University of Amsterdam

Final Report

North Sea Watch
Unveiling The Hidden Impact Of Shipping: How Scrubbers Shift Pollution

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Executive Summary

The North Sea Watch[1] project addresses an under-examined yet urgent environmental issue in maritime regulation: the widespread use of exhaust gas cleaning systems (EGCS) – more commonly known as scrubbers – by commercial vessels in the North Sea. Although these systems reduce sulphur oxide emissions to comply with air pollution standards, they shift the environmental burden from air to sea. More than 80% of scrubbers in operation use open-loop configurations, which dump contaminated wastewater directly into marine environments. These discharges contain toxic compounds such as heavy metals, sulfates, and polycyclic aromatic hydrocarbons (PAHs), contributing to ocean acidification and ecological disruption. Despite these risks, regulation across North Sea countries is fragmented, ranging from complete absence of regulations to comprehensive national bans. This inconsistency enables pollution displacement, undermines regional environmental protection efforts, and creates an uneven economic landscape.

This study employed a mixed-method approach that combined computational, empirical, and qualitative research strategies. Real-time maritime traffic data was collected through AISStream.io and processed using ship specification data and modelling inputs from the International Council on Clean Transportation to estimate scrubber discharge volumes. An agent-based model (ABM) was developed using the Python Mesa framework to simulate port selection behaviour, pollution patterns, and revenue effects under three regulatory scenarios. To complement quantitative data methods, four semi-structured interviews were conducted. Among the interviewees were two officials from the Danish Ministry of Environment and Gender Equality, two representatives from

[1]The North Sea Watch website can be visited via https://northseawatch.org

the NGO One Planet Port, a policy advisor from the Port of Amsterdam, and a non-expert stakeholder from the University of Amsterdam's Green Office. These interviews provided insights into the ethical trade-offs, enforcement limitations, and communication challenges related to policy development and implementation. The research process was supported by a broad theoretical framework, which employed systems thinking principles, behaviour change models, and policy analysis, to facilitate the development of the North Sea Watch platform.

Key Findings

- Countries with national scrubber discharge bans (e.g., France) show significantly lower pollution levels, while countries with weak or no regulations (e.g., the UK) exhibit discharge spikes of up to 40 million kilograms per day.
- The ABM reveals that isolated national bans may unintentionally increase total pollution due to traffic displacement, while coordinated bans offer optimal environmental and economic outcomes.
- Policymakers face tensions between economic certainty and precautionary regulation, often acting in the absence of definitive scientific consensus.
- Public and industry awareness of scrubber discharge is remarkably low, limiting grassroots pressure for change.
- Stakeholders emphasise the importance of visual communication tools in driving engagement and regulatory momentum.

The North Sea Watch Platform Summarised

- **Homepage:** Introduces the scrubber pollution issue through accessible storytelling and visuals.
- **Live Map:** Displays real-time shipping data and estimated scrubber discharge, with interactive port-level policy information.
- **Simulation Dashboard:** Enables users – particularly policymakers and port authorities – to model and compare regulatory scenarios and their impact on both pollution and economic activity.

Implications of the North Sea Watch Platform

North Sea Watch has the potential to influence stakeholder behaviour across multiple levels of maritime governance. For environmental organisations like Stichting De Noordzee, the platform consolidates previously scattered scrubber discharge data into a unified advocacy tool, enhancing their ability to demonstrate the geographic scope and scale of pollution to key stakeholders across the maritime sector. The unified presentation of data that was previously available only across multiple sources significantly strengthens the foundation for policy advocacy efforts.

Within the maritime industry, the intervention creates visibility around regulatory inconsistencies across North Sea ports and countries. Port authorities considering scrubber regulations can use the simulation dashboard to examine potential economic and environmental trade-offs before implementation, while policymakers can model regulatory impacts at national scales. The platform provides independent access to visual representations of pollution patterns and regulatory scenarios, which can be crucial in communicating the scale of the problem to stakeholders who may not fully realise its magnitude.

Beyond institutional users, the platform serves an important awareness-raising function by making visible an environmental issue that has remained largely out of public view. While its accessible design supports broader engagement with marine pollution issues, the platform's transformative potential ultimately depends on how it is used. Its long-term impact will rely on continued uptake by advocacy groups, policymakers, and regulators who can use the website as an informational and strategic tool to support more coherent and ambitious environmental protections across the North Sea.

Contents

1 Introduction

The North Sea is one of the largest and most vital ecosystems in Europe (Ducrotoy, Elliott, and De Jonge 2000). However, being a body of water that connects many large cities and countries, the North Sea has been subjected to a vast amount of shipping traffic for centuries. As a consequence, concerns about the emission of harmful chemicals such as sulphur oxides (SO_X) from industrial shipping emerged in the late 20th century, eventually leading to the introduction of international and regional regulations – such as the International Maritime Organization's (IMO) global sulphur cap which was implemented in January 2020 – limiting permitted sulphur levels in exhaust emissions (Matthias et al. 2010; Zis and Cullinane 2020). These regulations forced maritime transportation companies to adapt by either switching to less harmful, low-sulphur fuels, or by investing in exhaust gas cleaning systems (EGCS), also known as scrubbers (Zis and Cullinane 2020). As suggested by the name, EGCSs operate by treating exhaust gases to remove sulphur contents. This process however, involves the intake of seawater, which then becomes contaminated with various chemicals – most notably heavy metals, polycyclic aromatic hydrocarbons (PAHs), and sulphates – before often being discharged back into the environment (Zannis et al. 2022). Despite this, and despite the significant costs of installing EGCSs, various investigations found scrubbers to be more profitable than switching to cleaner fuels, especially for large ships with high levels of fuel consumption (Lindstad, Rehn, and Eskeland 2017; Panasiuk and Turkina 2015; Zis and Cullinane 2020). Even though some ports were quick to implement bans on the discharge of wastewater or the usage of certain scrubber types, EGCSs were widely adopted to comply with the IMO's emission caps (Zis and Cullinane 2020).

The large-scale usage of EGCSs however, sparked investigations regarding their potential ecological impacts, stressing the idea that EGCSs essentially shift harmful pollutants from air to water (Hassellöv 2022). Many such investigations highlight the expected acceleration of sea and ocean acidification, which can lead to disruptions in a multitude of marine species' behaviours and populations (Endres et al. 2018; Shi and Li 2024). Additionally, several studies assess the direct toxicity of EGCS wastewater on different species of zooplankton, discouraging the use of these systems (Jönander et al. 2023; Thor et al. 2021).

While it must be acknowledged that there exist different categories of scrubbers, research indicates that both closed-loop and open-loop – simply put, storage and compaction of pollutants vs. direct discharge – EGCSs contribute to the pollution of shipping waters (Hassellöv 2022; Jönander et al. 2023). Open-loop systems add up to an estimated 80% of all scrubbers, compared to a mere 2% for closed-loop systems and roughly 18% for hybrid systems (scrubbers which can switch between closed-loop and open-loop operating modes) (Delikonstantis et al. 2025). The most notable difference between the categories is the scale at which polluted water is dumped into the environment.

In response to this issue, Stichting De Noordzee, a non-profit NGO located in the Netherlands, has been advocating for stronger regulations and bans on scrubber usage. As of January 1, 2025, the Port of Amsterdam has prohibited the discharge of scrubber water from moored seagoing vessels, making it the first Dutch port to implement any form of regulation against the usage of scrubbers (Port of Amsterdam 2024). In March 2025, the Dutch government announced its intention to prohibit seagoing vessels from discharging scrubber wastewater in all ports and inland waters (Ministry of Infrastructure and Water Management 2025). Although these initiatives show that authorities are moving in the right direction, scrubber pollution will likely remain an issue until the usage of this technology is permanently banned. As such, this project aims to elevate the reach and impact of Stichting De Noordzee's efforts through the development and implementation of a digital intervention. The intervention targets relevant stakeholders, such as policymakers and port authorities, as well as a broader audience to increase public awareness. The end product is a comprehensive digital platform designed to inform, engage, and mobilise support for stricter regulations on scrubber pollution. By leveraging data visualisation and interactive content, it seeks to bridge the gap between scientific research, policy advocacy, and public engagement – filling a critical empty space in the progression toward a sustainable shipping industry and the protection of marine ecosystems (Endres et al. 2018).

In short, the digital intervention – titled *North Sea Watch* – consists of three main elements: a homepage that leverages actionable design and behaviour change principles; an interactive map displaying shipping traffic and scrubber pollution density; and a simulation dashboard aimed at allowing policymakers and port authorities to examine the effects of potential regulations. Altogether, the intervention serves to raise awareness about a seemingly hidden problem, while providing motivation and information for change-makers to act on.

This report provides an analysis of the scrubber problem through literature review, application of systems thinking principles and relevant social science theories, existing policy frameworks, and stakeholder mapping. Furthermore, it elaborates on the quantitative and qualitative data collection methods that facilitated the development of the intervention. As such, it presents the theoretical and empirical foundation of the North Sea Watch web platform, and assesses the intervention's potential future impact accordingly.

2 Theoretical and Practical Framework

Addressing the environmental impact of scrubber water discharge requires a multidisciplinary approach that integrates policy analysis, stakeholder engagement, and technological intervention. The following section situates the issue within existing maritime literature, highlighting regulatory gaps and the need for more comprehensive policy response. It also outlines key stakeholders, their influence, and their interests in shaping environmental policies. Furthermore, it lays the foundation for bridging the gap between scientific evidence and actionable policy by using well established frameworks such as the Levels of Analysis, Technology Acceptance Model (TAM), and Integrated Change Model (I-Change Model). The theoretical approach is grounded in systems thinking, strengthening the identification, assessment, and analysis of relevant factors and dynamics. Ultimately, this foundation guides the development of a theoretically grounded digital intervention to support informed decision-making.

2.1 Situating in Literature

The issue of scrubber water discharge is deeply rooted in the broader context of maritime pollution and the pursuit of sustainable shipping. Academic literature highlights the environmental impact of scrubber water, primarily through ocean acidification and heavy metal contamination (Endres et al. 2018; Teuchies et al. 2020). Policy literature – such as the 2008 MARPOL Annex – addresses air pollution from ships by permitting the use of scrubbers as a compliance mechanism (International Maritime Organization 2023; Jalkanen, Kalli, and Stipa 2009). However, this regulation has been criticised for failing to consider the environmental effects of scrubber water discharge adequately. Some authorities have implemented regulations or bans on open-loop scrubber discharge in certain areas (Dulière, Baetens, and Lacroix 2020). At the European level, the EU Water Framework Directive mandates the phase-out of priority hazardous substances found in scrubber discharge water, pushing for stricter environmental protection measures (Lunde Hermansson, Hassellöv, Jalkanen, et al. 2023).

Alternative emission reduction methods such as the usage of cleaner fuels and novel engine technologies could serve as more sustainable solutions, but the economic profitability of using scrubbers often outweighs environmental considerations (Endres et al. 2018). This highlights the need for policy and decision-making that accounts for both economic and ecological costs.

