56–59]. In particular, the corridor lacks fully integrated logistics platforms, harmonised data exchange mechanisms across transport modes and comprehensive digital coordination between maritime, road and rail transport systems. These limitations indicate that corridor development remains focused on the port-terminal interface, while fully integrated door-to-door logistics processes have yet to emerge.

### 5.6. Corridor Replication

The corridor also benefits from conditions that may not be easily replicable elsewhere, including exceptionally high passenger volumes, mature institutional cooperation, extensive EU financial support, and relatively advanced digital infrastructure [6,58,59]. Hence, while the Helsinki–Tallinn case provides significant insights into digital corridor development, its governance and operational model cannot necessarily be transferred directly to smaller or less resource-intensive maritime corridors.

Overall, the Helsinki–Tallinn corridor shows how digitalisation and sustainability can develop in parallel within a mature cross-border maritime transport system. Its development demonstrates the importance of combining smart port technologies, coordinated governance structures, environmental investments and cross-border institutional cooperation in the transition towards more sustainable and digitally integrated maritime corridors.

The findings suggest that successful digital shipping corridor development requires sustained institutional collaboration, long-term financing mechanisms and interoperable governance arrangements that can support coordination across multiple stakeholders and jurisdictions.

## 6. Discussion

The findings of this study demonstrate that digital shipping corridors should be understood as integrated socio-technical systems in which digitalisation, sustainability transitions, operational coordination and governance mechanisms evolve simultaneously across multiple actors, jurisdictions and infrastructures. Building on this perspective, the

study demonstrates how smart port research, sustainability-transition theory, and business ecosystem perspectives can be integrated into a corridor-level analytical framework for digital shipping corridors. The resulting framework is structured around four interrelated dimensions: smart port concepts and technological foundations, port development and intelligent systems, performance-focused digitalisation, and strategic governance and sustainability. These dimensions form a cluster-based analytical framework that integrates technological, operational, environmental, and governance perspectives into a unified structure for analysing corridor development. The framework contributes to existing literature by extending smart port and sustainability-transition research from individual ports toward interconnected cross-border maritime ecosystems [21,33,39,49].

The empirical analysis of the Helsinki–Tallinn corridor further addressed the second research question by examining the ways in which the corridor illustrates and deviates from the proposed analytical framework. The findings show that the corridor strongly illustrates several dimensions of the framework, particularly regarding implementing smart port technologies, coordinated digital infrastructure, intelligent traffic and terminal systems, and collaborative governance arrangements between ports, municipalities, ferry operators, and public institutions. The findings further indicate that the corridor has achieved significant progress towards digital integration at the port-terminal level and therefore provides a relatively advanced and illustrative example of how digitalisation and sustainability can develop in parallel within a mature cross-border maritime transport system. At the same time, the analysis also reveals critical deviations from the ideal characteristics of a fully integrated digital shipping corridor, particularly regarding hinterland logistics integration, customs systems, and corridor-wide sustainability coordination. The empirical findings particularly reinforce the importance of interoperability and coordinated digital infrastructure in smart port development. Previous studies have emphasised the role of Port Community Systems, data-sharing platforms, and integrated digital infrastructures in enabling operational coordination and improving supply chain visibility across maritime ecosystems [12,17]. The Helsinki–Tallinn corridor extends these insights by illustrating how interoperability challenges emerge between ports operating across national boundaries. The jointly developed SmartPort interoperability standard between Helsinki and Tallinn demonstrates that successful corridor digitalisation depends on coordinated standards, shared information systems, and institutional cooperation between ports and ferry operators. This finding supports earlier research arguing that smart port performance relies on ecosystem-level integration [19,20]. At the same time, the findings suggest that achieving interoperability at the corridor level remains more complex than within individual ports, because it requires sustained coordination across multiple organisations, regulatory environments, and digital systems. The case further demonstrates how digitalisation and sustainability transitions are intertwined within maritime transport systems. Existing literature has identified digital technologies as important enablers of greener logistics systems, operational optimisation, and emissions reduction strategies [9,10,13]. The Helsinki–Tallinn corridor reflects this relationship through investments in smart traffic management, automated boarding systems, LNG-fuelled vessels, onshore power supply infrastructure, and emerging bio-LNG initiatives. At the same time, the findings also illustrate the incremental and path-dependent nature of maritime sustainability transitions. Although LNG-based technologies contribute certain emission reductions, particularly sulphur oxides (SO<sub>x</sub>), particulate matter, and in some cases carbon dioxide emissions compared to conventional marine fuels, they do not yet represent fully zero-emission solutions. A key limitation is methane slip, referring to the release of unburned methane during combustion and across the fuel supply chain. Since methane is a highly potent greenhouse gas, these emissions may partially offset the climate benefits associated with lower CO<sub>2</sub> emissions from LNG

