



**TURUN  
YLIOPISTO**  
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OF TURKU

# Decarbonising maritime transport

Digitalisation and environmental management  
paving the transition for Baltic ports

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Olli-Pekka Brunila





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## ABSTRACT

Ports and shipping are under mounting pressure to decarbonise while maintaining operational efficiency. The challenge is intensified by uneven capabilities: large hubs advance digital and environmental agendas, whereas smaller ports face resource and interoperability gaps. At the same time, new global and EU regulations tighten requirements on fuel quality, lifecycle emissions and shore-power use, creating complex compliance landscapes. This dissertation integrates three themes: (i) a comparative synthesis of mitigation options for black carbon emissions in Arctic-relevant shipping; (ii) a multi-case analysis of port digitalisation to identify conditions for environmental co-benefits; and (iii) the design and pilot of a lean self-assessment tool enabling small ports to evidence environmental performance. These themes are combined through a place-sensitive transition model linking policy drivers, local capabilities and measurement. For Arctic operations, the most effective near-term package combines cleaner fuels, particulate filtration and operational optimisation. Digitalisation reduces emissions only when supported by interoperable standards, cyber-resilience and governance. The small-port tool lowers entry barriers to environmental management, improves comparability and accelerates readiness for certification. Together, these results show that regulatory ambition translates into outcomes only when digital and managerial infrastructures co-evolve. Policy makers should complement global decarbonisation measures with geographically targeted controls and fund standards-based digital governance. Port authorities should treat digitalisation as a platform strategy and use modular tools to stage environmental management. Researchers should quantify the environmental effect sizes of digital interventions and extend longitudinal trials of lean tools across diverse geographies.

**KEYWORDS:** maritime decarbonisation, black carbon, port digitalisation, environmental management, Arctic shipping, sustainability transitions

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## TIIVISTELMÄ

Satamat ja meriliikenne kohtaavat paineita vähentää päästöjä, samalla säilyttäen toiminnan tehokkuuden. Haaste korostuu, koska valmiudet vaihtelevat: suuret satamat etenevät digitaalisissa ja ympäristöön liittyvissä ratkaisuisa, kun taas pienemmät satamat kamppailevat resurssipulan ja yhteensopivuusongelmien kanssa. Samaan aikaan uudet kansainväliset ja EU:n säännökset kiristävät vaatimuksia polttoaineiden laadusta, elinkaaripäästöistä ja maasähkön käytöstä, mikä tekee sääntelyn noudattamisesta monimutkaista. Tämä väitöskirja yhdistää kolme näkökulmaa: (i) vertailuanalyysi keinoista vähentää mustan hiilen päästöjä arktisessa meriliikenteessä, (ii) tapaustutkimukset satamien digitalisaatiosta ja sen ympäristöhyötyjen edellytyksistä, sekä (iii) kevyen itsearviointityökalun suunnittelu ja pilotointi, jotta pienet satamat voivat arvioida ympäristönsuojelun tasonsa. Nämä osat kytetään yhteen mallilla, joka huomioi paikalliset olosuhteet ja yhdistää sääntelyn, kyvykkyydet ja mittaamisen. Arktisilla alueilla tehokkain lähiajan ratkaisu on yhdistelmä puhtaampia polttoaineita, hiukkassuodatusta ja toimintatapojen optimointia. Digitalisaatio vähentää päästöjä vain silloin, kun tiedonsiirto on yhteensopivaa, tietoturva kunnossa ja hallintamallit selkeitä. Pienille satamille kehitetty työkalu madaltaa kynnystä ympäristöjohtamiseen, parantaa vertailtavuutta ja nopeuttaa valmiutta sertifiointeihin. Tulokset osoittavat, että kunnianhimoiset tavoitteet toteutuvat vain, jos digitaaliset ja johtamiseen liittyvät rakenteet kehittyvät rinnakkain. Päättäjien tulisi täydentää maailmanlaajuisia päästövähennystoimia aluekohtaisilla ratkaisuilla ja tukea standardeihin perustuvaa digitaalista hallintaa. Satamien kannattaa nähdä digitalisaatio yhteisenä alustana ja hyödyntää modulaarisia työkaluja ympäristöjohtamisen vaiheistamiseen. Tutkijoiden tulisi mitata digitaalisten ratkaisujen todellisia ympäristövaikutuksia ja laajentaa kevyiden työkalujen pitkäaikaista testausta eri maantieteellisissä ympäristöissä.

ASIASANAT: merenkulun päästövähennykset, musta hiili, satamien digitalisaatio, ympäristöjohtaminen, arktinen meriliikenne, kestävä kehitys siirtymät

# Table of Contents

<b>Abbreviations</b> .....	<b>7</b>
<b>List of Original Publications</b> .....	<b>9</b>
<b>1 Introduction</b> .....	<b>10</b>
1.1 Regulatory drivers, digital pathways and voluntary actions for maritime decarbonisation .....	12
1.2 Research gap and objectives .....	14
<b>2 Data and Methods</b> .....	<b>16</b>
2.1 Arctic shipping and black carbon mitigation .....	17
2.2 Port digitalisation and environmental co-benefits.....	18
2.3 Small-port environmental performance tool .....	19
2.4 Cross-cutting policy documents and integration logic .....	20
2.5 Ethics, confidentiality and quality assurance.....	20
<b>3 Theoretical Framework</b> .....	<b>22</b>
3.1 Positioning the dissertation in economic geography and maritime studies .....	22
3.2 Governance, spatial sensitivity considerations and transition dynamics in maritime decarbonisation.....	24
3.3 Digital platforms, measurement, and transition pathways .....	26
3.4 Global and regional governance, Arctic sensitivity, and digital complements.....	28
3.5 Small port and voluntary actions and the place sensitive transition framework .....	29
<b>4 Summary of the findings in the individual research articles</b> .....	<b>33</b>
4.1 Article I: Black Carbon, Maritime Traffic and the Arctic .....	33
4.2 Article II: Hindrances in Port Digitalisation? Identifying Problems in Adoption and Implementation .....	34
4.3 Article III: Sustainable Small Ports: Performance Assessment Tool for Management, Responsibility, Impact, and Self Monitoring .....	36
4.4 Cross-article synthesis and the overarching research question .....	37
4.5 Robustness, limitations, and practical directions for future research and policy .....	40

**5 Conclusions ..... 42**  
**Acknowledgements..... 44**  
**List of References ..... 46**  
**Original Publications..... 53**

# Abbreviations

AFIR	Alternative Fuels Infrastructure Regulation
AMAP	Arctic Monitoring and Assessment Programme
API	Application Programming Interface
BC	Black Carbon
BSR	Baltic Sea Region
CII	Carbon Intensity Indicator
CMO	Context–Mechanism–Outcome (analysis framework)
CO <sub>2</sub>	Carbon Dioxide
CSRD	Corporate Sustainability Reporting Directive
EEXI	Energy Efficiency Existing Ship Index
EMAS	Eco-Management and Audit Scheme
EMSA	European Maritime Safety Agency
EMTER	European Maritime Transport Environmental Report
EMS	Environmental Management System
ESG	Environmental, Social and Governance
ESPO	European Sea Ports Organisation
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GPN	Global Production Network
GRI	Global Reporting Initiative
GVC	Global Value Network
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
IoT	Internet of Things
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MLP	Multi-level Perspective
MRV	Monitoring, Reporting and Verification
NO <sub>x</sub>	Nitrogen Oxides

OPS	On-shore Power Supply
PCS	Port Community System
PM	Particular Matter
PERS	Port Environmental Review System (EcoPorts)
PM	Particulate Matter
TEN-T	Trans European Transport Network
WtW	Well-to-Wake

# List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Brunila, O-P., Inkinen, T., Kunnaala-Hyrkki, V., Hämäläinen, E. & Ala-Rämi, K. (2020). Black Carbon, Maritime Traffic and the Arctic. In: Pongrácz, E., Pavlov, V., Hänninen, N. (eds) *Arctic Marine Sustainability. Springer Polar Sciences. Springer*: 165–177.  
[https://doi.org/10.1007/978-3-030-28404-6\\_8](https://doi.org/10.1007/978-3-030-28404-6_8)
- II Brunila, O-P., Kunnaala-Hyrkki, V. & Inkinen, T. (2021). Hindrances in port digitalisation? Identifying problems of adoption and implementation. *European Transport Research Review*. 13, 62.  
<https://doi.org/10.1186/s12544-021-00523-0>
- III Brunila, O-P., Kunnaala-Hyrkki, V. & Inkinen, T. (2023). Sustainable small ports: performance assessment tool for management, responsibility, impact, and self-monitoring. *Journal of Shipping and Trade*. 8; 14.  
<https://doi.org/10.1186/s41072-023-00142-s>

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# 1 Introduction

Maritime transport creates the backbone of global trade, carrying most of the world's cargo and supporting the efficiency of modern supply chains (Corbett et al., 2010; Brunila et al., 2020; van Hassel & Vanelslander, 2022; Wu et al., 2022). Within this system, the Baltic Sea Region (BSR) stands out as one of the world's busiest short sea shipping areas. It comprises more than 80 internationally significant seaports and maintains strong intermodal connections to the European hinterland. Recent activities, COVID-19, geopolitical tensions, along with structural drivers such as digitalisation, decarbonisation and sustainability have exposed uneven capabilities across ports, creating both risks and opportunities for sustainable transition (van Hassel & Vanelslander, 2022; Ostrowska et al., 2022; Kizielewicz, 2024).

Although historically peripheral to the main deep-sea loops served by Northern Range ports, the BSR has strengthened its role in European logistics through feeder networks, selective deep-water investments, and policy support via the Trans European Transport Network (TEN T) corridors. Between 2014 and 2024 the regional port system adjusted to major disruptions, including the COVID 19 pandemic and the Russia–Ukraine war, as well as to sectoral drivers such as containerisation, digitalisation, and decarbonisation. These dynamics created divergent development paths across subregions, reflecting differences in market exposure, network position, and investment capacity (Öberg et al., 2018; Bartosiewicz et al., 2024; Kizielewicz, 2024).