Current approaches to addressing scrubber water discharge are significantly flawed. Regulations and assessments often focus on single waste streams or activities without accounting for cumulative impacts (Endres et al. 2018). Scrubber water discharge remains under-regulated, with few comprehensive environmental risk assessments in place. Additionally, there is a lack of sufficient monitoring data on wastewater contaminant concentrations, as well as spatial and temporal measurements of pollutants along shipping lanes and ports. Another key challenge lies in the interaction between science and policy. Despite advocacy against scrubbers, there is often a delay in translating research findings into policy measures (Hermansson 2024). This regulatory friction, coupled with the economic advantages of scrubber use, has resulted in continued environmental harm.

Our intervention aims to address these gaps by providing comprehensible information. More specifically, through the real-time calculation and visualisation of scrubber wastewater streams and 'hotspots', we provide means for the regulatory assessment of scrubber pollution. Through the incorporation of needs expressed by relevant stakeholders, the intervention is tailored to bridge the gap between scientific data and policy.

2.2 Systems Thinking Approach

A vital component of developing and tailoring an intervention to address the issue of scrubber pollution is the identification and assessment of the factors and interdependent mechanisms that drive the broader system dynamics. Through investigation of such factors, and their systematic mapping, a systems thinking approach facilitates the identification of core leverage points within a complex web of regulatory influence, pollution factors, and enforcement dynamics (Anderson and Johnson 1997; Cabrera, Colosi, and Lobdell 2008). By exploiting such leverage points, the designed intervention is ensured to be tailored specifically to the goals that are set for its use and impact.

To facilitate the process of mapping this complexity, our approach includes the utilisation of causal loop diagramming (CLD). By modelling the system dynamics using CLDs, a foundation through which basic experiments can be run is created. A CLD of the system provides an interpretable view of all relevant factors, aiding a holistic approach to further investigations, such as policy analyses (Cavana and Mares 2004; Gudlaugsson et al. 2022; Veldhuis et al. 2025). Additionally, this same foundation can be utilised in the development of a more complex Agent-Based Model (ABM), which enables further experimentation using more detailed simulation scenarios, and can act as an interactive tool for policymakers to investigate the effects of potential regulatory decisions (Malik 2024; Merali and Allen 2011; Schünemann et al. 2024).

2.2.1 Preliminary Modelling Through Causal Loop Diagramming

The CLD displayed in Figure 1 models the interplay of factors affecting scrubber pollution in the North Sea. The analysis centres around two stock variables – 'Scrubber Discharge in the North Sea' and 'Water Quality' – representing the core environmental metrics our intervention aims to address. A full analysis of the CLD and its dynamics can be found in Appendix B.

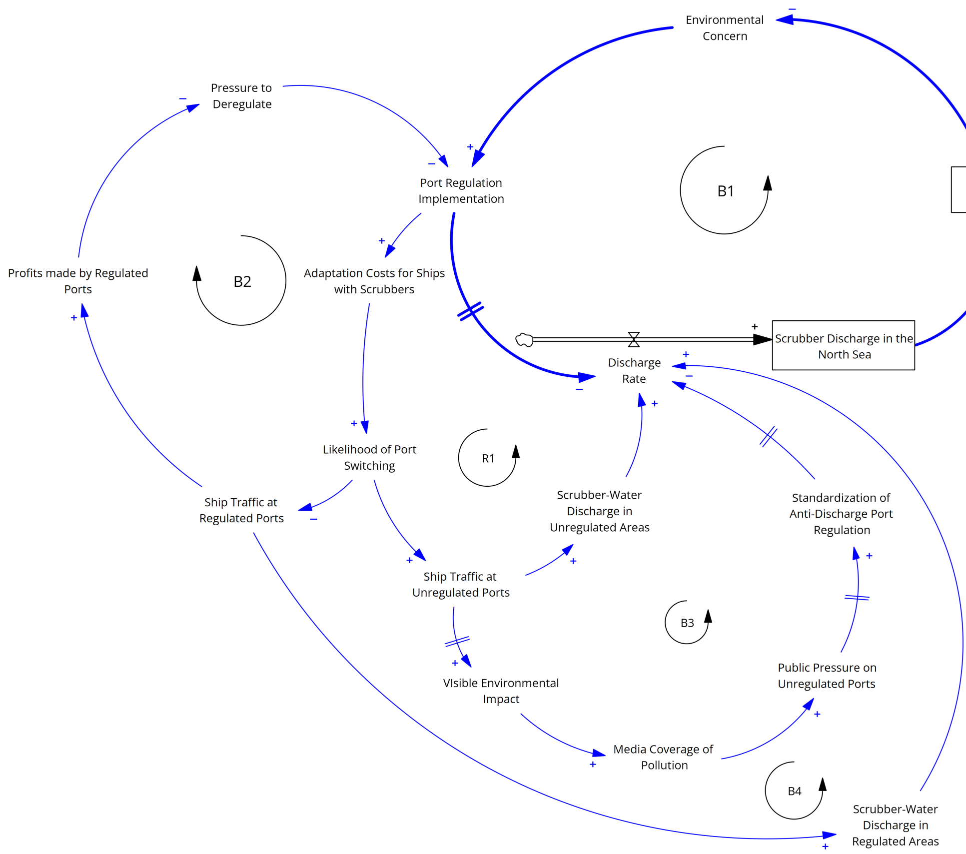

Figure 1: Causal Loop Diagram of EGCS System Dynamics and Regulatory Interactions

The CLD reveals a fundamental tension at the heart of scrubber pollution governance. While environmental regulations implemented at individual ports can reduce local discharge (as seen in balancing feedback loop B1), these isolated efforts may inadvertently shift the problem elsewhere. Ships facing stricter regulations at certain ports could redirect their routes to less regulated areas, creating what Levinson and Taylor (2008) identify as a 'pollution haven effect' – where economic activities with high environmental compliance costs shift to jurisdictions with less stringent regulations (captured in reinforcing feedback loop R1).

However, the system also demonstrates a more optimistic pathway through the regulated discharge redistribution mechanism (loop B4). When ports implement regulations, the potential resulting reduction in ship traffic could successfully decrease local pollution levels. If this improvement is substantial enough and not completely offset by increases in unregulated areas, it can contribute to overall water quality improvements.

Regardless, this dynamic highlights a crucial insight for effective policy intervention: addressing scrubber pollution requires coordinated cross-border regulation rather than piecemeal approaches. The standardisation of anti-discharge regulations across multiple ports emerges as a key leverage point (depicted in loop B3), potentially capable of overcoming the economic pressures that typically resist environmental policies (loop B2).

The CLD also illustrates the role of public awareness and media coverage in driving regulatory change. As environmental impacts become more visible, increasing media attention can generate public pressure on previously unregulated ports, potentially catalysing a broader regulatory response. This pathway offers an alternative mechanism for achieving standardisation when direct policy coordination proves challenging.

2.3 Theoretical Frameworks

This research is further guided by a set of social science frameworks to facilitate a stronger understanding of the current regulatory environment surrounding the issue. The Levels of Analysis framework is used to dissect the problem across multiple dimensions, which enables the rationalisation of the digital intervention at the meso-level, targeting policy- and decision-makers with tailored information and tools (Serpa and Ferreira 2019).

To facilitate a theoretically grounded approach to intervention development, we adopt several principles of well-established behavioural frameworks. More specifically, the Integrated Change Model and Technology Acceptance Model are utilised to support an intervention that is more likely to create lasting impact.

2.3.1 Levels of Analysis and Policy Overview

The Levels of Analysis framework offers a lens through which to examine the actors, incentives, and governance structures shaping scrubber discharge regulation around the North Sea. By analysing the issue across micro, meso, and macro levels, it becomes possible to reveal why fragmented responses persist, and how coordinated interventions can be more effectively designed. An overview of insights from the Levels of Analysis framework can be found in Figure 2.

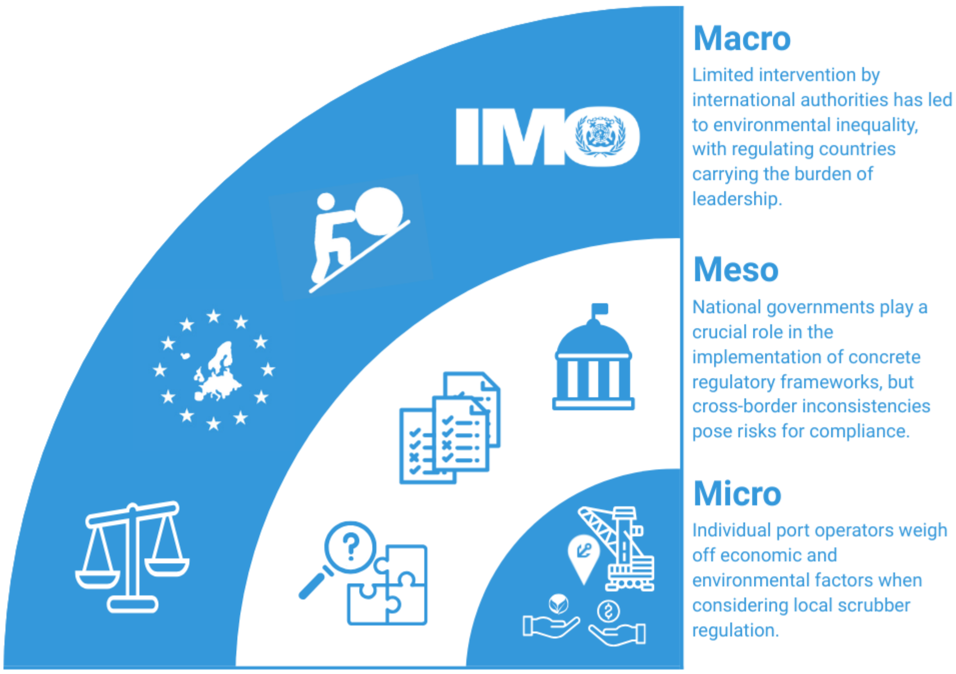

Figure 2: Levels of Analysis Overview Diagram

Micro-Level: Local Initiatives and Operational Trade-Offs

At the micro level, individual port authorities emerge as pivotal actors in local governance. Ports are increasingly making autonomous decisions about whether to permit or prohibit the discharge of scrubber wastewater within their jurisdictions. Choices to enforce local bans can originate from a combination of environmental awareness, local stakeholder pressure, and anticipated regulatory shifts.

The Port of Amsterdam introduced a ban on open-loop scrubber discharge in January 2025, requiring vessels to switch to closed-loop systems or use compliant fuels while at berth (Port of

Amsterdam 2024). Shortly following the port's decision, the Dutch Ministry of Infrastructure and Water Management announced that the Netherlands is preparing a nationwide ban on scrubber wastewater discharge from open-loop systems across all ports and inland waters (Ministry of Infrastructure and Water Management 2025). This development shows how leadership at the micro level could potentially aid in pressuring national governments to expand environmental initiatives. In the United Kingdom, Forth Ports has implemented similar bans at the Ports of Leith, Dundee, and Tilbury under Bylaw 59 and Circular No. 45, demonstrating another case where proactive port-level regulation emerges in the absence of national direction (Forth Ports Limited 2019; Port of London Authority 2024).