combustion [63]. Consequently, the case illustrates that digitalisation and environmental improvements do not necessarily translate into immediate decarbonisation outcomes and that transitional technologies may involve notable trade-offs and unintended consequences. This indicates that maritime decarbonisation remains a gradual process shaped by technological maturity, infrastructure availability, regulatory pressures, and economic constraints. This observation is consistent with sustainability transition theory, which emphasises that socio-technical transitions unfold progressively through experimentation, infrastructure adaptation and institutional alignment [33,34]. The findings therefore reinforce the interpretation of digital shipping corridors as evolving transition processes that have not yet reached a fully stabilised state.

The findings also highlight the importance of governance structures and collaborative ecosystem coordination in corridor development. Prior research has emphasised that digital transformation outcomes depend on stakeholder coordination, regulatory alignment, organisational readiness and collaborative governance arrangements [9–40]. Helsinki–Tallinn corridor strongly reflects these characteristics through long-term institutional cooperation between ports, municipalities, ferry operators, national authorities, and EU funding mechanisms. The TWIN-PORT programmes and the FIN-EST Green Corridor initiative demonstrate how corridor development is supported through sustained public–private cooperation and cross-border governance structures that facilitate infrastructure investments, operational coordination, and shared sustainability objectives. These findings reinforce the ecosystem perspective presented in the theoretical framework, where value creation depends on interdependent relationships among multiple stakeholders. At the same time, the findings suggest that the ability to establish and maintain collaborative governance arrangements may be a more critical determinant of corridor development than the deployment of digital technologies themselves.

The empirical findings also suggest that the relative importance of the four analytical dimensions (Figure 1) differs somewhat from the initial conceptualisation. While technological capabilities and intelligent systems are necessary preconditions for corridor development, the case indicates that governance arrangements and institutional coordination play an especially critical role in enabling long-term integration. In practice, the deployment of digital technologies appears to be less challenging than achieving sustained cooperation across multiple organisations, jurisdictions and regulatory environments. The findings therefore suggest that strategic governance and sustainability should be viewed as an enabling condition that shapes the effectiveness of the remaining dimensions and influences the overall trajectory of corridor development.

In line with [51], the case-study approach also demonstrates how empirically grounded analysis can contribute to the refinement and extension of conceptual categories related to digital shipping corridors. The Helsinki–Tallinn case confirms that corridor development cannot be reduced to technological adoption alone but instead emerges through the interaction of smart port technologies, intelligent operational systems, performance-focused digitalisation, and strategic governance and sustainability processes. The empirical findings therefore reinforce the interpretation of digital shipping corridors as integrated socio-technical systems shaped by technological, organisational, environmental, and institutional interdependencies. The study contributes theoretically by adapting and operationalising the four-cluster framework for corridor-level analysis and by demonstrating that digital shipping corridor development is shaped by interactions among technological, operational, governance and sustainability dimensions. The empirical analysis also revealed several critical deviations from the ideal characteristics of a fully integrated digital shipping corridor. The findings indicate that the Helsinki–Tallinn corridor demonstrates significant progress toward digital integration at the port-terminal level. However, full corridor-wide

integration, particularly with customs systems, hinterland logistics and energy networks, remains incomplete. The available material primarily highlights initiatives related to terminal operations, traffic management, and SmartPort interoperability, suggesting that the strongest forms of integration currently occur at the port-terminal interface. Similarly, sustainability initiatives are progressing rapidly, but the transition toward fully zero-emission maritime transport is still incomplete. These observations indicate that digital shipping corridors are evolving transition processes that have not yet reached a fully stabilised state.

Several factors may explain why full corridor-wide integration has not yet been achieved. Cross-border maritime systems face regulatory complexities arising from differing national administrative practices, data governance requirements, and sector-specific regulations. In addition, the development of interoperable digital systems often requires substantial financial investments and long implementation periods, creating economic barriers to deeper integration. The coordination of multiple public and private stakeholders may also generate differences in priorities, investment capacities, and strategic objectives, which can slow decision-making and hinder the establishment of fully integrated corridor-wide systems. These findings suggest that institutional alignment and governance coordination may constitute greater challenges than technological deployment itself [17,21,33,34,39].