The climate implications of shipping extend beyond carbon dioxide to short-lived forcers such as black carbon (BC), which accelerates Arctic ice melt when deposited on snow (AMAP, 2011; Bond et al., 2013). This places Arctic-relevant shipping under examination. At the same time, ports face rising expectations to cut emissions and demonstrate environmental responsibility, while digitalisation is promoted as a lever for efficiency and sustainability, yet its benefits remain unevenly distributed. Climate change is transforming Arctic navigability, increasing interest in seasonally viable routes such as the Northern Sea Route and the Northwest Passage, with potential distance and time savings for Asia–Europe and trans Arctic trades (Corbett et al., 2010; Kiiski, 2017; Yi et al., 2025).

Political tension in the Arctic has increased in the year 2025. Especially, the United States of America has put a lot of tension Arctic Sea routes. However, locational sensitivity and the prospect of increased near surface emissions call for stringent mitigation strategies, especially for BC and CO emitted species (Corbett et al., 2010; AMAP, 2011; Zhang et al., 2025). Empirical and scenario-based studies indicate that shipping growth in the Arctic, even from a low baseline, can materially increase local environmental pressures (Dalsøren et al., 2013; Winther et al., 2014). In this regard, a combined approach, technological abatement (e.g., particulate filtration, fuel switching), alternative fuels (e.g., LNG, methanol, biofuels), and operational measures (e.g., slow steaming, engine tuning), is required to reduce both CO<sub>2</sub> and BC (Assara et al., 2015; Brunila et al., 2020).

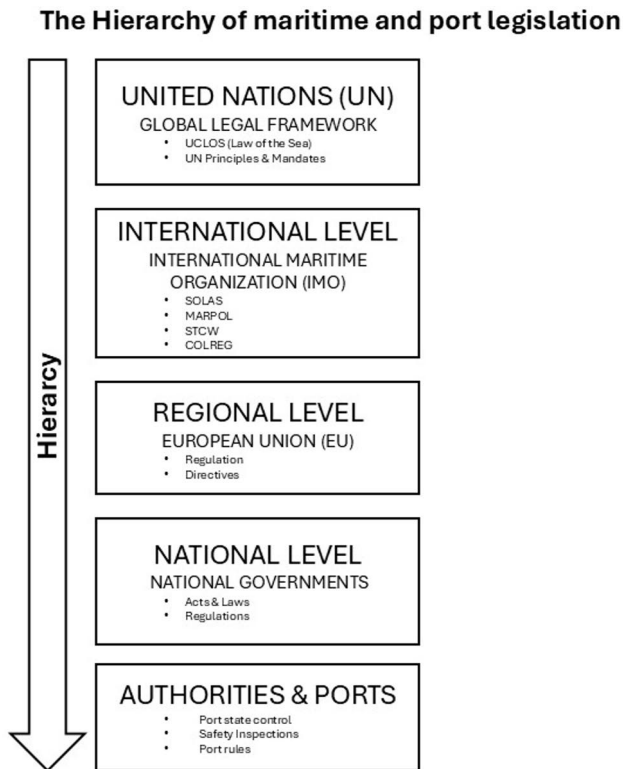
Artificial Intelligence (AI) is emerging as a significant technological development in the port and maritime sector, with growing attention in both research and practice (Dulai et al., 2025; Lysenko et al., 2025). AI-based systems are increasingly applied to enhance operational safety, education, and security, while also optimizing logistics processes and supporting simulation-based analysis of complex operational scenarios (Kizilay et al., 2025; Lv et al., 2025). In recent years, AI has been rapidly deployed across a wide range of tasks and everyday operational contexts. By processing real-time data on weather conditions, vessel performance, and maritime traffic, AI systems can generate optimized routing solutions that reduce fuel consumption and emissions while maintaining schedule reliability. These adaptive models not only lower operational costs but also contribute to decarbonisation objectives by enabling more energy-efficient voyages (Ghobakhloo et al., 2024; Wamba et al., 2024; Cocho-Bermejo et al., 2025).

In parallel, predictive maintenance supported by generative algorithms improves fleet reliability by identifying potential equipment failures before they occur, thereby reducing unplanned downtime and extending asset lifecycles. While AI creates substantial opportunities for performance improvement and environmental optimisation, its implementation also presents significant challenges. These include issues related to data quality and ownership, technological readiness, organisational capabilities, and governance, as well as questions concerning transparency, accountability, and the trustworthiness of AI-generated information (Oveis et al., 2024; Wamba et al., 2024; Dulai et al., 2025).

Meeting these challenges requires more than technology: it demands governance, measurement, and capability building. This dissertation addresses three interlinked gaps: (i) how to prioritise BC mitigation in Arctic shipping under evolving IMO and EU rules; (ii) under what conditions port digitalisation delivers measurable environmental benefits; and (iii) how small ports can adopt credible, low-cost tools for environmental management. Together, these themes form a place-sensitive transition model linking global policy drivers with local capabilities.

## 1.1 Regulatory drivers, digital pathways and voluntary actions for maritime decarbonisation

Maritime and port regulation is structured as a layered hierarchy that progresses from the top down, and its configuration is presented in **(Figure 1)**. The United Nations provides the highest legal framework, primarily through the United Nations Convention on the Law of the Sea (UNCLOS), and the International Maritime Organization (IMO), operating under the UN, establishes the core international standards (Ringbom, 2008; Fan, 2019). At the regional level, the European Union refines and harmonizes these norms through binding regulations and directives requiring national implementation. At the national level, states incorporate IMO and EU obligations into their domestic legal systems through acts, decrees, and administrative procedures, which authorities and port operators then apply and enforce in practice. In this way, the multilayered structure shown in **Figure 1** illustrates how international principles are transformed into EU-level instruments and, ultimately, into national competences and operational practices (Alavi, 2018; Fan, 2019; Tsaroucha & Terling, 2021).



**Figure 1.** The hierarchy of maritime and port related legislation.

The transition towards zero-carbon maritime operations is shaped by three interrelated themes: tightening regulatory requirements, expanding role of digital technologies and the voluntary initiatives. While policy frameworks set mandatory targets and create economic incentives for emissions reductions, digitalisation provides the operational tools and data infrastructure needed to monitor compliance, optimise performance, and implement cleaner solutions at scale. Voluntary initiatives are needed to encourage sustainable practices like reducing emissions from air and water, promoting clean technologies or improving waste management. Understanding how these forces interact, and where implementation gaps persist, is essential for assessing the capacity of Baltic Sea ports to navigate the green transition (Bakkar et al., 2025; Wang et al., 2025; Xu et al., 2025).

The regulatory landscape for maritime decarbonisation and air pollution control is constantly evolving and adding new stricter requirements. In April 2025 the International Maritime Organisation (IMO) approved the IMO Net Zero Framework, a package combining a global fuel standard, which progressively reduces well to wake GHG fuel intensity, and a global economic measure with pricing and crediting elements, supported by an IMO Net Zero Fund. These measures are scheduled for formal adoption in 2026 and entry into force in 2028 (Jesus et al., 2024; Bakkar et al., 2025). At the regional level, the European Union's Fit for 55 package has become a near term driver of change. The Fuel EU Maritime Regulation entered into force on 1 January 2025, requiring ships  $\geq 5,000$  GT calling at EU ports to reduce the annual average GHG intensity of onboard energy by 2% in 2025 on a trajectory toward 80% by 2050, and mandating on shore power supply (OPS) at berth for passenger and container vessels in TEN T ports from 2030 (and in all OPS equipped EU ports from 2035). In parallel, the EU Emissions Trading System (EU ETS) has been extended to shipping, with the surrender obligation phasing up to 70% of 2025 emissions (from 40% in 2024), increasing the cost signal for fossil fuel use and rewarding efficiency and cleaner energy choices (industry guidance summarising the legislation). Taken together, the IMO and EU measures reshape investment incentives for shipowners and ports, accelerating the uptake of low and zero carbon solutions and raising requirements for compliance, measurement, and reporting (EMSA/EEA 2025; also Wang & Kuusi, 2024; Lehmann et al., 2025).

Regulatory tightening and stakeholder expectations have encouraged the adoption of environmental management systems (EMS) and sustainability reporting frameworks in ports. While ISO 14001, EMAS, GRI and port specific instruments such as PERS (EcoPorts) provide structured approaches, they can be resource intensive for smaller ports (Peris Mora et al., 2005; ESPO, 2016; Puig et al., 2017; Wang et al., 2020; MacNeil et al., 2021; Dorado et al., 2022). Recent research proposes checklist based, self-diagnostic tools tailored to small ports, emphasising four dimensions: environmental management, responsibility, impact assessment, and

self-monitoring, to enable continuous improvement and benchmarking at lower cost (Brunila et al., 2023). Such tools can complement (not replace) formal certifications, enhance transparency, and support compliance readiness under evolving EU disclosure regimes such as the Corporate Sustainability Reporting Directive (CSRD), if indicators balance quantitative rigour with contextual relevance and that data governance is credible (Puig et al., 2017; Brunila et al., 2023; Dorado et al., 2022).

Digitalisation is increasingly viewed as a core enabler of safe, efficient, and sustainable port and shipping operations. Smart systems, ranging from IoT enabled condition monitoring and real time situational awareness to be integrated to Port Community Systems and 5G and 6G assisted automation, can reduce idle time, optimise asset utilisation, and lower energy use and emissions (Heilig et al., 2017; Buck et al., 2019; Bastug et al., 2020; Ahokangas et al., 2021; Gunes et al., 2021). Yet, the diffusion of digital capabilities is uneven. Small and medium sized ports, in particular, face a persistent combination of interoperability gaps, resource and skills constraints, cybersecurity risks, and organisational resistance to change (Brunila et al., 2021). Case evidence from pilot projects confirms that benefits materialise when digital investments are modular, standards based and embedded in long term transformation roadmaps that include cybersecurity governance and workforce upskilling (Heilig et al., 2017; Brunila et al., 2021). European policy initiatives (e.g., eFTI data environment; emerging EU port strategy) aim to harmonise data exchanges and strengthen interoperability, but implementation remains a managerial and technical challenge for many port communities (Brunila et al., 2021; de Langen, 2025).