However, many ports still refrain from adopting such measures, potentially due to concerns over industry competition. In a deregulated maritime economy, stricter environmental policies could potentially drive vessels toward ports with weaker or absent regulations. This has led to a fragmented port governance structure, where proactive efforts are weakened by inconsistencies and jurisdictional arbitrage, limiting the effectiveness of micro-level regulation in achieving broader environmental goals.

Meso-Level: International Policy Fragmentation

At the meso level, national governments play a critical role in shaping the consistency and coverage of scrubber regulation. Several countries in the North Sea region have implemented, or are preparing to implement, national bans on open-loop scrubber discharge, overruling local regulations and standardising enforcement across ports.

Belgium and France have adopted national policies that prohibit open-loop scrubber discharges within three nautical miles of their coastlines. In Belgium, this is regulated by both federal and Flemish law, with enforcement across major ports such as Antwerp, Zeebrugge, and Ghent (ClassNK 2019a). France's restriction, enacted through amendments to Division 213 in 2021, similarly applies to all French ports, including Calais and Dunkerque – which are both directly connected to the North Sea (The Maritime Executive 2024). While these national frameworks demonstrate alignment in principle, they remain geographically limited, as their effectiveness could be significantly enhanced by extending coverage to the full 12 nautical mile range of territorial waters.

Alternatively, Sweden and Denmark are implementing the most comprehensive frameworks in the region. Sweden's national ban on open-loop scrubbers, taking effect on 1 July 2025, will be followed by a ban on closed-loop systems beginning 1 January 2029 (Offshore Energy 2025). Denmark is pursuing a similar timeline, introducing a full ban within 12 nautical miles of its coastline in 2025, with a closed-loop phase-out by 2029 (Maritime Activity Reports, Inc 2024). These two cases represent the most thorough national approaches, offering both short-term clarity and long-term environmental foresight.

Germany applies the CDNI Convention, banning the use of open-loop scrubbers in inland waterways, leading to enforcement in ports such as Bremen, Brake, and Hamburg. This regulation does not extend to the country's coastal waters, resulting in gaps that reduce effectiveness at a national scale (ClassNK 2019b).

The United Kingdom has not yet shown any interest in a national ban. While this permits innovation at the local level, it also results in inconsistencies across the country. A similar approach is taken in Norway, where national regulations are absent, but selected ports and sensitive areas, such as the World Heritage fjords, have implemented restrictions under Section 14b of the Norwegian Maritime Authority's environmental safety regulations (NorthStandard 2024; Norwegian Maritime Authority 2012). These fragmented meso-level arrangements highlight both the potential and the limitations of decentralised environmental governance.

Macro-Level: Centralised Regulatory Approaches

At the macro level, international organisations – particularly the IMO – are responsible for establishing global frameworks within which environmental regulations are formulated. The IMO's MARPOL Annex VI permits the use of open-loop scrubbers as a means of compliance with sulphur emission limits, and does not impose binding restrictions on the discharge of wastewater (International Maritime Organization 2023).

This regulatory omission has allowed harmful pollutants to shift from air to sea, without any corresponding international constraints. As a result, countries and ports are left to determine their own responses, producing an uneven and fragmented regulatory environment across the North Sea. While some regional frameworks, such as the EU Marine Strategy Framework Directive, provide guidance on marine environmental protection, they lack enforceable mandates. Without binding international standards, even the most rigorous national or port-level bans can be bypassed by vessels operating in adjacent waters where discharges remain permitted.

The absence of harmonised international regulation creates environmental inequality. Nations and ports that choose to regulate carry the burden of leadership as others delay or abstain, creating incentives for vessels to exploit jurisdictional loopholes, and undermining the effectiveness of the overall regime.

Integrating Micro, Meso, and Macro Dynamics for Regulatory Coherence

The governance of scrubber discharge in the North Sea is marked by a misalignment between institutional levels that operate with different logics, authorities, and incentives. Yet within this misalignment lies the potential for reform, if these layers of governance can be made to interact more strategically.

Ports, though limited in jurisdiction, can act as accelerators of national change. Their strategic leverage lies not just in their regulatory autonomy, but in their visibility. When a high-volume port like Amsterdam imposes restrictions, it signals reputational risk for non-compliant operators and political risk for passive regulators. The result is a ripple effect that can potentially reshape meso-level agendas.

Meanwhile, national governments have the legal reach to close gaps that local actors cannot. Yet, their effectiveness depends not solely on adopting regulations, but on the scope and coherence thereof. While Belgium and France have taken steps toward control, their limitation to three nautical miles leaves gaps that diminish enforcement power. This contrasts with the regulatory clarity in Sweden and Denmark, where upcoming policies eliminate ambiguity and opportunities for avoidance.

The lack of international regulation is not just a legal gap, it is a structural weakness that affects national and local efforts. An uneven distribution of responsibility between countries creates disincentives for coordination unless overarching frameworks are established. If North Sea coastal states adopt harmonised bans with similar ambitions to Denmark and Sweden's, they can establish a normative baseline that shifts regional expectations upward. In doing so, they increase the political cost of international inaction and create the groundwork for a broader regulatory framework.

A consistent and effective regulatory regime cannot be built by any single level of governance acting alone. Progress depends on coordination of responsibilities: ports must continue to lead through local enforcement, national governments must provide territorial coverage and legal certainty, and regional alignment must create the groundwork for international standards to follow. The goal should not be uniformity for its own sake, but strategic coordination, where each level addresses the gaps others cannot.

2.3.2 Theories for Intervention Design

Regulatory coherence should thus be a centrepiece of any intervention approach. More specifically, the effective communication of the scrubber problem itself and current regulatory distributions should go hand in hand with theoretically backed principles for user engagement and impact. The Integrated Change Model suggests that an individual's abilities, such as their understanding of complex system dynamics, can help them execute their behavioural intentions (Vries et al. 2005). Furthermore, pre-motivational factors covered by the I-Change Model, such as knowledge and risk-perception, play a key role in forming one's intentions of performing certain behaviours (Kasten et al. 2019). These concepts are integrated in the intervention development by prioritising an adequate provision of relevant information and highlighting the importance of policy-driven action.

The successful implementation of the intervention further depends on its acceptance and utilisation by the target audience. The Technology Acceptance Model guides the development of a user-friendly digital platform by considering factors such as perceived usefulness and perceived ease of use (Marangunić and Granić 2015; Venkatesh and Bala 2008).

2.4 Stakeholder Analysis

Relevant stakeholders can be categorised into three main groups: Environmental Organisations, the Maritime Industry, and the Public. The maritime industry primarily consists of actors directly impacting the scrubber issue. These include the Port of Amsterdam and other North Sea ports, the IMO, and ship owners. As illustrated in Figure 3, these actors demonstrate varying levels of influence and interest regarding EGCS regulation.

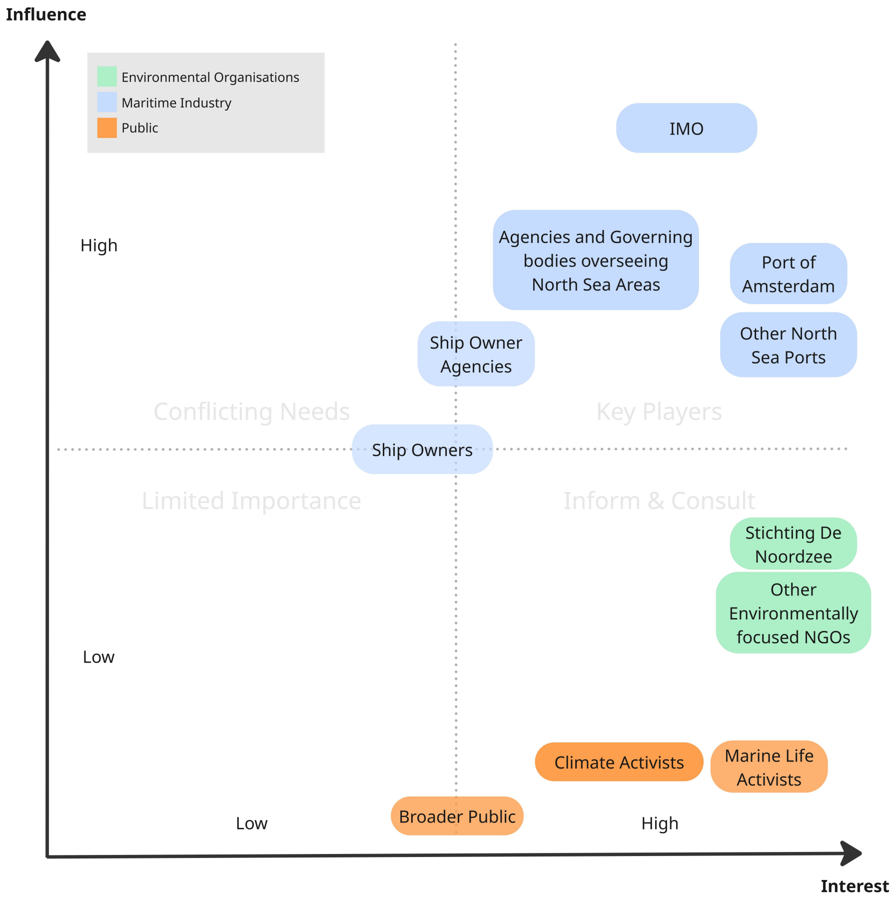

Figure 3: Stakeholder Map (see Appendix C for complete stakeholder analysis)

Ship owner agencies occupy a position of moderate influence, as they can establish industry standards and coordinate collective responses to regulatory changes. They serve as intermediaries between individual ship owners and regulatory bodies, wielding considerable power in shaping industry positions on environmental regulations. Ship owners, positioned as less influential, demonstrate conflicting needs as they must balance compliance costs against operational efficiency.

Agencies and governing bodies overseeing North Sea areas, such as the Oslo and Paris (OSPAR) Commission, possess substantial influence over regional standards and protocols. These organisations play a crucial role in coordinating trans-boundary governance and establishing evidence-based policy recommendations. The IMO maintains the highest level of influence due to its global authority over maritime operations.

Stichting De Noordzee, along with other environmentally focused NGOs, is positioned with high interest but lower direct regulatory influence. Their roles as environmental advocates, research contributors, and knowledge brokers make them valuable partners for information sharing and policy development. Despite lacking formal regulatory authority, these organisations serve as critical voices in translating scientific evidence into policy advocacy and maintaining public awareness of environmental issues.

Public stakeholders demonstrate varied positioning within the matrix. Climate and marine life activists maintain high interest and serve as critical voices for environmental protection, though their direct influence remains limited. Broader public audiences are expected to exhibit limited interest due to a general lack of awareness regarding the issue. Nevertheless, their potential for driving change should not be underestimated, as public opinion and activism have been shown to often play a vital role in policy development and implementation (Burstein 2003; Ellersiek, Pianta, and Utting 2012).