The findings additionally raise important questions regarding replicability and transferability. Helsinki–Tallinn corridor benefits from exceptionally favourable conditions, including high passenger volumes, mature institutional cooperation, advanced digital infrastructure, and extensive EU financial support [58,59]. Such conditions may not exist in smaller or less economically significant maritime corridors. Hence, while the case provides valuable insights into corridor development, its governance structures and operational solutions cannot necessarily be transferred directly to all maritime contexts without considering local institutional, technological, and economic conditions. Similar corridor development elsewhere may require several enabling conditions, including sustained institutional cooperation, stable governance arrangements, long-term investment mechanisms, interoperable digital infrastructure, and sufficient traffic volumes to justify large-scale investments. The absence of these conditions may significantly constrain the pace and scope of digital shipping corridor development [21,33,34,39].

A comparison with other green and digital shipping corridor initiatives further illustrates the distinctive characteristics of the Helsinki–Tallinn case. The Singapore–Rotterdam Green and Digital Shipping Corridor primarily focuses on global supply-chain decarbonisation, digital standards, and the development of alternative fuel ecosystems across long-distance container shipping routes [22]. Similarly, the Los Angeles–Shanghai and Singapore–Los Angeles–Long Beach initiatives emphasise large-scale decarbonisation strategies, stakeholder partnerships, and the deployment of zero- and near-zero-emission technologies across trans-Pacific shipping networks [46,47]. Recent research on green shipping corridors in the Pacific Northwest further highlights that corridor development depends on extensive collaboration among ports, shipping companies, public authorities, and energy stakeholders, while also facing challenges related to infrastructure readiness, financial investments, and cross-border policy coordination [48]. In contrast, the Helsinki–Tallinn corridor demonstrates an advanced level of operational and institutional integration supported by frequent RoPax services, long-standing cross-border cooperation, and highly interconnected port and terminal systems. Although decarbonisation remains an important objective, the corridor places greater emphasis on operational interoperability, digital integration, and institutional coordination than on large-scale fuel transition strategies alone. These differences suggest that digital shipping corridors may evolve through multiple pathways depending on their geographical, institutional, and operational contexts. Therefore,

no single corridor model is universally applicable, and successful corridor development requires adaptation to local institutional, economic, and operational conditions.

The findings also generate several implications for policymakers and practitioners seeking to advance digital shipping corridor development. First, the results highlight the importance of establishing common cross-border data standards and interoperable digital platforms that facilitate seamless information exchange among ports, shipping operators, and public authorities. Second, the development of integrated digital infrastructures requires sustained financial support, suggesting an important role for national governments and supranational institutions, such as the European Union, in providing funding mechanisms for digitalisation and decarbonisation investments. Third, the findings underline the need for greater regulatory harmonisation and institutional coordination to address differences in administrative procedures, data governance requirements, and operational standards across jurisdictions. Finally, the study suggests that policy interventions should adopt a multi-stakeholder perspective that combines technological innovation with governance arrangements, infrastructure development, and long-term collaborative partnerships. Such measures may significantly enhance the capacity of maritime corridors to achieve both digitalisation and sustainability objectives [21,33,34,39].

At the same time, the findings should be interpreted with caution, because the analysis primarily focuses on institutional and organisational perspectives derived from documentary evidence. The experiences and perspectives of passengers, local communities, environmental organisations, and other societal stakeholders remain underrepresented. Future research could therefore adopt broader stakeholder approaches to examine how digital shipping corridor development influences social acceptance, environmental justice considerations, and community-level sustainability outcomes.

Overall, the discussion demonstrates that digital shipping corridors represent more than technologically enhanced transport routes. Rather, they function as evolving cross-border socio-technical ecosystems in which digital infrastructures, sustainability strategies, operational practices, governance mechanisms, and stakeholder networks co-develop over time. Helsinki–Tallinn corridor illustrates both the opportunities and the complexities associated with these transitions, demonstrating significant progress in digital and institutional integration, while also revealing critical challenges related to corridor-wide interoperability, hinterland integration, and long-term decarbonisation. The case therefore provides an empirically grounded and illustrative example of how digitalisation and sustainability can become increasingly integrated within contemporary maritime transport systems, while simultaneously highlighting the importance of governance and institutional coordination in shaping corridor development and enabling corridor-level integration.

## 7. Conclusions

This study examined the concept of digital shipping corridors through the case of the Helsinki–Tallinn maritime corridor and addressed two research questions concerning how smart port, sustainability-transition and business ecosystem perspectives can be integrated into a corridor-level analytical framework and how the Helsinki–Tallinn corridor illustrates and deviates from the components of the proposed framework. Building on previous research on smart ports, sustainability transitions, and maritime business ecosystems, the study developed a cluster-based analytical framework consisting of four dimensions: smart port concepts and technological foundations, port development and intelligent systems, performance-focused digitalisation, and strategic governance and sustainability.