## 1.2 Research gap and objectives

Despite significant advances, notable gaps remain at the intersection of Arctic shipping, port digitalisation, and environmental performance management. First, while mitigation options for BC are known, their deployment economics and operational integration in Arctic contexts under new IMO/EU rules require further empirical assessment (Assara et al., 2015; Brunila et al., 2020; Dorado et al., 2022). Second, the digital divide between large hubs and small/medium ports risks undermining sector wide efficiency and sustainability gains unless interoperability, cyber resilience, and capability building are addressed (Brunila et al., 2021; Heilig et al., 2017). Third, there is a need for comparable, and scalable performance metrics that allow smaller ports to demonstrate progress and align with tightening reporting obligations (ESPO, 2016; Meyer, 2021; Brunila et al., 2023; Kosek et al., 2025). The overarching question that this dissertation addresses is therefore “How can ports and Arctic-relevant shipping navigate a place-sensitive green and digital transition that

is environmentally effective, organisationally feasible, and scalable across diverse geographies?” This can be broken down into three key research questions:

1. How to prioritise BC mitigation in Arctic shipping under evolving IMO and EU rules?
2. Under what conditions port digitalisation delivers measurable environmental benefits?
3. How small ports can adopt credible, low-cost tools for environmental management?

The three research themes are conceptually interlinked through a place-sensitive transition logic, a transition from environmental pressure to practical action. The black carbon analysis shows where emission reductions are most urgent, port digitalisation explains how emissions can be monitored and managed in practice, and the small-port tool demonstrates how these ideas can be applied in everyday port operations.

Integrative regulatory analysis of technological appraisal, and management tool development is required to answer these questions. This study contributes to a holistic transition pathway that is environmentally effective, economically viable, and organisationally feasible for diverse for port and maritime transportation sector. This is integrating regulatory analysis, technological appraisal, and management tool development, the study contributes to a transition plan that is environmentally effective, economically viable, and organisationally feasible for diverse smaller ports and maritime stakeholders.

## 2 Data and Methods

This chapter outlines the data sources and methodological approaches employed in the three peer-reviewed articles that form the basis of this dissertation. Each article addresses a distinct but interrelated aspect of sustainable port and maritime transportation development: digitalisation, environmental management, and black carbon emissions. The research design is qualitative and exploratory in nature, combining document analysis, stakeholder interviews, pilot testing, and literature review. The following sections describe the data sources and methods used in each article in detail. This dissertation employs a mixed-methods design that combines an extensive theme, synthesising engineering and regulatory evidence at scale, with intensive themes, qualitative case analysis and design-science prototyping. **Table 1** outlines the data sources, methods utilised and the policies employed for each of the articles comprising the thesis.

The extensive theme integrates technical evidence on fuels, engines, after-treatment and operations for black carbon (BC) mitigation in Arctic contexts with the current global and regional policy mix shaping incentives and constraints. The intensive themes investigate port digitalisation (conditions under which digital projects deliver environmental co-benefits) and develop a lean environmental performance tool tailored for small ports.

Three principles guide the design: (1) Place sensitivity, externalities and capabilities are spatially uneven (e.g., the Arctic's high vulnerability to BC deposition and the capability gaps in small/medium ports); (2) Policy–capability complementarity, global standards and regional regulation must be translated into local outcomes through digital and managerial capacities; and (3) Measurement as practice, consistent indicators aligned with UN SDGs, ISO 14001 evidence base turn intent into accountability.

**Table 1.** Summary of data and methods.

Theme	Data	Method	Key policy anchors
<b>I. Arctic BC</b>	Technical data on fuels, engines, after-treatment; Regulatory documents, large international questionnaire	Engineering analysis, Policy review, Scenario modelling	IMO Net-Zero; Polar Code
<b>II. Digitalisation</b>	Literature review, Professional and academic reports	Qualitative case study, Document analysis, Reflective literature review	IMO digitalisation guidelines, EU digital strategy
<b>III. Small-port tool</b>	ISO/EMAS/PERS/GRI; expert panels; pilot ports	Design-science build–evaluate; usability/integration tests	UN SDGs, ISO 14001,

## 2.1 Arctic shipping and black carbon mitigation

The first empirical part addresses the significance of BC emissions from Arctic-relevant shipping to the climate and evaluates feasible near-term mitigation actions under evolving IMO and EU rules. The analysis begins with a structured review of combustion and engine literature, consolidating BC and particulate matter emission factors across fuel classes (residuals, distillates, low-sulphur blends, bio-blends), engine generations, and after-treatment technologies such as diesel particulate filters and oxidation catalysts. Special attention is given to operational variables such as engine load profiles, maintenance regimes, and slow-steaming practices because these factors strongly influence BC formation.

To translate technical evidence into actionable insights, the study employs a multi-criteria decision analysis (MCDA) framework. Options are assessed against five criteria: mitigation effectiveness, technology readiness, regulatory compatibility (e.g., IMO Net-Zero fuel standard and polar-fuels track), cost order (CAPEX/OPEX), and operational risk. Scenario reasoning complements this assessment by contrasting three policy-consistent futures: (a) a global well-to-wake standard combined with pricing under the IMO Net-Zero Framework; (b) Arctic-specific fuel constraints; and (c) an EU overlay incorporating ETS costs and FuelEU intensity limits.

Heterogeneity in emission factors is addressed by reporting intervals rather than single-point estimates, reflecting real-world variability in duty cycles, maintenance quality, and fuel properties. The structured review and MCDA together provide a transparent basis for ranking mitigation options, while scenario reasoning situates these rankings within plausible regulatory trajectories. By combining technical

evidence, policy analysis, and performance-based comparisons, the approach ensures that recommendations are both scientifically grounded and operationally feasible.

## 2.2 Port digitalisation and environmental co-benefits

The second part investigates the conditions under which port digitalisation delivers measurable environmental benefits rather than remaining a purely operational upgrade. Data collection combines documentary evidence from European Port Community System pilots, IoT/5G trials, and cybersecurity baselining with semi-structured interviews ( $n \approx 15$ ) involving port authorities, terminal IT managers, and solution providers. Purposive sampling ensures variation in port size, governance model, and IT maturity, enabling comparative insights across contexts.

Analytically, the study applies literature review draws on selected peer-reviewed publications retrieved from the Web of Science (WoS) and Scopus databases. Rather than constituting a systematic literature review in the strict methodological sense, the approach adopted here is reflective and problem-oriented in the port digitalisation. Searches conducted in WoS using the keyword “port digitalisation” yielded approximately 70 articles, while the corresponding search in Scopus produced 103 articles. However, when the focus of the search was narrowed to explicitly problem-oriented terminology, such as “problems” or “hindrances”, the volume of relevant research decreased substantially. The use of the keyword “hindrances” did not produce any results in either database. This indicates that while port digitalisation as a general concept has attracted increasing scholarly attention, explicit examination of its challenges, barriers, and unintended consequences remains limited.

The final reference list comprises 61 publications, covering nearly all relevant WoS-indexed studies identified under the selected search criteria and a clear majority of pertinent Scopus-indexed contributions. The relatively small number of studies directly addressing the critical and environmental implications of port digitalisation further underlines the relevance of this research. The emphasis is placed on identifying and synthesising the most critical challenges, limitations, and enabling factors linking port digitalisation to environmental outcomes, rather than exhaustively categorising the full body of existing research.

The empirical work is anchored in the EU ETS extension to maritime (in force since 1 January 2024; surrender obligations phased at 40%, 70%, and 100% for 2024–2026; scope: 100% intra-EU and 50% extra-EU legs) and the FuelEU Maritime Regulation (applicable from 1 January 2025), which sets well-to-wake GHG-intensity trajectories and mandates on-shore power supply (OPS) use at berth

for passenger and container ships from 2030 (TEN-T ports) and 2035 (all OPS-equipped EU ports). These instruments create strong incentives for interoperable data systems and reliable reporting, making digitalisation a prerequisite for compliance and optimisation. By combining documentary evidence, interview insights, and regulatory context, the analysis demonstrates that environmental benefits from digitalisation are conditional rather than automatic. They materialise only when interoperable standards, cyber-resilience, and governance frameworks are in place, enabling verified data flows and operational changes that reduce emissions.

## 2.3 Small-port environmental performance tool

The third part adopts incorporates elements commonly associated with heuristic research. This type of methodology emphasizes problem-solving and decision-making through the use of rules of thumb and intuitive judgment. Heuristic research is particularly applicable in situations where traditional scientific methods are not feasible, for example due to the complexity of the phenomenon under investigation, limited availability of data, time constraints, or other practical limitations (see, e.g., Geiger et al., 2018). Typically, heuristic research draws on data from multiple sources, including literature reviews, case studies, expert interviews, and observational data. Rather than aiming for definitive causal explanations, the primary objective of this approach is to generate insights, working hypotheses, or practical solutions that can subsequently be tested, refined, or validated through further investigation or experimentation. Heuristic research is widely applied in the social sciences, particularly in disciplines such as psychology, education, and management, where the emphasis lies in understanding complex decision-making processes and contextualized human behaviour (e.g., Leech and Onwuegbuzie, 2009; Fischhoff, 2015). to develop and validate a lean self-assessment tool for environmental management in small ports.