2.5 Research Questions

To address the main goal of this project, and to account for the theoretical and practical context described above, the following research question was constructed:

> *How can research findings on the impact of scrubber water discharge in the North Sea be made into an explainable and actionable digital intervention for policymakers and the broader public?*

This question addresses the main challenge of translating scientific evidence into practical tools for protecting the marine environment. To break this down, several sub-questions are presented:

Quantitative:

- To what extent do varying regulatory approaches to scrubber discharge regulation across North Sea countries influence pollution patterns?
- How can scrubber discharge estimates be predictively modelled for North Sea countries?
- How can agent-based modelling facilitate the assessment of different policy scenarios?

Qualitative:

- How do policymakers navigate ethical trade-offs between economic impacts on industry and environmental protection when implementing scrubber discharge regulations?
- What is the current state of public awareness regarding scrubber discharge, and how do policymakers view its role in policy development?
- How do port authorities currently monitor and enforce scrubber discharge regulations, and what are the challenges they currently face?

3 Methods and Analysis

As suggested by the presentation of both qualitative and quantitative research questions, this research follows a multidisciplinary approach to data collection and analysis methods. The following sections will address these methods and their outcomes, providing an empirical foundation for intervention development. More specifically, it first explains the collection and subsequent analysis of shipping data, which provides insights into the geospatial distribution of scrubber pollution, and facilitates the real-time display of this information through the North Sea Watch platform. Then, the section addresses how this data was used to develop an agent-based model, which enabled the simulation and analysis of different policy scenarios. Lastly, the section describes the qualitative data collection process and some of its key insights, before revisiting the sub-questions presented above.

3.1 Shipping Traffic and Scrubber Pollution

This study follows a structured data pipeline to collect, process, and analyse real-time vessel data using Automatic Identification System (AIS) signals (Figure 4). This data is publicly broadcasted by sea-faring vessels, but is not available universally without commercial intermediaries. The project utilises AISStream.io, a land-based AIS aggregator that provides access to real-time AIS broadcasts via a WebSocket API – enabling consistent, low-latency data collection.

Incoming data is geographically filtered for the North Sea region using geospatial libraries such as geopandas and shapely. The captured AIS data is initially stored in a temporary staging table for batch processing and cleaning. This step involves aggregating the raw data with static libraries of ship types, navigational statuses, and port information to enhance the interpretability of the data. The cleaned and structured data is then stored in a Google Cloud SQL instance running PostgreSQL, with data security ensured through the Cloud SQL Auth Proxy. Datasets received from the International Council on Clean Transportation (ICCT) are used to identify ships fitted with scrubbers. See Appendix A for an overview of the data sources used.

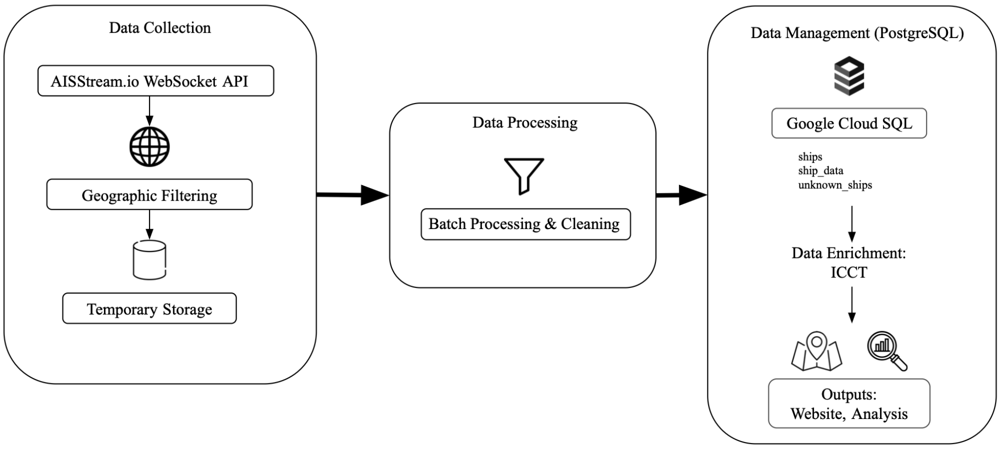

Figure 4: Data Collection and Analysis Pipeline

3.1.1 Preliminary Analysis

Data analysis was performed on a subset of our database from April to May 2025. Figure 5 illustrates the spatial distribution of scrubber-fitted ships across the North Sea. The visualisation reveals distinct traffic concentration areas, particularly around major ports. High-density lanes connect ports such as Rotterdam, Antwerp and Hamburg to the English Channel. The distribution of scrubber-equipped vessels suggests both potential hotspots for scrubber water discharge and a lack of adequate regulation.

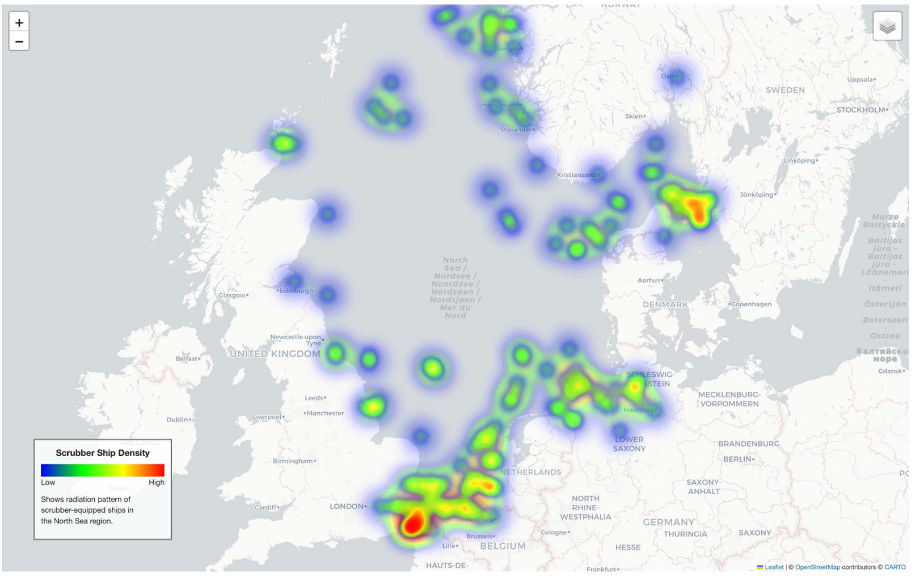

Figure 5: Spatial Heatmap of Scrubber Ship Traffic

The diagrams presented in Figures 6 and 7 illustrate the flow of the most common ship types to the most popular North Sea destinations, both for scrubber-equipped vessels and non-scrubber ships. The figures reveal that Rotterdam dominates as a primary shipping destination, handling the largest volume of traffic across both categories, followed by Antwerp. Hamburg and Bremerhaven also emerge as significant regional hubs. Cargo vessels represent the dominant ship category in both diagrams, and tankers constitute the second largest vessel group. The collected AIS data reveals that around 18% of cargo ships and 13% of tankers are equipped with scrubbers. These two categories make up the vast majority of scrubber ships in the North Sea.

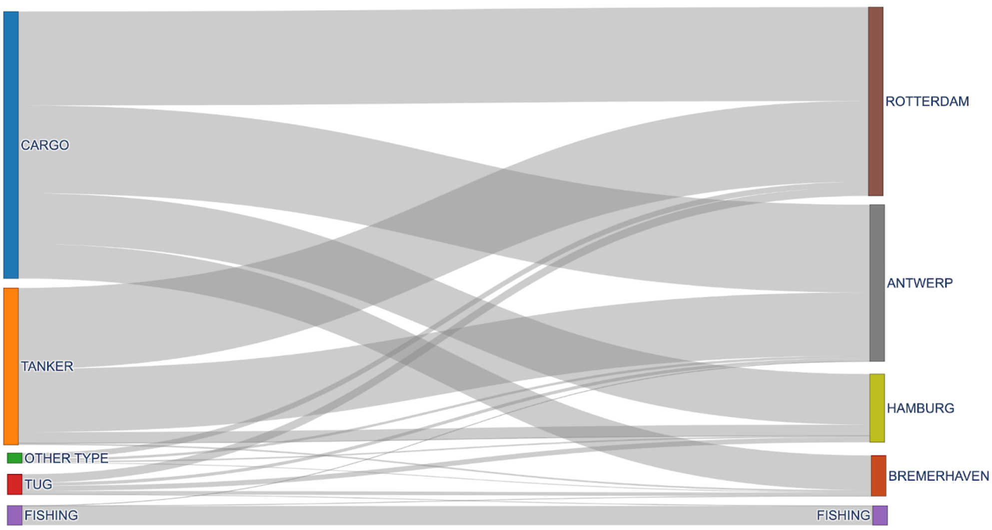

Figure 6: Port Popularity by Ship Type – Non-Scrubber Vessels

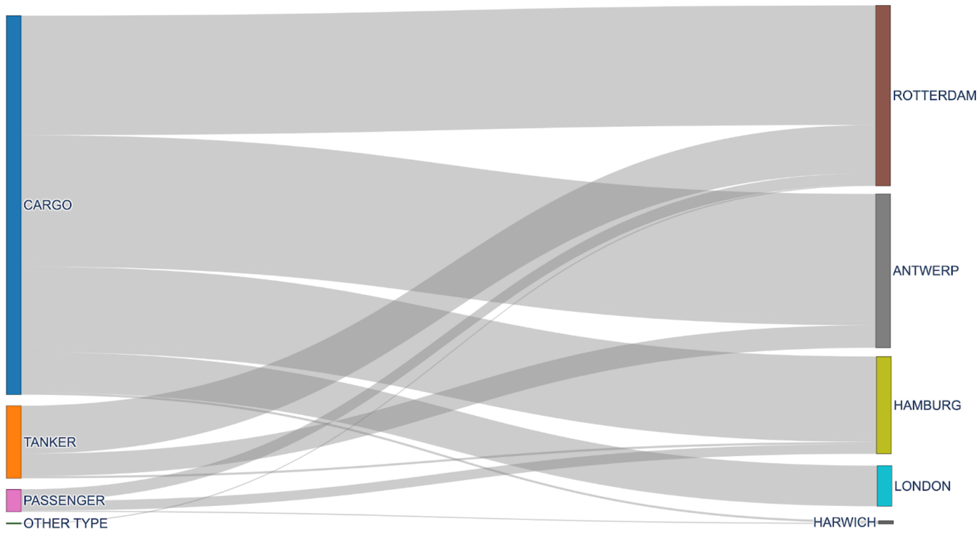

Figure 7: Port Popularity by Ship Type – Scrubber Vessels

3.1.2 Scrubber Discharge Estimation

Data on ship dimensions, such as beam, length, and maximum draught, are used to estimate scrubber discharge volumes. These parameters are essential for calculating a vessel's deadweight tonnage (DWT), which can be used to estimate its power consumption in different operating modes. Given that raw dimensions represent a rectangular shape, custom coefficients are used for different vessel types – primarily cargo and tanker – to approximate their hull geometry. This allows for realistic estimations of displacement specific to each type, enabling more accurate calculations of DWT.