The findings show that the Helsinki–Tallinn corridor strongly reflects many characteristics identified in existing literature on smart ports and maritime digitalization [12,15,20]. The implementation of SmartPort systems, automated gate technologies, digital traffic man-

agement, interoperable information exchange and coordinated TWIN-PORT investments demonstrate how digital infrastructure and operational coordination increasingly extend beyond individual ports toward corridor-level integration. Similarly, the Green Corridor initiative, LNG-powered vessels, bio-LNG experimentation and onshore power investments support sustainability transition research emphasising the importance of coordinated governance and cross-border cooperation in maritime decarbonization [33,34].

At the same time, the case also indicates that corridor integration remains partial. While digitalisation and sustainability initiatives are well developed at the port-terminal level, broader integration with hinterland logistics systems, corridor-wide environmental monitoring, and shared performance indicators remains more limited. This suggests that digital shipping corridors evolve incrementally and have not achieved fully integrated transformation.

The study contributes by adapting and operationalizing an existing smart port analytical framework to corridor-level analysis and by integrating smart port, sustainability-transition, and business ecosystem perspectives into a unified analytical lens for examining digital shipping corridors. The study demonstrates how existing theoretical perspectives can be combined and extended to better understand corridor-level integration processes. In line with Eisenhardt's (1989) [51] case-based theory-building approach, the Helsinki–Tallinn case demonstrates how empirical analysis can refine conceptual understanding of digital shipping corridors as interconnected socio-technical systems shaped by technological, operational, governance, and sustainability interactions. The findings further suggest that governance arrangements and institutional coordination constitute enabling conditions for corridor development and may be more critical than technological deployment alone.

The findings also have several practical implications. For corridor planners, the results suggest that investments in governance mechanisms, stakeholder coordination and institutional cooperation are as critical as investments in digital technologies themselves. For policymakers, the study draws attention to the importance of supporting cross-border data standards, interoperable information systems, and regulatory harmonisation to facilitate corridor development. For port authorities and maritime stakeholders, the findings indicate that prioritising interoperability and ecosystem integration may generate greater long-term benefits than pursuing isolated technological solutions at individual ports.

Several limitations should nevertheless be acknowledged. First, the study relies primarily on qualitative documentary sources and publicly available institutional material, while operational datasets and stakeholder interviews were not included. Consequently, the findings primarily reflect institutional and organisational perspectives and may underrepresent the experiences and perceptions of passengers, local communities, environmental organisations, and other societal stakeholders. Second, the analysis provides a cross-sectional assessment of the corridor at a particular stage of development and therefore cannot fully capture how digital shipping corridors evolve over time. Third, the selection of the Helsinki–Tallinn corridor as a relatively advanced and well-funded case introduces an element of selection bias, as the findings may not fully reflect the challenges faced by less mature or resource-constrained corridors. Finally, the single-case design limits the broader generalisability of the findings. Conclusions should therefore be interpreted as analytically transferable and should not be considered statistically representative.

Future research could apply the proposed framework across different maritime corridors to assess how varying institutional, technological and regulatory contexts influence corridor development and identify alternative pathways toward integration. Longitudinal studies provide valuable insights into how digital shipping corridors evolve over time and how technological and governance arrangements change throughout different stages of development. In addition, greater use of stakeholder interviews, surveys and opera-

tional performance data would provide a deeper understanding of how digitalisation is implemented in practice and how benefits and costs are distributed across port ecosystems and local communities. Attention could be given to the challenges of interoperability, data sharing, and platform integration among public and private actors, as these issues remain central to the broader digital transformation of maritime transport systems. Further research could also explore environmental justice and social equity dimensions of digital shipping corridors, including the distributional impacts of decarbonisation measures and the perspectives of communities affected by corridor development. The use of qualitative data analysis software, such as NVivo or ATLAS.ti, may further support systematic coding and comparative analyses of digital shipping corridors in future research.

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## Abbreviations

The following abbreviations are used in this manuscript:

|                 |                                      |
|-----------------|--------------------------------------|
| AI              | Artificial Intelligence              |
| BIM             | Building Information Modelling       |
| CEF             | Connecting Europe Facility           |
| CO <sub>2</sub> | Carbon Dioxide                       |
| ESG             | Environmental, Social and Governance |
| EU              | European Union                       |
| GIS             | Geographic Information System        |
| IoT             | Internet of Things                   |
| LNG             | Liquefied Natural Gas                |
| PCS             | Port Community Systems               |
| RoPax           | Roll-on/Roll-off Passenger           |
| ro-ro           | Roll-on/Roll-off                     |
| SO <sub>x</sub> | Sulphur Oxides                       |
| TEN-T           | Trans-European Transport Network     |

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