The tool synthesises ISO 14001, EMAS, EcoPorts/PERS, and GRI/ESG frameworks into a four-pillar checklist: Environmental Management, Responsibility, Impact Assessment, and Self-Monitoring, operationalised through Yes/Partial/No items with evidence prompts. Expert panels provided initial validation of content clarity, followed by pilot testing in three Finnish major ports (HaminaKotka, Helsinki, Turku). The Port of HaminaKotka is Finland's largest universal port and its principal export hub. The Port of Helsinki is among the largest cruise ports in the Baltic Sea region, and most important import port in Finland. The Port of Turku is the country's second-largest cruise port. Feedback informed iterative refinements to wording, indicator ordering, and guidance notes.

The build phase distilled the four-pillar structure from ISO/EMAS/PERS/GRI frameworks and formulated it into practical Yes/Partial/No items with evidence

prompts. The evaluate phase combined expert validation for content clarity with pilot use in three ports to test usability, integration, and identify data gaps. Final outputs include a pillar scorecard and an action roadmap that sequences immediate improvements, such as metering, idle reductions, and OPS readiness, toward longer-term certification and disclosure goals.

## 2.4 Cross-cutting policy documents and integration logic

To ensure consistency across chapters, the dissertation draws on global and regional regulatory anchors: IMO Net-Zero Framework materials (MEPC 83 summary, Secretariat briefings), IMO LCA Guidelines (2024) on well-to-wake accounting, EU ETS/MRV guidance and THETIS-MRV user materials, and FuelEU Maritime and AFIR texts on OPS supply and use. These sources provide the normative backdrop for empirical analysis and inform indicator design, ensuring that findings remain policy-relevant and future-proof.

Building on these anchors, the three themes are integrated through a place-sensitive transition model that links policy drivers, local capabilities, and measurement practices. Drivers include IMO Net-Zero and EU overlays (ETS, FuelEU, AFIR); capabilities encompass interoperable digital platforms, cyber-resilience, and managerial routines such as lean checklists; and measurement covers MRV/ETS verified emissions, FuelEU well-to-wake intensity, OPS hours, and indicators aligned with EMTER 2025. This synthesis enables evidence mapping from interventions to outcomes, clarifies data requirements, and strengthens compliance pathways.

## 2.5 Ethics, confidentiality and quality assurance

Interviews were conducted under informed consent, with anonymisation and aggregation of quotes and case details to protect confidentiality. Sensitive materials were generalised in reporting, and GDPR principles guided data minimisation, secure storage, and scheduled deletion. Reflexive field notes documented researcher positionality and potential sources of bias, ensuring transparency in interpretation. Quality assurance relied on triangulation across technical, organisational, and managerial evidence, supported by regulatory validation (e.g., MEPC 83 outcomes and European Commission guidance). Coding and instrument documentation were maintained for transparency, and transferability was addressed through context-aware reasoning using CMO chains rather than universal claims. For Arctic BC analysis, heterogeneity in emission factors arising from duty cycles, maintenance states, and fuel batch variability was managed by reporting intervals instead of

single-point estimates, and by recommending performance-based rules for operations in sensitive regions. In the digitalisation theme, causal attribution of environmental benefits remains challenging; future research should employ quasi-experimental designs to isolate effect sizes. For the framework tool, pilots were geographically limited to Finnish ports, highlighting the need for multi-country trials and longitudinal measurement to validate scalability and comparability.

# 3 Theoretical Framework

## 3.1 Positioning the dissertation in economic geography and maritime studies

This dissertation sits at the intersection of economic geography, socio-technical sustainability transitions, and maritime logistics. From an economic-geographical perspective, ports operate as territorially embedded yet globally networked centres that mediate flows of capital, commodities, technologies, and information (Notteboom & Rodrigue, 2005; de Langen, 2007). Their development trajectories reflect path dependence and institutional thickness in local and regional contexts (Amin & Thrift, 1994; Martin & Sunley, 2006), while competitiveness and environmental performance are shaped by their position within global production networks (GPNs) and global value chains (GVCs) (Coe & Yeung, 2015).

Sustainability transitions literature provides complementary lenses. The multi-level perspective (MLP) conceptualises change as interactions among niche innovations, socio-technical regimes, and landscape pressures (Geels, 2002; Markard et al., 2012). In shipping and ports, landscape pressures include climate change, geopolitics, and regulatory tightening; regimes encompass bunkering infrastructure, vessel technologies, operational norms, and port governance; niches include emergent fuels (e.g., methanol, ammonia), digital twins, shore power, onboard carbon capture, and new business models. These frameworks help explain why transitions are uneven, contested, and path dependent.

The three empirical parts of this dissertation align with these theoretical perspectives. The study on Arctic black carbon addresses climate externalities in a geographically peripheral yet highly sensitive region (Brunila et al., 2020). The analysis of port digitalisation examines regime-level lock-ins and organisational capabilities that influence technology adoption (Brunila et al., 2021). The development of small-port performance tools represents a pragmatic niche intervention designed to scale and diffuse improved practices across diverse local contexts with voluntary actions (Brunila et al., 2023). Together, these parts illustrate how global pressures and local capabilities interact to shape feasible transition pathways.

Bringing these elements together, the dissertation synthesises three interrelated themes: port digitalisation, environmental management, and black carbon mitigation, through the lens of maritime logistics and port operations. Digitalisation emerges not as a single technology upgrade but as a system-level transformation requiring interoperability, stakeholder alignment, and long-term planning. When implemented effectively, digital solutions act as catalysts for sustainability by enabling efficient logistics, supporting data transparency, and reducing emissions. This logic is reinforced by the lean environmental performance tool developed for small ports, which addresses resource constraints and creates a structured pathway toward compliance and continuous improvement. These findings confirm that digitalisation and environmental management are not separate agendas but mutually reinforcing processes.

Environmental management systems (EMS) are shown to be more than compliance instruments; they function as strategic tools for competitiveness. Ports that proactively engage in monitoring and reporting are better positioned to meet stakeholder expectations, attract sustainable cargo flows, and comply with emerging climate policies such as the EU Green Deal and IMO regulations. At the same time, the Arctic BC analysis underscores the urgency of emission control for short-lived climate forcers. Ports play a vital role in enabling emissions reductions in maritime transport, as they function not only as nodes in transport networks but also as interfaces within broader energy systems. The availability of alternative fuels and energy solutions in ports directly influences the technological and operational choices available to shipping companies. Consequently, fuel and energy infrastructure has become an increasingly central element of ports' strategic development and competitiveness.

Digital tools, such as real-time monitoring and automated reporting platforms, enhance the accuracy and efficiency of emission tracking, while the self-assessment tool can be extended to include BC metrics, aligning local actions with global climate goals. The combined insights support a holistic model for smart and sustainable ports. This model rests on three principles: (1) Digitalisation as a foundational enabler of operational efficiency and environmental responsibility; (2) Environmental management embedded in port strategy rather than treated as a compliance exercise; (3) Emission control, particularly for short-lived climate forcers like black carbon, requiring both technological innovation and policy alignment. By integrating these dimensions, ports can move from reactive compliance to proactive leadership in sustainability.

## 3.2 Governance, spatial sensitivity considerations and transition dynamics in maritime decarbonisation

Maritime decarbonisation is shaped by uneven spatial impacts, layered governance structures, and complex socio-technical dynamics. From an economic geography perspective, externalities of global shipping are not evenly distributed across places (Cowen, 2014). There are many special or vulnerable areas not just the Arctic (van Roy et al., 2023). The Baltic Sea is one of the world's first and most stringent Emission Control Areas (ECA) designated by the IMO (Jonson et al., 2019). Since 2006, it has been designated as a Sulphur Emission Control Area (SECA), requiring ships to use fuel with a sulphur content significantly lower than the global limit. In 2015, the sulphur cap in the Baltic Sea was reduced to 0.10%, making it one of the strictest regulatory environments for maritime emissions. In addition, the Baltic Sea was designated as a Nitrogen Oxide Emission Control Area (NECA) in 2021, applying stricter NO<sub>x</sub> emission standards to newly built ships operating in the region (Jonson et al., 2015; Olaniyi, 2017).

The ECA status of the Baltic Sea reflects its environmental sensitivity and dense coastal population. Reduced air emissions from shipping are particularly important in the region due to the proximity of major ports and urban areas, as well as the semi-enclosed nature of the sea, which limits pollutant dispersion. As a result, ECA regulations in the Baltic Sea have accelerated the adoption of cleaner fuels, exhaust gas cleaning systems, and alternative energy solutions such as LNG, methanol, shore power, and hybrid propulsion systems. More broadly, the Baltic Sea ECA illustrates how place-based maritime regulation can drive technological innovation while addressing region-specific environmental risks. The experience gained in the Baltic Sea has influenced the development of other ECAs globally and continues to serve as a reference point for discussions on stricter carbon and pollutant controls in vulnerable marine regions (Sampson et al., 2016; Jonson et al., 2019; van Roy et al., 2023).

The Arctic exemplifies a peripheral space with disproportionate vulnerability: BC deposition on snow and ice reduces albedo and accelerates melt, amplifying radiative forcing and local warming (Bond et al., 2013; Flanner, 2013). Although shipping's global share of BC is modest, its regional forcing in polar latitudes is disproportionately large (Brunila et al., 2020), and seasonal peaks coincide with navigable windows (Corbett et al., 2010; Winther et al., 2014). In global production network terms, the Arctic is a thin node linked by volatile corridors, where cost-minimising routing incentives can conflict with precautionary governance. This asymmetry underpins the case for place-sensitive regulation, where instruments account for geographic vulnerability (AMAP, 2011; Assara et al. 2015).

Recent policy developments illustrate this multi-scalar logic. At the global level, the IMO Net Zero Framework (draft amendments approved April 2025; adoption expected 2026; entry into force 2028) introduces a goal-based GHG intensity standard and a pricing/crediting mechanism, complemented by polar fuel discussions aimed at curbing BC through distillate or zero-carbon fuels in Arctic waters. At the regional level, FuelEU Maritime imposes well-to-wake GHG intensity targets ( $-2\%$  by 2025;  $-80\%$  by 2050) and mandates on-shore power supply (OPS) for passenger and container ships at berth, reinforcing port-side abatement (European Commission, 2025). These measures interact with EU ETS obligations, creating cost signals that accelerate low-carbon adoption. Together, they form a policy mix that links geographically targeted controls with sector-wide decarbonisation, supporting a multi-scalar governance view, where global, regional, national, and port-level measures converge (Bridge & Perreault, 2009).