(1) Mass displacement (t) (Charchalis 2013)

$$\Delta = B \times T \times L \times C_B \times d_{sw}$$

B – Beam (m)

T – Maximum draught (m)

L – Length (m)

C_B – Block coefficient (cargo: 0.625; tanker: 0.825) (Diesel and Turbo 2011)

d_{sw} – Seawater density (1.025 tonnes/m^3) (Diesel and Turbo 2011)

(2) Deadweight tonnage (DWT)

$$DWT = \Delta - (\Delta \times C_{lwt})$$

C_{lwt} – Lightweight coefficient (cargo: 0.32; tanker: 0.16) (Diesel and Turbo 2011)

Furthermore, it is essential to estimate power consumption, as this is the primary indicator of discharge flow. Due to limited accessibility of ship engine data, power consumption estimates are based on boiler (BO) and auxiliary engine (AE) power output assumptions across different operating modes for predetermined ship types and DWT classes, as presented in the ICCT's SAVE model (Mao et al. 2025). The ICCT further provides normalised scrubber wastewater flow rates of

45 t/MWh and 0.1 t/MWh for open-loop and closed-loop systems respectively (Osipova, Georgeff, and Comer 2021). Hybrid scrubbers are assumed to always operate in open-loop mode (Osipova, Georgeff, and Comer 2021). Discharge masses are calculated in kg.

(3) Amount of wastewater discharge (modified from Osipova, Georgeff, and Comer 2021)

$$D = EED \times r$$

EED – estimated energy demand per ship (AE power output + BO power output) (kWh)

r – scrubber wastewater flow rate (kg/kWh)

Figure 8 presents time-series data of estimated daily scrubber wastewater discharge across North Sea countries from April to May 2025. Pollution estimates are calculated using the methods described above, and account for regulatory policies in different areas that may limit pollution. When a ship is located within a country's territorial waters, its estimated discharge mass is assigned to that country. Great Britain exhibits the highest peak discharge levels, reaching over 40 million kilograms on a single day. France, a nationally regulated country, exhibits much lower discharge levels. The pronounced spikes observed in certain countries such as the Netherlands may correspond to seasonality in concentrated shipping activity. However, due to the limited time-frame of the research and data, this cannot be confirmed. While the comparison of absolute discharge estimates can cloud representativeness, it reveals where pollution happens at the largest scales. Overall, the variations in discharge levels between countries empirically highlight the challenges of managing trans-boundary marine pollution in a fragmented regulatory environment.

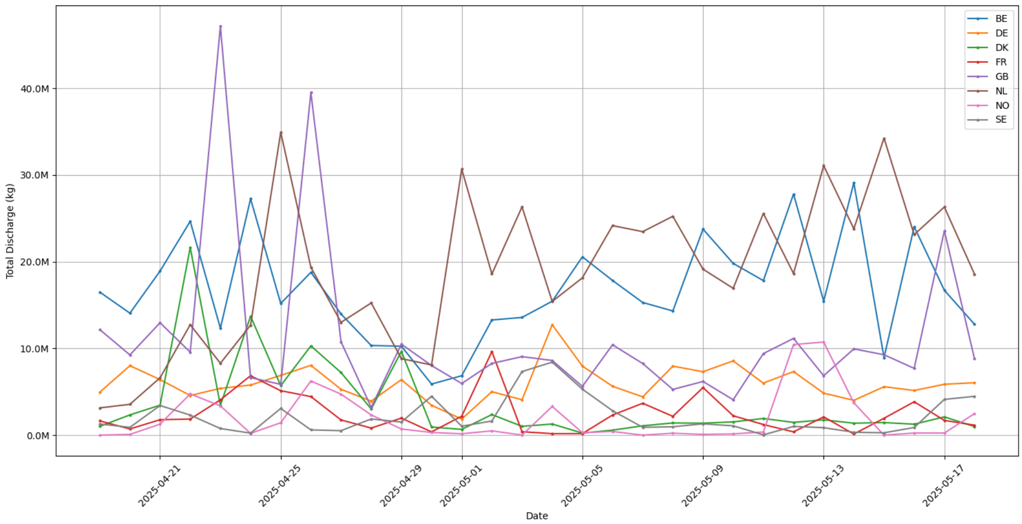

Figure 8: Daily Discharge Estimates Per North Sea Country

3.1.3 Time Series Forecast

To project scrubber discharge patterns and assess potential regulatory impacts, a random forest regression model was implemented to generate time-series forecasts for each North Sea country. Random forest regression was selected for its ability to capture non-linear relationships and time dependencies without requiring strong assumptions about the underlying data – a characteristic which enables forecasting with limited training data. The forecasting model incorporates multiple feature sets to capture the temporal structure of shipping activity such as day-of-the-week, hourly, and weekly cyclical patterns. This feature engineering approach accounts for both short term operational patterns and medium term trends in maritime traffic. The model was trained on historical discharge data from April to May 2025, with predictions extending 30 days into the future.

Prediction uncertainty was quantified using the variance across individual decision trees within the random forest, providing 95% confidence intervals around the central forecasts. This approach provides bounds that reflect both model uncertainty and the inherent variability in maritime traffic patterns.

To exemplify, Figures 9 and 10 present predictive models for scrubber discharge in French and Dutch territorial waters. France exhibits very low and consistent pollution levels during the forecast period. The model fit is nearly identical to the true data, and the confidence interval is relatively narrow. This pattern reflects both the lower baseline shipping activity in French North Sea waters and the potential stability that comes with having a national regulation on scrubber water discharge. The forecast for the Netherlands consistently demonstrates higher predicted pollution levels during the forecast period. The model fit is not as accurate, and it seems unable to fully capture the peaks and troughs in the true data. The confidence intervals are notably wider, suggesting higher uncertainty in discharge predictions. This could be a reflection of the lack of a robust regulatory landscape across the country, as well as the high levels of shipping traffic that Dutch ports experience.

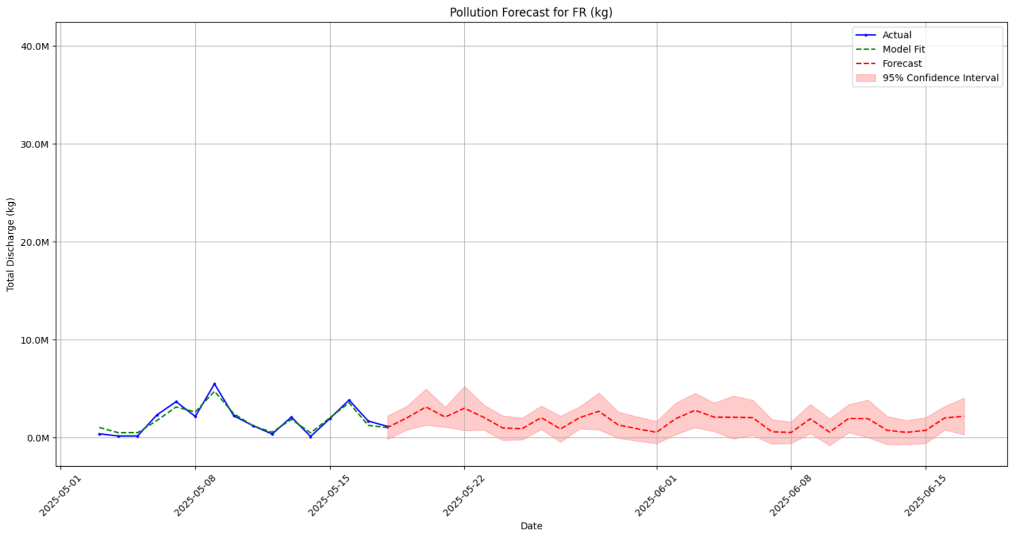

Figure 9: Discharge Time Series Forecast – France

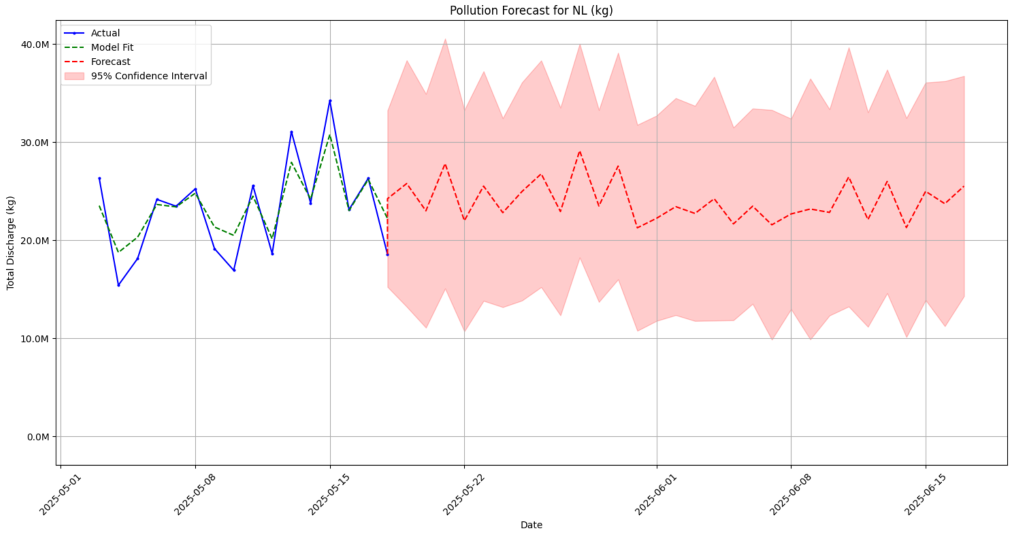

Figure 10: Discharge Time Series Forecast – Netherlands

While the random forest forecasting models provide insights into expected pollution patterns under current regulatory conditions, they are inherently limited to extrapolating existing trends and cannot capture the dynamic behavioural responses that would emerge under alternative policy scenarios. The forecasts assume fixed scrubber adoption rates, and unchanged operational behaviours, which are problematic when evaluating the potential impacts of new regulations or coordinated policy interventions across the North Sea. To address these limitations and explore how North Sea actors might adapt their behaviours under different regulatory frameworks, more advanced methods are required.

3.2 Agent-Based Modelling

This study's approach to such advanced data collection and analysis methods involves an ABM developed using the Python Mesa framework to simulate ship traffic and scrubber pollution in the North Sea. ABMs are particularly well-suited to explore emergent phenomena in complex systems by modelling how individual agents – such as ships – interact within structured environments. In this context, the model serves as a 'how-possibly' explanation – demonstrating plausible outcomes of regulatory scenarios and agent behaviours (Grüne-Yanoff and Verreault-Julien 2021).