Ecological modernisation theory argues that well-designed regulation can induce innovation and decouple growth from environmental harm (Mol & Sonnenfeld, 2000). However, instrument choice matters. A coherent policy mix combining standards, pricing, and support measures reduces lock-in risks and manages transition uncertainty (Rogge & Reichardt, 2016). At the global layer, IMO's fuel standard and pricing architecture set an umbrella incentive structure, while Arctic-specific polar fuel provisions introduce place-based constraints. At the regional layer, FuelEU Maritime and the EU ETS extension to shipping create binding intensity limits and carbon costs, with surrender obligations reaching 70% of 2025 emissions. At the port and firm layer, environmental management systems (ISO 14001/EMAS), EcoPorts/PERS, and GRI/ESG frameworks structure disclosure and continuous improvement, though scale diseconomies challenge smaller ports (Peris Mora et al., 2005; ESPO, 2016; Puig et al., 2017; Brunila et al., 2023). This multi-layered architecture underpins a compliance–innovation loop: standards and pricing trigger search for alternative fuels and efficiency measures, while ports act as orchestrators by enabling bunkering, OPS, and stakeholder coordination (de Langen, 2007; Woo, Moon, & Lam, 2017).

Socio-technical transitions scholarship explains why these changes are non-linear and contested. The multi-level perspective (MLP) frames transitions as interactions among niche innovations, incumbent regimes, and landscape pressures (Geels, 2002; Markard et al., 2012). In shipping, the regime couples entrenched fuel infrastructures (HFO/MDO), vessel designs, class rules, and cost-focused chartering. In ports, regime elements include legacy terminal systems, siloed data architectures, and analogue processes (Brunila et al., 2021). Lock-ins arise from asset longevity, network externalities, and standardisation inertia (Unruh, 2000). Niche innovations like methanol, ammonia, hydrogen, OPS, digital twins, onboard carbon capture face challenges unless enabling infrastructures, interoperable standards, and market pull

are present. Digitalisation operates as both an enabler and a new regime element: it improves situational awareness, reduces dwell times and energy waste, and supports predictive maintenance, yet adoption is hampered by interoperability gaps, cyber risks, skills shortages, and organisational resistance (Heilig et al., 2017; Brunila et al., 2021). EU-level efforts toward a digital single transport environment (eFTI) and port data harmonisation aim to build institutional complementarities, but implementation costs remain significant for smaller actors (Rodrigue et al., 2022). These dynamics confirm that the greater the legacy asset specificity and the lower the interoperability of digital and energy infrastructures, the stronger the socio-technical lock-in and the slower the uptake of decarbonisation measures (Unruh, 2000; Geels, 2002; Brunila et al., 2021).

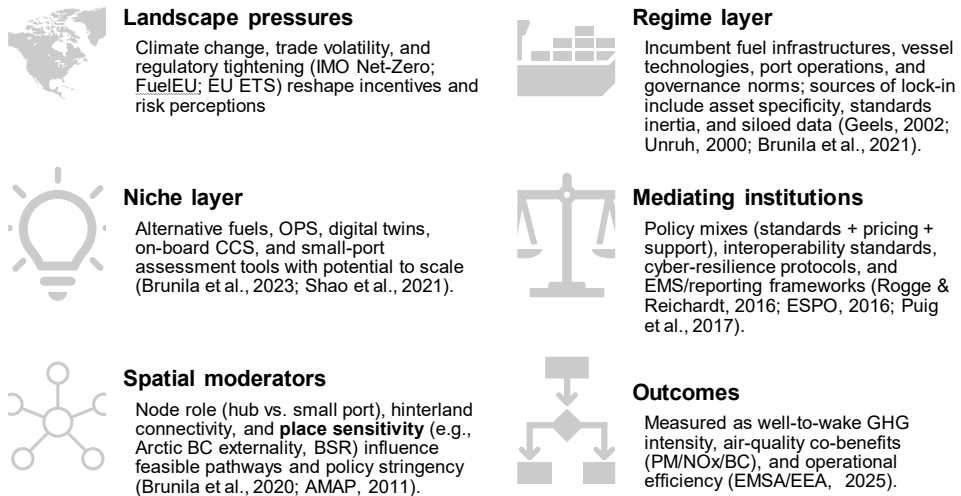
### 3.3 Digital platforms, measurement, and transition pathways

Digitalisation and environmental performance measurement are central to enabling maritime decarbonisation. From a platform economics perspective, Port Community Systems (PCS) and standards-based APIs function as governed platforms that coordinate multi-sided interactions among terminals, shipping lines, hinterland carriers, customs, and regulators (Gawer & Cusumano, 2014; Tsiulin et al., 2020). Network effects and data externalities make platform governance, access rules, data rights, and cybersecurity critical to trust and operational efficiency (Cennamo, 2021). Empirical evidence shows that ports with modular, standards-compliant architectures achieve greater efficiency and are better positioned to internalise environmental co-benefits, such as reduced auxiliary engine use at berth through optimised calls (Carlan et al., 2016; Brunila et al., 2021). However, cyber-physical risks are rising in maritime transport (Jensen, 2015; Inkinen et al., 2019; Tam & Jones, 2019), and resilience depends on shared protocols, continuous monitoring, and incident response capacities, capabilities often underdeveloped in smaller ports (Brunila et al., 2021; Senarak, 2021). Interoperability standards and cyber-resilience practices therefore mediate the relationship between digital investment and environmental outcomes; without them, digitalisation may fail to deliver sustained emissions reductions (Carlan et al., 2016; Tam & Jones, 2019; Wang & Sarkis, 2021).

Performance measurement frameworks complement digitalisation by operationalising environmental goals. ISO 14001 and EMAS institutionalise continuous improvement cycles, while GRI and ESG provide disclosure frameworks, though comparability and materiality remain concerns (Searcy, 2012; Christensen et al. 2021). In the port sector, EcoPorts/PERS adapts environmental management systems to sector-specific challenges, whereas checklist-based tools

can lower entry barriers for small ports and support stepwise alignment with best practices (Peris-Mora et al., 2005; ESPO, 2016; Puig et al., 2017; Brunila et al., 2023). Methodologically, indicator systems should balance quantitative dimensions, such as energy consumption per TEU, well-to-wake GHG intensity, OPS utilisation hours, and BC proxy metrics, with qualitative aspects like governance routines and stakeholder engagement (Puig et al., 2015; Brunila et al., 2021; Brunila et al., 2023). Lean and modular performance tools that mirror ISO and PERS logic, but allow partial adoption, can catalyse continuous improvement and enhance comparability while avoiding excessive resource demands (Peris-Mora et al., 2005; Brunila et al., 2023).

Bringing these themes together, the dissertation conceptualises a place-sensitive transition model that links regulatory drivers, digital and energy infrastructures, organisational capabilities, and environmental performance across diverse port geographies, including the Arctic periphery. Landscape pressures, climate change, trade volatility, and regulatory tightening (IMO Net Zero; FuelEU; EU ETS), reshape incentives and risk perceptions. At the regime level, entrenched fuel infrastructures, vessel technologies, and siloed port systems create lock-ins, while niche innovations such as alternative fuels, OPS, digital twins, and lean environmental tools offer pathways for change (Unruh, 2000; Geels, 2002; Brunila et al., 2021; Shao et al., 2021). Mediating institutions determine with policy mixes, interoperability standards, cyber-resilience protocols, and EMS frameworks whether these niches scale. Spatial moderators, including node role (hub versus small port) and Arctic sensitivity to BC, influence feasible pathways and policy stringency (AMAP, 2011; Brunila et al., 2020). Outcomes are measured through well-to-wake GHG intensity, air-quality co-benefits, and operational efficiency (EMSA/EEA 2025). Decarbonisation success depends on coherence across scales: global and regional instruments must be complemented by port-level digital and managerial capabilities and place-sensitive measures that internalise geographically uneven externalities. **Figure 2** brings together the core idea and shows that maritime transition is a multilayer process. Global forces, trade, tightening regulations create a pressure for change.



**Figure 2.** Maritime decarbonisation transition.

### 3.4 Global and regional governance, Arctic sensitivity, and digital complements

Maritime decarbonisation is shaped by a global framework that now couples technical standards with economic measures, and by a regional overlay that links pricing, intensity limits, and infrastructure obligations. At the global level, the IMO has complemented earlier short-term measures, EEXI and CII, with a Net-Zero Framework that was approved as draft at MEPC 83 and is scheduled for adoption in October 2025 with entry into force in 2027 under tacit acceptance. The framework combines a goal-based global fuel standard that progressively reduces well-to-wake GHG intensity for marine energy with a global economic measure that prices ship GHG emissions and establishes an IMO Net-Zero Fund to recycle revenues, for example to reward early movers and support a just transition. The 2024 LCA Guidelines standardise well-to-wake accounting across diverse fuel pathways and anchor future standards in transparent lifecycle methods.

In the EU, three instruments form a coherent overlay. The EU ETS for maritime entered into force on 1 January 2024 with surrender obligations phased at 40 per cent, 70 per cent, and 100 per cent for 2024, 2025, and 2026, with 100 per cent coverage of intra-EU legs and 50 per cent of extra-EU legs. FuelEU Maritime has applied since 1 January 2025 and reduces the well-to-wake GHG intensity of on-board energy on a defined trajectory while mandating the use of on-shore power

supply at berth for passenger and container ships from 2030 in TEN-T ports and from 2035 in all EU ports that are equipped with OPS. AFIR provides supply-side obligations so that TEN-T maritime ports ensure sufficient OPS provision by 2030. Taken together, the overlay internalises emissions costs through ETS, constrains fuel intensity through FuelEU, and builds infrastructure through AFIR. This increases the value of trusted, interoperable data and of OPS-readiness for both compliance and operational optimisation.

Within this governance setting, two complementary themes are central to the theoretical framing of this dissertation. First, black carbon in Arctic contexts demonstrates the need for place sensitivity in regulation and practice. Baltic Sea is also sensitive area with its special requirements and limitations like ECA BC is a short-lived climate forcer formed by incomplete combustion. While shipping's global share is moderate, deposition on snow and ice reduces albedo, amplifies regional radiative forcing, and accelerates melt. Policy advances have begun to reflect this science. After MEPC 82 the IMO process identified the polar fuels concept to reduce BC from ships in or near the Arctic, and technical work continued at PPR 12 with a timetable aligned to the Net-Zero process. In practical terms, and consistent with Article I, distillate switching and diesel particulate filtration, coupled with operational measures such as slow steaming and maintenance, can reduce BC at current technology maturity. These options bring co-benefits for particulate matter and local air quality, which explains their prominence in near-term policy discussion.

Interoperability through standardised data models and APIs, robust cybersecurity, and credible data governance are the conditions that convert digital projects into environmental outcomes, for example shorter turnarounds, fewer anchorage and idle hours, higher OPS utilisation, and optimised duty cycles. These conditions align with the EU compliance stack. THETIS-MRV and related guidance make verified data the basis for ETS surrender and company oversight. FuelEU intensity accounting and OPS obligations increase the marginal value of granular energy and OPS data. AFIR's OPS build-out creates the physical complement to digital readiness. Article II expresses these relationships through Context–Mechanism–Outcome chains and shows that standards-first architectures reduce lock-in and support measurable environmental effects.

### 3.5 Small port and voluntary actions and the place sensitive transition framework

Small ports occupy a distinctive position within the maritime transport and logistics system. While they share many of the environmental and social challenges faced by larger ports, their operational scale, governance structures, financial capacity and stakeholder environments differ markedly (Puig et al. 2015; Brunila et al., 2023).

These characteristics significantly influence how sustainability is understood, implemented and prioritized in small ports. In this sense, voluntary actions—particularly those framed through corporate social responsibility (CSR) and the adoption of best practices—play a disproportionately important role in shaping sustainable development pathways for small ports (Karagiannis et al., 2022; Marco-Lajara et al., 2022; Brunila et al., 2023; Tsatsaronis et al., 2024).

Environmental concerns have become a central issue in maritime logistics, encompassing political, regulatory and reputational dimensions. Increasing regulation of port-related pollution, together with growing public awareness and societal expectations, has made environmental performance unavoidable also for small ports (Brunila et al., 2023; Fatima & Elbanna, 2023; Lu, 2024; Rodrigues et al., 2024). At the same time, ports are under pressure to improve economic efficiency in response to intensifying inter-port competition. For small ports, which often operate with limited cargo volumes and narrow profit margins, the need to balance economic viability with environmental responsibility is particularly acute (Meyer, 2021; Pelevic et al., 2024). Sustainable management of operations therefore becomes not only a normative objective but also a strategic necessity, requiring the simultaneous consideration of economic, environmental and social factors (Ashrafi et al., 2020; Lu, 2024).

Within this context, voluntary actions emerge as a key mechanism through which small ports can pursue sustainability beyond mere regulatory compliance. Corporate social responsibility provides a conceptual framework for understanding these actions (Vanellander, 2016; Brunila et al., 2023; Satta et al., 2025). CSR emphasizes that organizations voluntarily integrate environmental and social concerns into their operations and stakeholder interactions, with the recognition that such integration may also generate long-term economic benefits. For small ports, voluntary engagement in CSR is seldom driven by marketing visibility or brand differentiation in consumer markets, as port operations are typically business-to-business in nature. Instead, CSR in small ports is often closely linked to local legitimacy, continuity of operations and the maintenance of trust with surrounding communities, authorities and other non-commercial stakeholders.

The dual nature of responsibility is particularly relevant for small ports. On one hand, responsibility can function as an internal management tool aimed at improving operational efficiency, reducing costs and enhancing long-term resilience. On the other hand, responsibility also arises from external pressures, including expectations from local communities, municipalities and regional authorities, even when formal stakeholder pressure from customers remains limited. In small ports, these external expectations are often intensified by spatial proximity between port activities and urban or residential environments. As a result, social and environmental impacts—

such as noise, air emissions, dust and odours—are more visible and immediate, strengthening the importance of voluntary mitigation measures.

CSR in small ports thus encompasses environmental, social and economic dimensions in a manner that is often more integrated and context-sensitive than in large hub ports. Environmentally responsible actions may include managing energy consumption, reducing and safely disposing of waste, monitoring emissions and investing in cleaner technologies. While these measures may initially appear costly, they often align with operational efficiency goals by reducing energy use, material losses and future compliance risks. From a social perspective, voluntary actions that reduce noise and emissions contribute directly to improved living conditions in adjacent communities, reinforcing the port's social licence to operate. Economically, sustainability-oriented decisions can enhance predictability, reduce long-term costs and improve the port's reputation among partners and authorities (Christodoulou, et al., 2021; Haezendonck, 2021; MacNeil et al., 2021; Brunila et al., 2023).

The specific environmental impacts associated with ports—including construction activities, water and road transport, waste generation and various forms of disturbance—are also present in small ports, albeit at a different scale. Voluntary measures such as life-cycle assessment in infrastructure development, waste management systems, renewable energy use and continuous environmental monitoring can therefore be highly relevant. On-shore power supply serves as a good example of a voluntary action where environmental and social benefits align. By reducing the need for auxiliary engines, such systems mitigate local air pollution and noise, which is particularly important for small ports located near city centres or residential areas. Although technical and standardization challenges remain, the willingness of small ports to participate in pilot projects or incremental implementation reflects how voluntary action can precede regulatory obligation (Mokashi, 2012; Christodoulou et al., 2021; Herrero et al., 2022; Costa et al., 2024; Gerlitz et al., 2024).

A notable challenge for small ports is that CSR activities are often not systematically formalized. Limited organizational capacity and resources may constrain the adoption of comprehensive CSR strategies or certification schemes. Nevertheless, this does not imply an absence of responsibility. Instead, CSR in small ports tends to be practice-oriented and embedded in everyday operational decisions rather than articulated through formal policies. Stakeholder dialogue, particularly with local communities and public authorities, plays a central role in identifying expectations and shaping voluntary actions. In this respect, direct interaction and informal communication can compensate for the lack of structured CSR frameworks (Morsing & Spence, 2019; Kuzey et al., 2024).

Voluntary actions in small ports are also closely connected to the development and adoption of best practices. Sharing best practices enables ports to learn from

each other, avoid costly mistakes and identify cost-effective measures for reducing environmental impacts (Karagkouni & Boile, 2024). For small ports, which often lack extensive in-house expertise, access to shared knowledge is especially valuable. Best environmental practices are not universal solutions but context-dependent combinations of measures that achieve superior outcomes relative to other alternatives. While each port is unique in its physical setting, cargo profile and stakeholder structure, many environmental challenges—such as emissions, waste management and energy use—are common across ports of different sizes (Brunila et al., 2023; Deng et al., 2023; Bostoughli & Saraceni, 2025).

The importance of best practices is further amplified by economic constraints. Following periods of economic downturn, investments in environmental measures may be perceived as unaffordable, particularly for small ports. However, voluntary adoption of state-of-the-art sustainable practices can also function as a competitive asset, enhancing operational efficiency and strengthening the port's position within regional logistics networks. In this way, sustainability shifts from being viewed solely as a regulatory burden to becoming an economic driver, a shift that is central to the Green Port concept (Hiranandani, 2014; Marco-Lajara et al., 2022).

Small ports often face fixed costs of certification and documentation and fragmented data that hinder credible reporting and benchmarking. A lean environmental management instrument that follows the logic of ISO, EMAS, EcoPorts and PERS, and GRI, but without the initial documentation burden, lowers the entry threshold while allowing stepwise convergence on best practices (Meyer, 2021; Brunila et al., 2023; Gerlitz et al., 2024). The instrument used in Article III organises four pillars, Environmental Management, Responsibility, Impact Assessment, and Self-Monitoring, and uses a Yes, Partial, or No logic to surface data gaps, structure engagement with tenants and municipalities, and create comparable baselines for energy, emissions, waste, and OPS planning.

These themes come together in a place-sensitive transition framework. Drivers consist of IMO Net-Zero standards and pricing and the EU overlay of ETS, FuelEU, and AFIR. Capabilities include interoperable digital platforms, baseline cyber-resilience, and managerial routines expressed through lean checklists. The framework expects the strongest outcomes where policy drivers and local capabilities are complementary and where spatial sensitivity, for example the Arctic BC externality, is reflected in fuel choice and operational practice. The theoretical implication is that governance signals, infrastructural complements, and measurement routines must evolve together if decarbonisation is to move beyond compliance toward sustained performance improvement.

## 4 Summary of the Findings in the Individual Research Articles

This chapter synthesises the empirical and conceptual results from the three peer reviewed articles that constitute the core of the dissertation. Each subsection states the article’s aim, dataset and method, and the main findings. Chapters then address robustness and boundary conditions before drawing out implications for policy, management, and future research. A final section integrates the papers into a place sensitive transition logic that underpins the dissertation’s overall answer to the research question.

### 4.1 Article I: Black Carbon, Maritime Traffic and the Arctic

Article I examines the climatic significance of black carbon (BC) emissions from ships operating in Arctic and sub-Arctic settings and evaluates feasible near-term mitigation measures. The central premise is that place matters: BC deposited on snow and ice reduces surface albedo, meaning that the same tonne of BC has a disproportionately high marginal impact in polar environments compared to temperate latitudes. Mitigation is therefore framed not only as a technological challenge but also as a spatial targeting problem.