Ship agents are initialised based on empirical distributions of ship types and are probabilistically assigned scrubber systems based on their type, reflecting real-world adoption rates as found in the preliminary analysis described in Section 3.1.1. Movement is governed by routing logic, where ships dynamically adjust their paths based on port attractiveness relative to ship type and accessibility. Ports, in turn, implement docking decisions influenced by capacity constraints and scrubber acceptance policies. Each successful docking generates revenue based on a baseline fee that gets adjusted by occupancy-driven pricing and monetary policies on scrubbers, simulating supply-demand dynamics.

To ensure that the model accurately reflects the real-world system, several validation strategies are used. Parameter values for ship types, port capacity, port popularity, and scrubber adoption rates are empirically grounded using collected AIS data. Face validation was performed by comparing simulation behaviour with known patterns for maritime traffic and port congestion. For example, larger ports consistently attracted higher volumes of ship traffic, and revenue patterns aligned with port popularity and docking capacity, mirroring real-world trends (Roadknight, Aickelin, and Sherman 2013). Further validation and experimentation steps included tracking aggregate indicators like scrubber discharge and port-level docking events, and confirming that these follow expected theoretical behaviour – as described in Section 2.2.1 – under different regulatory scenarios. This combination of empirical, theoretical and simulation-based checks supports the model's validity for analysing policy interventions in the North Sea.

3.2.1 Scenario Analysis

To evaluate the effectiveness of different regulatory approaches to managing scrubber water discharge in the North Sea, the ABM was used for simulating three distinct policy scenarios. Each simulation was run 20 times with 1000 time-steps each to ensure statistical robustness. Results are interpreted from the 200th step with 95% confidence intervals, ignoring model calibration and accounting for variability to strengthen the reliability of the findings.

Baseline Scenario

The baseline scenario mirrors the current fragmented regulatory landscape, where only Denmark and Sweden have implemented comprehensive national scrubber policies, while most others rely on inconsistent port-level regulations. This scenario serves as a control condition and directly reflects the meso-level policy fragmentation identified in Section 2.3.1.

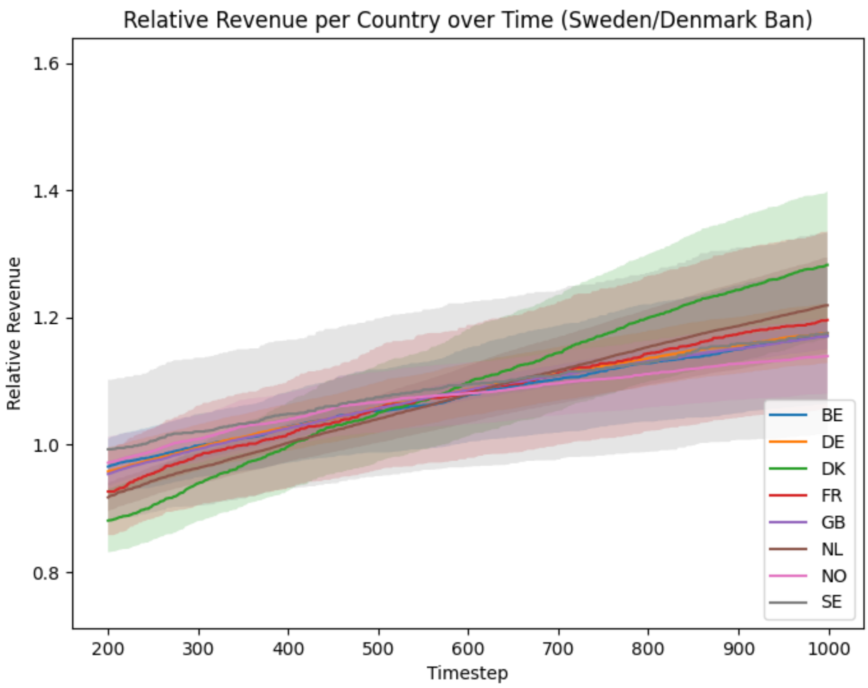

Figure 11: Relative Revenue per North Sea Countries - Baseline Scenario

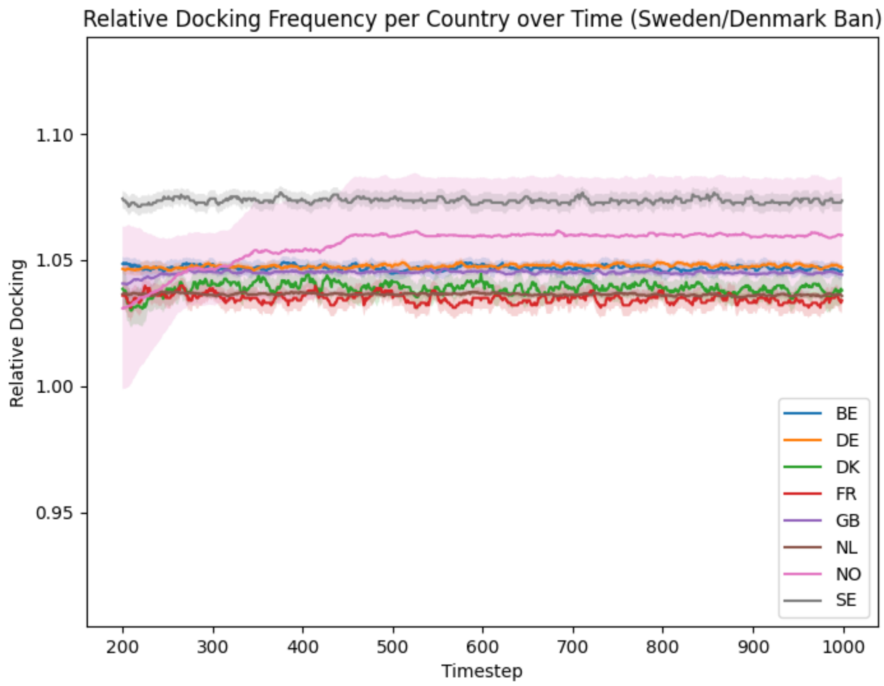

Figure 12: Relative Docking Frequency per North Sea Countries - Baseline Scenario

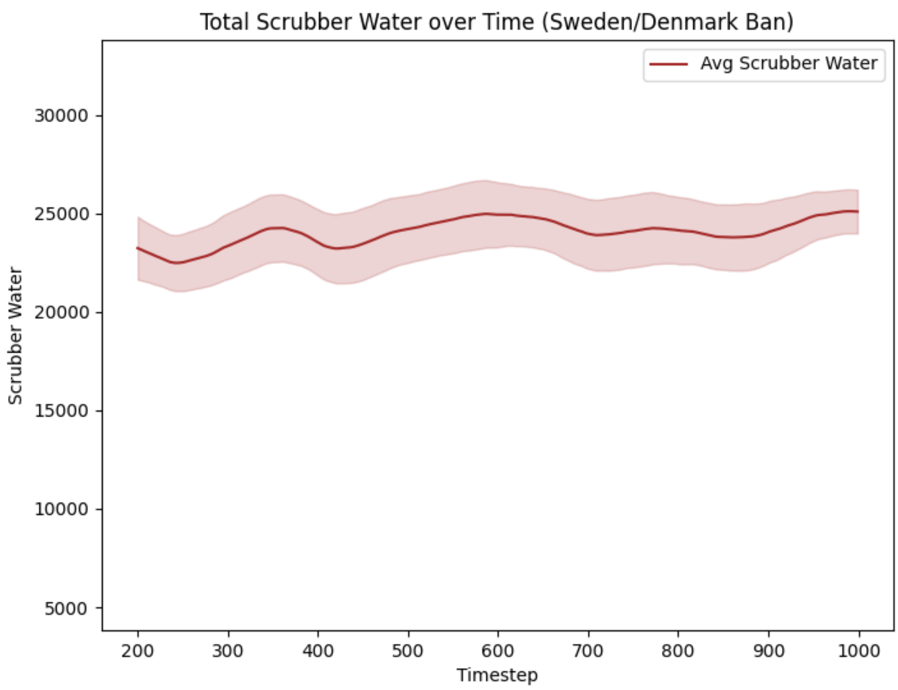

Figure 13: Total Scrubber Water Discharge (point based) - Baseline Scenario

The baseline scenario establishes reference patterns for scenario comparison, as shown in Figures 11, 12, and 13. Economic performance in the form of revenue relative to the average port demonstrates varied gradual growth patterns across countries. The overlap of confidence intervals suggests no clear competitive advantage emerging from environmental leadership. This supports the micro-level rational choice behaviour identified in Section 2.3.1. Port traffic patterns remain relatively stable, with Sweden showing slight deviation – possibly due to existing national restrictions. More critically, this scenario establishes the environmental cost of fragmented governance. The baseline pollution levels represent the cumulative effect of North Sea actors exploiting regulatory inconsistencies.

National Ban: Netherlands

This scenario simulates the effects of a national ban on scrubber water discharge in all Dutch ports. It represents the type of isolated leadership observed in countries like Belgium and France, while still being exploratively relevant, as the Netherlands plans on passing a similar policy strategy. This scenario enables the examination of whether meso-level leadership can overcome the structural limitations identified previously.

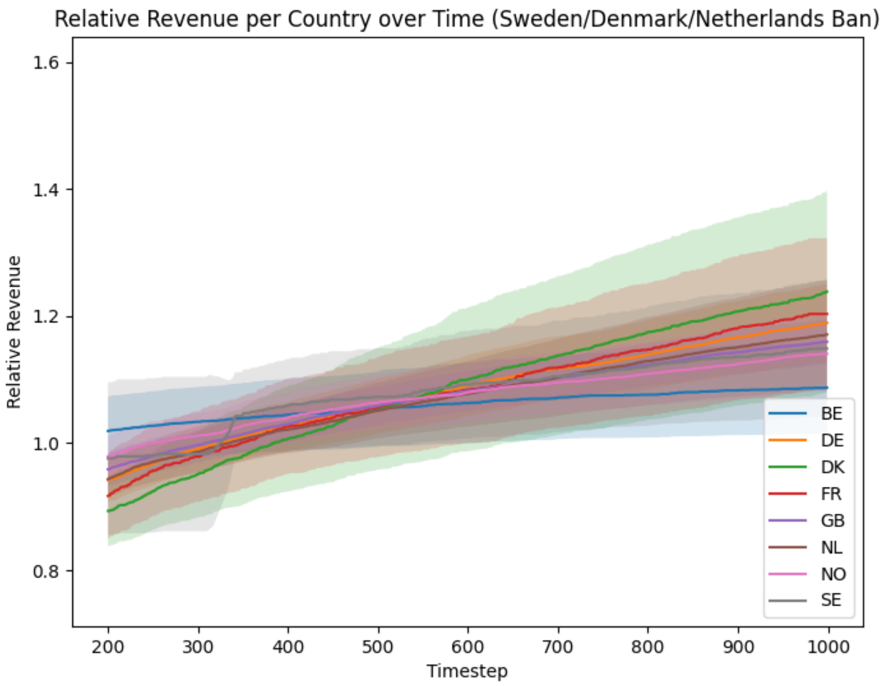

Figure 14: Relative Revenue per North Sea Countries - NL Ban Scenario

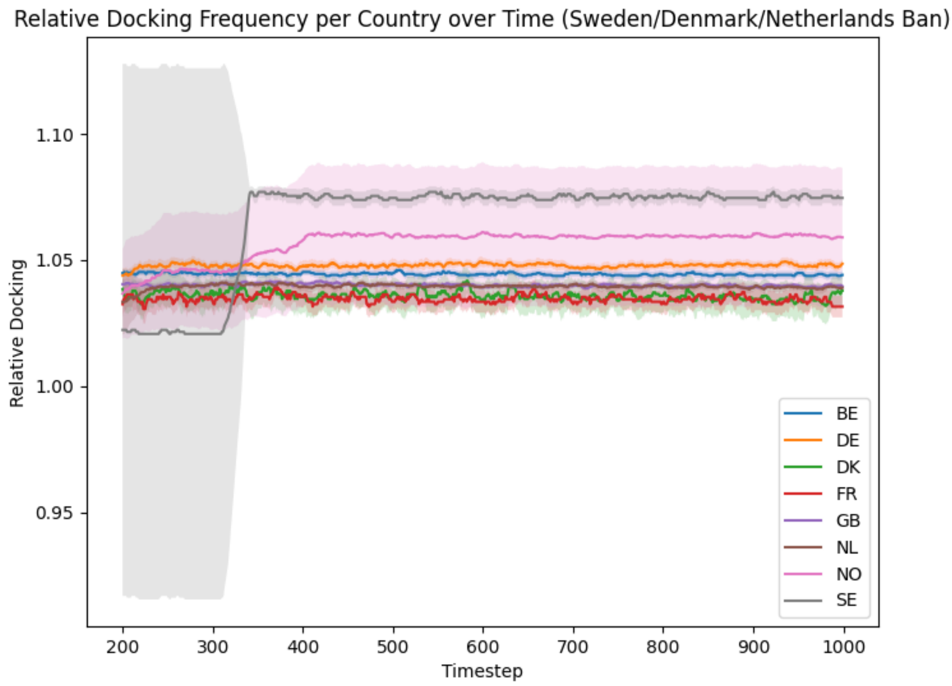

Figure 15: Relative Docking Frequency per North Sea Countries - NL Ban Scenario

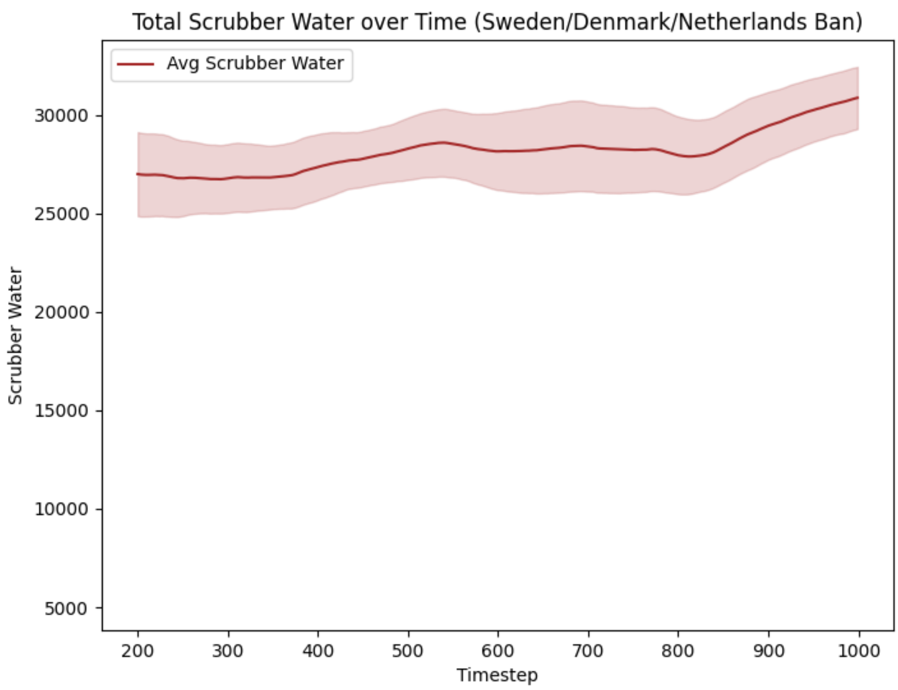

Figure 16: Total Scrubber Water Discharge (point based) - NL Ban Scenario

Economic performance and traffic patterns remain largely consistent with the baseline scenario, suggesting that introducing additional environmental policies does not necessarily affect competitiveness. Counter-intuitively, scrubber pollution in this scenario is higher than the baseline. This suggests a pollution displacement effect; Rotterdam, a popular destination for scrubber ships, becomes unavailable, forcing them to travel longer distances to alternative ports, increasing their total discharge output. This validates the theoretical prediction that meso-level governance, while locally effective, faces structural constraints in addressing trans-boundary environmental problems. However, it must be acknowledged that this also presents a fundamental shortcoming of the ABM, as it does not account for ships switching to compliant fuel while in regulated areas – something which does occur in the real world.

Uniform Ban Scenario

The uniform ban scenario implements a consistent ban on scrubber discharge across all simulated ports. This represents the coordinated macro-level governance approach expected to be necessary for effective environmental protection.

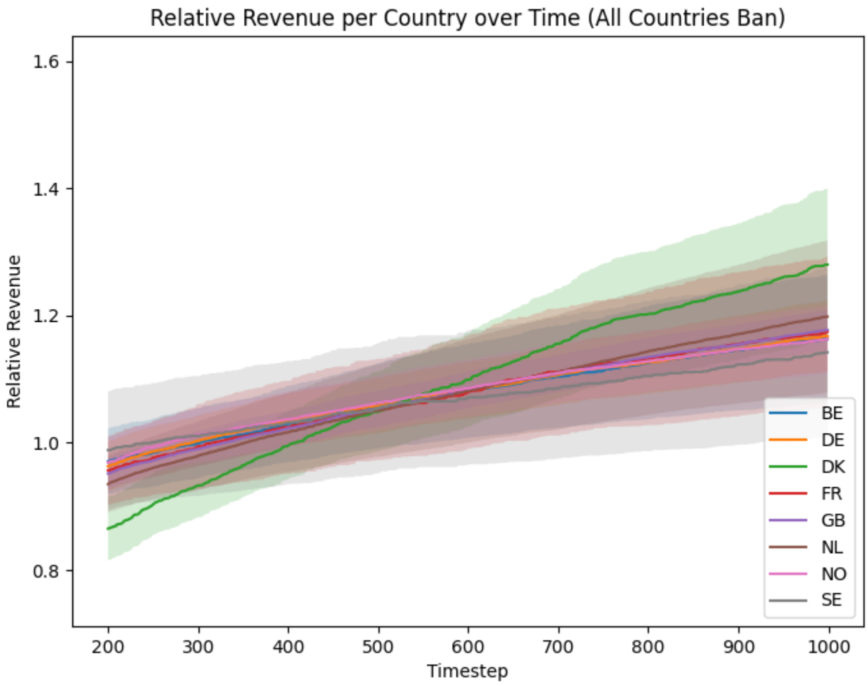

Figure 17: Relative Docking Frequency per North Sea Countries - Uniform Ban Scenario

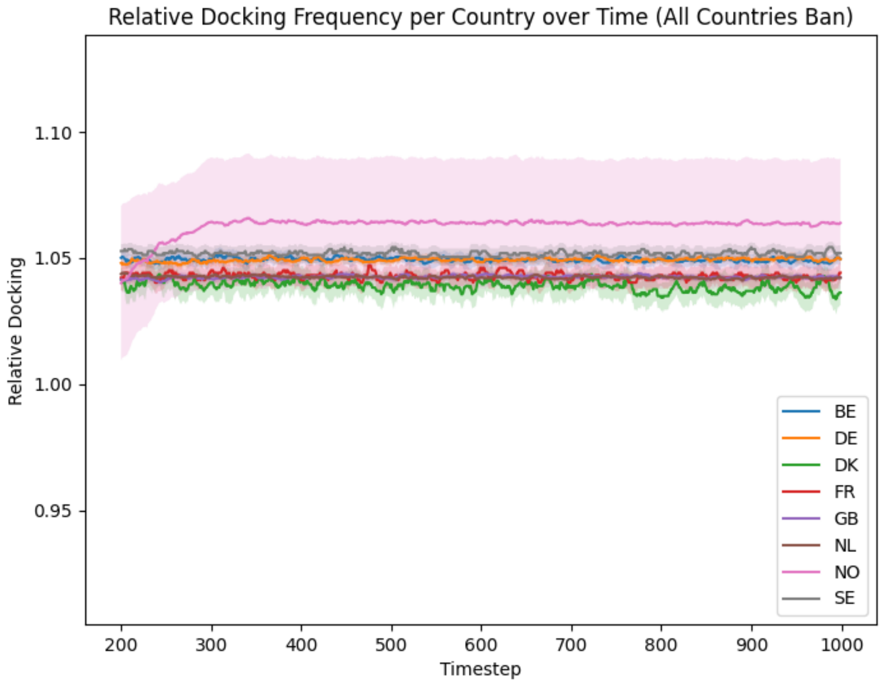

Figure 18: Relative Docking Frequency per North Sea Countries - Uniform Ban Scenario

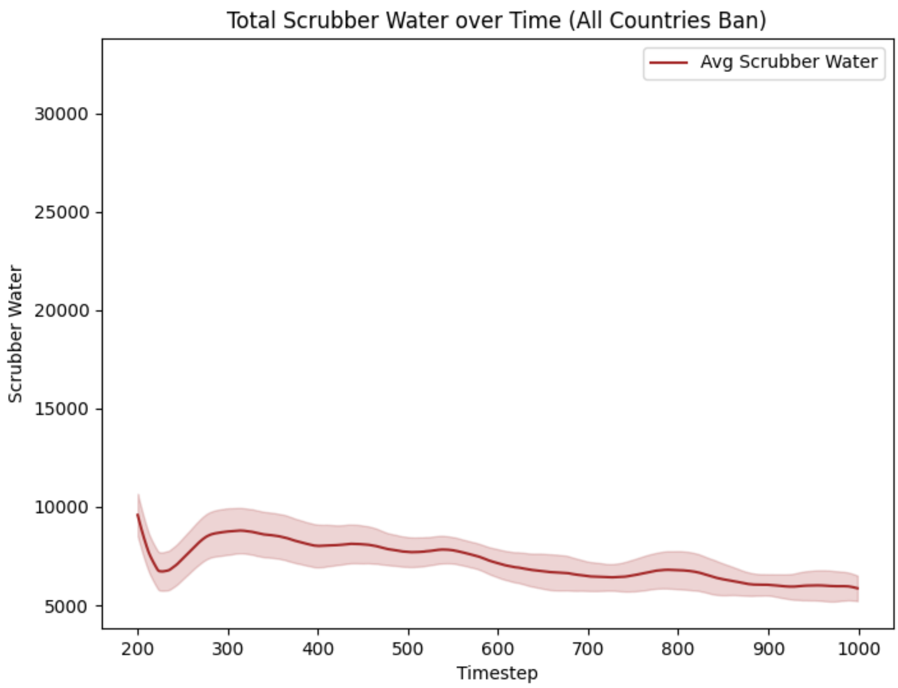

Figure 19: Total Scrubber Water Discharge (point based) - Uniform Ban Scenario

The uniform ban scenario presents the most significant environmental improvements, with average scrubber water discharge decreasing substantially. Stable confidence intervals indicate consistent environmental impact reductions across all simulation runs, suggesting that coordinated policy approaches produce reliable positive outcomes. Furthermore, economic performance and docking frequencies remain stable within their respective confidence intervals, indicating that uniform regulations eliminate the competitive disadvantages that individual ports and nations may fear when considering unilateral measures. This addresses micro-level concerns about loss of competitiveness and meso-level reluctance to act independently.