The study adopts a state of the art synthesis of combustion and engine literature, triangulating evidence on emission factors across fuel classes: residuals, distillates, low sulphur blends, and bio blends, alongside engine generations, after treatment technologies such as diesel particulate filtration and oxidation/SCR systems, and operational profiles including engine load, maintenance status, and slow steaming regimes. Rather than relying on single point estimates, the analysis reports intervals and emphasises performance-based comparisons to reflect real world heterogeneity.

The findings underscore that spatial sensitivity is decisive. Although shipping’s global contribution to BC is moderate, Arctic exposure transforms relatively small emission reductions into materially significant climate benefits, justifying geographically differentiated mitigation priorities rather than uniform

global averages. Fuel selection emerges as the dominant lever for immediate reductions: switching from residual fuels to distillates produces substantial BC cuts under realistic loads. Evidence for bio blend performance is promising but contingent on blend quality and engine compatibility, leading to a recommendation for controlled deployment rather than blanket substitution. After treatment and operational measures are shown to be additive. Particulate filtration can remove a large share of BC mass when correctly specified and maintained, while operational practices such as slow steaming, combustion tuning, and adherence to maintenance schedules stack with cleaner fuels to deliver reductions that are both rapid and operationally feasible.

Policy relevance lies in the variability of outcomes across test conditions, engine states, and fuel batches. The article argues for performance-based provisions, verified reductions rather than prescriptive technologies, and for place sensitive rules, in practice fuel quality requirements and operational constraints when ships operate in or near Arctic waters. Robustness checks confirm that the relative ranking of options remains stable across load assumptions, although absolute effect sizes vary with duty cycles, maintenance quality, and fuel properties. Filtration performance depends on specification, back pressure management, and fouling control, while bio blend outcomes require assurance of consistent batch quality. These conditions motivate monitoring regimes that are verifiable yet practical for operators.

For policy, global decarbonisation measures should be coupled with Arctic specific BC controls that focus on fuel quality and verified in service performance. For industry, a “no regrets” package, distillates or vetted bio blends combined with filtration and operational optimisation, should be prioritised on trades with Arctic exposure. For research, the next step is to progress standardised BC metrics and well to wake accounting that can follow ships across engines, fuels, and operational states.

## 4.2 Article II: Hindrances in Port Digitalisation? Identifying Problems in Adoption and Implementation

Article II investigates why port digitalisation has progressed unevenly and under which conditions it delivers measurable environmental co-benefits, particularly in its initial phases. Rather than presenting a technology inventory, the article conceptualises digitalisation as an organisational and infrastructural challenge, treating digital projects as platform strategies whose value materialises only when multiple actors can reliably exchange data and coordinate actions.

The study is based on an extensive literature review and empirical evidence derived from research and development projects conducted over the past decade. It

applies a narrative synthesis anchored in multiple case studies from regions worldwide, including implementations of Port Community Systems (PCS), IoT and 5G pilot projects, data exchange standards, as well as materials related to cybersecurity and governance. The findings identify interoperability as the first-order bottleneck. Fragmented message sets, proprietary interfaces, and legacy silos create “digital islands,” escalating integration costs, delaying end-to-end visibility, and weakening the data quality required for optimisation. Capability and resource constraints further slow progress, particularly in small and medium-sized ports. Limited IT budgets, skills gaps, and insufficient change-management capacity lead to partial or stalled deployments, leaving operations in hybrid analogue–digital states that cannot support systematic optimisation.

Cybersecurity emerges as a non-negotiable precondition for digitalisation. Weak identity and access management, outdated systems, and inadequate incident-response protocols undermine trust among port community actors and increase operational risk, thereby slowing or even reversing adoption. Governance ultimately determines whether digitalisation delivers value. Modular, standards-first architectures—such as open APIs and common data models—combined with shared governance arrangements within the port community, reduce vendor lock-in and create option value for incremental development. Environmental co-benefits, however, are conditional rather than automatic. Efficiency gains such as reduced auxiliary engine use, lower idle and anchorage times, and smoother yard and berth operations arise only when interoperable data are complete, timely, and trusted, and when business processes are re-engineered to utilise them effectively.

Robustness checks suggest that these mechanisms hold across different port sizes and governance models, although effect sizes vary with throughput volatility, tenant structure, and the degree of hinterland integration. Measurable environmental improvements—such as increased OPS utilisation or reduced anchorage times—require not only data interoperability but also operational levers, including berth-planning authority and terminal-level alignment. In the absence of these mechanisms, digitalisation risks producing dashboards rather than tangible outcomes.

Overall, the findings demonstrate that port digitalisation is primarily a strategic and organisational transformation, not merely a technological upgrade. Progress depends on the capabilities and readiness of the entire transport chain, including smaller operators, positioning ports as coordinators and data-sharing hubs rather than isolated technology adopters. A key implication concerns the critical importance of the initial phase of digitalisation: early decisions regarding architecture, standards, and governance structure long-term trajectories and can either enable flexibility or create costly lock-in effects. Digitalisation should therefore be pursued as a modular

and scalable platform strategy aligned with explicit business and environmental objectives, rather than as isolated or imitation-driven investments.

The results further indicate that resource asymmetries and organisational readiness shape uneven outcomes. Smaller ports are more exposed to the disadvantages of incompatible systems, limited expertise, and resistance to organisational change, underscoring the need for shared standards, supportive policy frameworks, and targeted capacity-building measures. Finally, cybersecurity and data governance emerge as foundational requirements. Treating ports as closed operational environments underestimates systemic cyber risks and can undermine trust and adoption. Integrating security and data governance from the outset is therefore essential to ensure that digitalisation produces durable gains in efficiency, competitiveness, and environmental performance.

### 4.3 Article III: Sustainable Small Ports: Performance Assessment Tool for Management, Responsibility, Impact, and Self Monitoring

Article III develops and pilots a lean, checklist-based tool designed to enable small ports to manage and demonstrate environmental performance without incurring prohibitive costs. The design retains compatibility with mainstream frameworks such as ISO 14001, EMAS, EcoPorts/PERS, and GRI/ESG, while stripping away the documentation burden that often deters first-time adopters. By simplifying entry requirements, the tool provides a practical pathway for ports with limited resources to engage in structured environmental management and prepare for future certification.

The study adopts a design science research approach complemented by case study elements and heuristic testing characteristics during the evaluation process. Established environmental management and reporting frameworks are synthesised into a four-pillar structure comprising Environmental Management, Responsibility, Impact Assessment, and Self-Monitoring. Each pillar is operationalised through clear Yes/Partial/No assessment items supported by explicit evidence prompts. The tool underwent expert validation and was piloted in three Finnish major ports: HaminaKotka, Helsinki, and Turku. Feedback from these pilots informed iterative refinements to wording, indicator ordering, and guidance notes, ensuring alignment with operational realities such as metering, equipment duty cycles, and OPS readiness. Additional stakeholder workshops and structured interviews with port managers and environmental officers provided further insights into usability and scalability, while comparisons with ISO and EMAS standards confirmed conceptual alignment.

The findings demonstrate that low-barrier design significantly increases adoption feasibility. Ports can begin from their current state, document partial compliance transparently, and sequence improvements toward full certification and credible disclosure. Comparability is achievable without imposing maximal paperwork: by aligning with the logic rather than the full documentation stack of ISO, PERS, and GRI, the tool enables benchmarking across ports while respecting operational and geographic differences. Beyond compliance, the instrument acts as a catalyst for data governance and stakeholder engagement. It surfaces data gaps, structures conversations with tenants and municipalities, and prepares ports for audits and ESG reporting. Operational co-benefits accrue early, as ports consistently prioritise metering, duty-cycle tracking, optimised lighting, and OPS readiness, producing tangible energy and emission improvements and establishing clearer baselines for long-term decarbonisation.

Robustness checks indicate that the tool's structure travelled well across the three pilots, but its pace of adoption depends on management attention, tenant cooperation, and access to basic metering infrastructure. The Yes/Partial/No logic is sufficiently expressive to document progress but should be complemented by quantitative indicators once foundational routines are in place. These conditions underscore the importance of sequencing: qualitative assessments provide an entry point, while quantitative metrics consolidate credibility over time.

The implications extend across policy, practice, and research. For policy, dissemination of open, lightweight tools should be coupled with funding for capacity-building and encouragement of peer benchmarking among small ports. For managers, the checklist offers a practical means to stage EMS adoption, close data gaps, and plan the step-up to ISO, EMAS, PERS, and ESG disclosure. For research, future work should extend pilots to more diverse geographies, incorporate longitudinal tracking, and estimate effect sizes on compliance, emissions, and stakeholder trust. By lowering entry barriers and embedding comparability, the tool positions small ports to participate meaningfully in the broader decarbonisation transition.

#### 4.4 Cross-article synthesis and the overarching research question

The synthesis of the three articles reveals a coherent transition logic that underpins the dissertation's central argument. First, the analysis confirms that place-sensitive externalities demand place-sensitive instruments. The Arctic's vulnerability to black carbon establishes a geographical hierarchy of harm, where targeted measures such as fuel-quality requirements and operational rules in polar waters, deliver greater climate benefits per unit of effort than undifferentiated global standards. This insight

reinforces the need for regulatory frameworks that recognise spatial heterogeneity rather than relying solely on uniform prescriptions.

Second, the findings demonstrate that technological and organisational infrastructures must co-evolve. Environmental payoffs from new technologies, including cleaner fuels and on-shore power supply, are conditional on organisational capabilities such as interoperable data platforms, cyber-secure information sharing, and pragmatic management routines. Digital and managerial capacities emerge not as optional enhancements but as structural complements to technical innovation. Without these, ports risk accumulating tools without translating them into measurable environmental outcomes.

Third, sequencing and modularity are shown to reduce transition frictions. High-leverage near-term packages, such as distillate switching combined with filtration and operational optimisation in Arctic trades, standards-first approaches to Port Community Systems and data governance, and lean environmental management tools create momentum for change while buying time and capability for more capital-intensive steps. Sequencing avoids organisational overload and mitigates the risk of themed investments, enabling ports to progress along credible pathways rather than pursuing fragmented initiatives.

Finally, measurement functions both as a capability and as an incentive. Trusted and comparable indicators, ranging from verified emissions and OPS hours to structured EMS checklists, transform strategic intent into accountability. Measurement systems not only enable benchmarking and compliance but also prime organisations for future certification and disclosure obligations, reinforcing the iterative nature of environmental improvement.

These themes converge in the overarching research question: How can ports and Arctic-relevant shipping navigate a place-sensitive green and digital transition that is environmentally effective, organisationally feasible, and scalable across diverse geographies? The empirical evidence provides a layered response. Article I shows that Arctic-exposed operations benefit most from a portfolio of feasible measures—fuel switching to distillates or controlled bio-blends, particulate filtration, and operational optimisation—supported by performance-based monitoring that prepares the ground for geographically differentiated regulation. Article II demonstrates that interoperability, cyber-resilience, and shared governance are necessary conditions for digitalisation to yield verifiable environmental benefits; absent these, digitalisation remains a technical upgrade rather than a systemic transformation. Article III introduces a lean, four-pillar instrument that offers small ports a credible, low-cost entry point to environmental management and comparable reporting, enabling sequenced capability building toward formal certification and robust ESG disclosure.

Taken together, the integrated answer is clear: effective maritime transitions are place-sensitive, infrastructure-complementary, and measurement-driven. Global and

regional rules achieve their intended effects only when local actors possess the digital and managerial capacities to operationalise them, and when measurement systems are simple enough to implement yet rigorous enough to matter. This synthesis positions the dissertation within a broader theoretical and practical discourse on how governance, technology, and organisational routines interact to shape sustainable pathways for ports and shipping.

Synthesis of dissertation is explained in the **Table 2** that collects the key findings and interconnections of each article. The individual articles address different but complementary aspects of the same transition. Article I focuses on emission challenges and mitigation priorities, Article II examines the conditions under which digital solutions support environmental performance, and Article III provides a practical management tool for implementation. Together, the articles explain how environmental goals can be translated into operational practices at port level.

**Table 2.** Synthesis of dissertation.

<b>Theme</b>	<b>Article Contribution</b>	<b>Key Findings</b>	<b>Interconnections</b>
<b>Port Digitalisation</b>	Brunila et al. (2021) – Hindrances in Port Digitalisation	Identifies barriers to digital transformation in ports, including technological incompatibility, resource constraints, cybersecurity risks, and resistance to change. Highlights digital maturity models and the role of digitalisation in improving efficiency and sustainability.	Digitalisation enables better environmental monitoring and emission tracking. Supports the implementation of environmental management systems and emission control strategies.
<b>Environmental Management</b>	Brunila et al. (2023) – Sustainable Small Ports	Introduces a self-assessment tool for environmental performance in small ports. Emphasises the need for accessible, scalable tools tailored to resource-constrained ports. Covers management, responsibility, impact assessment, and self-monitoring.	Environmental management is supported by digital tools for data collection and reporting. The self-assessment framework can integrate emission metrics, including black carbon.
<b>Black Carbon Emissions</b>	Brunila et al. (2020) – Black Carbon, Maritime Traffic and the Arctic	Analyses the impact of black carbon emissions from maritime traffic in the Arctic. Discusses fuel types, emission sources, and mitigation technologies. Highlights the disproportionate climate impact of BC in polar regions.	Emission control requires integration with digital monitoring systems and environmental management practices. Supports the need for policy alignment and technological innovation in ports.

## 4.5 Robustness, limitations, and practical directions for future research and policy

The dissertation contributes to academic discourse and practical policymaking by offering a multi-level, interdisciplinary perspective on maritime and port transition, demonstrating that ambition without capability is rhetoric, and capability without ambition is inertia. The robustness of the findings across the three articles rests on triangulation and context-aware interpretation, yet several limitations shape the scope of generalisation and point to future research needs. For Arctic black carbon mitigation, the magnitude of achievable reductions varies with operational factors such as engine duty cycles, maintenance regimes, and fuel quality. This variability confirms the value of performance-based provisions and in-service verification rather than rigid technology prescriptions. While the ranking of mitigation options remains stable, absolute effect sizes depend on operational conditions, underscoring the need for monitoring regimes that are both verifiable and practical.

In the digitalisation theme, causal attribution of environmental benefits remains a methodological challenge. Although case evidence strongly supports the mechanisms linking interoperability and governance to operational outcomes, estimating effect sizes requires quasi-experimental designs. Approaches such as difference-in-differences analysis on anchorage time, OPS hours, and equipment energy use would strengthen causal inference and move beyond anecdotal claims. Similarly, the lean environmental management tool piloted in Finnish ports demonstrated conceptual validity and usability, but its generalisability across diverse geographies and governance contexts calls for multi-country trials and longitudinal studies. These would calibrate realistic improvement trajectories and resource demands while testing scalability under varying institutional conditions. While digital systems are shown to enable environmental improvements, the magnitude of these benefits is not empirically quantified in this dissertation. Future studies should therefore focus on measuring the environmental impacts of digital solutions using quantitative data.

Future research should therefore prioritise three directions: evaluating policy-consistent BC mitigation portfolios using operational data from Arctic seasons; estimating digital–environment effect sizes through panel methods and quasi-experimental designs; and scaling the framework tool with shared indicator repositories to accelerate peer learning and comparability across ports. Alongside these research priorities, practical and policy implications including self-regulation in the form of voluntary environmental reporting emerge clearly from the synthesis. For policy makers, targeted Arctic BC measures should combine fuel-quality and operational provisions, supported by funding for standards-first digital governance and baseline cyber-resilience. Dissemination of lean EMS tools for small ports

should be tied to measurable milestones to ensure uptake and accountability. For port authorities and operators, digitalisation must be treated as a community platform rather than a series of isolated projects. Closing data and security gaps early, sequencing projects to deliver credible early wins, and embedding governance routines alongside technical upgrades are essential. The four-pillar checklist offers a structured pathway for environmental management, enabling ports to link operational key performance indicators, idle time, OPS hours, and duty cycles, to emission outcomes. On Arctic-relevant trades, deploying the “no-regrets” package of distillates or vetted bio-blends, particulate filtration, and operational optimisation remains the most immediate and effective strategy.

# 5 Conclusions

This dissertation set out to answer how ports and Arctic-relevant shipping can navigate a green and digital transition that is environmentally effective, organisationally feasible, and scalable across diverse geographies. The analysis combined three themes: mitigation of black carbon emissions in Arctic contexts, conditions under which port digitalisation delivers environmental co-benefits, and the development of a lean environmental performance tool for small ports. Together, these themes demonstrate that regulatory ambition translates into measurable outcomes only when digital and managerial infrastructures co-evolve with policy drivers.

The findings confirm four overarching propositions. First, place matters: Arctic sensitivity to black carbon justifies geographically differentiated measures, such as fuel-quality requirements and operational constraints, rather than uniform global averages. Second, technological and organisational infrastructures are complements: digitalisation reduces emissions only when supported by interoperable standards, cyber-resilience, and governance. Third, sequencing and modularity reduce transition frictions: near-term packages, distillate switching, particulate filtration, and operational optimisation, buy time for more capital-intensive steps. Fourth, measurement is both capability and incentive: trusted, comparable indicators turn strategy into accountability and prepare organisations for future disclosure obligations.

For policy makers, the results support coupling global decarbonisation measures with geographically targeted controls for high-sensitivity regions, notably the Arctic. Funding should prioritise standards-based digital governance and baseline cybersecurity to ensure that digitalisation delivers environmental payoffs rather than themed investments. For port authorities, digitalisation should be treated as a platform strategy rather than a series of isolated projects. Interoperability, shared governance, and modular architectures are prerequisites for measurable gains in energy efficiency and emissions reduction. Small and medium-sized ports should adopt lightweight environmental management tools as stepping stones toward formal certification and ESG disclosure. For industry stakeholders, the evidence points to a “no-regrets” package for Arctic trades: cleaner fuels, particulate filtration, and

operational optimisation. These measures are technologically mature, operationally feasible, and compatible with evolving IMO and EU frameworks.

The dissertation advances a place-sensitive transition model that integrates economic-geographic unevenness, policy mixes, and digital-infrastructure complementarities. It extends sustainability transitions theory by showing how global and regional instruments (IMO Net-Zero, EU ETS, FuelEU Maritime) interact with local capabilities to shape feasible pathways. This multiscalar perspective underscores that decarbonisation outcomes improve when policy drivers and local infrastructures are mutually reinforcing. Although the dissertation identifies clear links between digitalisation and environmental performance, the causal relationships between specific digital measures and emission outcomes could be analysed in more detail. This represents an important direction for future research.

Three priorities emerge. First, quantify effect sizes of digital interventions using quasi-experimental designs to strengthen causal attribution. Second, extend longitudinal trials of lean environmental tools across diverse geographies to calibrate improvement trajectories and resource demands. Third, evaluate policy-consistent mitigation portfolios with operational data from Arctic seasons to refine performance-based provisions for black carbon. The transition to smart and sustainable ports is neither linear nor uniform. It is shaped by geography, governance, and capability asymmetries. By integrating regulatory analysis, technological appraisal, and pragmatic tool design, this dissertation contributes to a holistic understanding of how maritime actors can move from compliance to leadership in sustainability. The central message is clear: ambition without capability is rhetoric; capability without ambition is inertia. Effective transitions requires them both.

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At the same time, there was uncertainty regarding the permanence of my job, and there were clear signs of change in the air. However, not everything went as planned, and I changed workplaces in 2017. In addition, at the end of 2016 a little girl was born into our family, marking the beginning of what is commonly known as the “busy years” of family life. Although the organisation changed, my colleagues and research partners remained the same despite organisational restructurings. We are still colleagues and members of the same research group—now already for 15 years.

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