The findings from these scenarios largely align with theoretical claims made in Section 2, validating that effective scrubber regulation requires moving beyond fragmented meso-level approaches, and toward coordinated macro-level governance frameworks. The results suggest that regional coordination mechanisms are essential for addressing the trans-boundary nature of North Sea pollution while maintaining economic competitiveness across the industry.

3.3 Stakeholder Interviews

To qualitatively assess the ethical, social, and policy dimensions of scrubber water discharge in the North Sea, part of our mixed-method research strategy entails integrating stakeholder interviews and policy insights. This approach provides qualitative insights that complement the quantitative analyses, offering stakeholder perspectives on the regulatory and implementation aspects of scrubber discharge management. The interviews help solidify our understanding of how regulations work in practice and what challenges policymakers face when implementing them.

3.3.1 Participant Sampling and Data Collection

The sampling strategy targeted four key stakeholder categories: environmental organisations, regulatory bodies, shipping industry representatives, and non-expert civil actors. Most participants were identified through the professional network of Stichting De Noordzee. The final sample included two representatives of One Planet Port (an NGO promoting clean shipping practices in Rotterdam); two policy officials from the Danish Ministry of Environment and Gender Equality involved in scrubber policy development; a policy advisor from the Port of Amsterdam; a representative from the University of Amsterdam's (UvA) Green Office. With the latter providing valuable insights into non-expert perspectives on marine environmental communication and digital platform usability.

Semi-structured interviews were conducted using a combination of in-person meetings and video conferencing. Interview guides were tailored to each stakeholder category (see Appendix E). All interviews were recorded with participant consent and lasted between 45-90 minutes. Interview guides covered key themes, including regulatory development processes, enforcement challenges, economic considerations, public engagement strategies, and digital communication preferences. Interviews were thematically coded using ATLAS.ti. Complete interview analyses can be found in Appendix F.

3.3.2 Key Insights

The interviews revealed significant insights into how policymakers navigate challenging ethical trade-offs, the role of public awareness in environmental policy, and the practical challenges of implementing maritime regulations across jurisdictional boundaries.

Ethical Decision-Making in Environmental Policy

Findings indicate that policymakers face two primary ethical tensions when developing scrubber discharge regulations. The first involves navigating the precautionary principle versus economic certainty when scientific evidence appears contradictory. This was exemplified in Amsterdam's experience, where Dutch research indicated minimal adverse effects from scrubber discharge, contradicting studies from Belgium and Sweden showing significant environmental harm. Despite this uncertainty, the port's clean shipping policy advisor explained their decision:

> *"The outcome of the Dutch study was well, it [scrubber discharge] is not so bad, but in Antwerp they had another study and in Sweden they had another study and that was completely 180 degrees the other way around... it [scrubber discharge] is very harmful and we said okay then we go for the fact that we want to take care of our future... We want to take care of our environment. So just to be sure, we want to have this ban."*

The second tension concerns balancing industry impact with environmental protection. Both jurisdictions resolved this through economic proportionality assessments, concluding that compliance costs ($400-10,000 per port call in Amsterdam; 39 million one-time and 19 million annual industry costs in Denmark) were manageable compared to the scale of industrial shipping operations and environmental benefits. Interestingly, both jurisdictions reached similar conclusions about manageable economic costs through different evidentiary approaches – Amsterdam chose precaution despite lacking conclusive domestic scientific support, while Denmark grounded decisions in comprehensive OSPAR studies, achieving unanimous parliamentary support.

However, the fair distribution of environmental leadership costs remains an unresolved tension. Both jurisdictions acknowledged the burden of being regulatory 'front runners', highlighting how environmental leadership can create competitive positioning challenges that current policy approaches don't fully address.

Limited Public Awareness with Strategic Implications

The interviews also revealed relatively low awareness of scrubber discharge issues in all stakeholder groups, extending even to maritime industry professionals. The interviewee from the Port of Amsterdam noted that he had to give internal presentations explaining what scrubbers are, emphasising that "they [colleagues] really don't know what it is." Even Danish Ministry officials didn't know what scrubbers were before starting work on this issue.

Despite this, policy development in both jurisdictions was primarily driven by internal environmental commitments and scientific evidence, rather than public pressure. However, stakeholders identified effective engagement strategies. The perspectives of One Planet Port and the UvA Green Office representatives converged on the critical importance of accessible visual communication in bridging the gap between environmental data and actionable policy insights. Interview participants suggested that policy-focused platforms benefit from simulation capabilities and transparent data sourcing, while public-facing content should prioritise simplified, interactive experiences that maintain user attention while conveying essential information. One Planet Port representatives specifically suggested using digital platforms like North Sea Watch as storytelling tools for in-person advocacy meetings rather than mass mobilisation instruments.

Sophisticated Monitoring Systems with Structural Limitations

Port authorities have developed comprehensive monitoring systems, but they still face fundamental structural constraints. Amsterdam's approach illustrates both capabilities and limitations: they maintain 24-hour surveillance using patrol vessels and scrubber-equipped vessel databases, but can only regulate vessels 'at berth' because the main port waters are government-owned. This jurisdictional limitation exemplifies how legal frameworks can constrain enforcement even when technical capabilities exist.

Both jurisdictions adopted pragmatic implementation strategies: Amsterdam began with warnings rather than immediate penalties, while Denmark implemented different phaseout timelines for open-loop and closed-loop systems. The most significant challenge identified was coordination across jurisdictional boundaries. One interviewee emphasised that effective monitoring "would of course be easier when more countries are making the same regulation."

Cross-Border Coordination as Essential Strategy

Cross-border coordination emerged as essential across all stakeholder groups, with participants emphasising that isolated regulatory efforts face inherent limitations when vessels can redirect to less-regulated areas. As Danish Ministry representatives explained:

> *"It's not a coincidence that Sweden and Finland and Denmark, that our regulation is going to enter into force at almost the same time. It's also a way to make it easier for the ships to navigate in the regional regulation."*

This coordination not only enhances environmental effectiveness but also addresses competitive concerns that individual ports face when implementing unilateral measures.

3.4 Main Findings

The methods described above provide key insights into scrubbed pollution patterns and regulatory governance frameworks. Insights support the larger project scope, and both directly and indirectly facilitate intervention development. Table 1 summarises the main findings related to the sub-research questions presented in Section 2.5.

Table 1: Findings by (sub)-Research Question

Research Question	**Findings**
Quantitative	
To what extent do varying regulatory approaches to scrubber discharge regulation across North Sea countries influence pollution patterns?	Analysis of daily pollution shows that varying regulatory approaches to scrubber discharge regulation across North Sea countries noticeably influences pollution patterns. Countries with existing regulations have lower discharge levels compared to unregulated countries.
How can scrubber discharge estimates be predictively modelled for North Sea countries?	Predictive modelling of scrubber discharge estimates for North Sea countries using random forest regression successfully generated 30 day forecasts with varying accuracy levels. Predictions were more stable in the more regulated French environment, compared to the Netherlands.
How can agent-based modelling facilitate the assessment of different policy scenarios?	ABM proves to be a powerful tool for assessing the nuanced effects of different policy scenarios on scrubber discharge. It demonstrates that a uniform ban scenario is optimal for reducing pollution while maintaining economic status quo. It establishes the value of ABMs as more than a research method, as interactivity enables its utilisation as a toolkit for policy testing.
Qualitative	
How do policymakers navigate ethical trade-offs between economic impacts on industry and environmental protection when implementing scrubber discharge regulations?	Policymakers navigate two primary ethical tensions: • Precautionary principle vs. economic certainty when scientific evidence is contradictory; and • Balancing industry impact with environmental protection. Both jurisdictions resolved these through different approaches but reached similar conclusions about manageable economic costs and implemented stakeholder engagement strategies.
What is the current state of public awareness regarding scrubber discharge, and how do policymakers view its role in policy development?	Public awareness remains low across all stakeholder groups, extending even to maritime industry professionals. Policy development appears primarily evidence-based rather than driven by public pressure, though policymakers acknowledge potential importance of public understanding for political legitimacy. Effective engagement strategies focus on visual communication and targeted approaches rather than mass mobilisation

Continued on next page

Table 1: Findings by (sub)-Research Question (Continued)

How do port authorities currently monitor and enforce scrubber discharge regulations, and what are the challenges they currently face?	Port authorities employ various monitoring systems (patrol vessels, databases, surveillance) with pragmatic enforcement approaches (graduated penalties, phased implementation). Major challenges include jurisdictional limitations, detection difficulties, legal framework constraints, and coordination across boundaries. Isolated enforcement efforts face inherent limitations when vessels can redirect to less-regulated areas.

4 Digital Intervention

The findings mentioned above strongly influenced the design of the North Sea Watch platform. Quantitative data and analysis methods facilitate real-time visualisation of shipping traffic and scrubber pollution, while interactive agent-based modelling enables user-controlled policy simulations. Furthermore, insights from several interviews supported the fine-tuning of homepage content and website appeal. The following section describes the intervention's main components and their theoretical relevance, while articulating the intended stakeholder impact.

4.1 Key Elements, Theory Links, and Impact Pathways

The development and design of North Sea Watch incorporated key principles of two theoretical frameworks: the Technology Acceptance Model and the Integrated Change Model. For general platform design, TAM supports the development of an intervention that is more likely to be recognised and used by key stakeholders. More specifically – as TAM emphasises the roles of *perceived usefulness* and *perceived ease of use* – the intervention contains features and tools that are relevant to the target audience to stimulate engagement and long-term or continued usage of the platform (Marangunić and Granić 2015). To facilitate meaningful engagement, the intervention leverages motivation factors described by the I-Change Model, such as self-efficacy and socio-environmental norms and pressures, as well as pre-motivational or awareness factors such as knowledge and risk perception (Kasten et al. 2019; Vries et al. 2005). The next paragraphs describe the majority of direct applications of these principles, as well as how their potential effectiveness was elevated by applying actionable design methods.

4.1.1 Homepage

The homepage of North Sea Watch introduces users to the seemingly hidden issue of scrubber pollution, and presents it through a structured narrative that progresses from awareness to action. It begins by engaging users with a visually impactful hero section and call to action, designed to stimulate curiosity and motivate further exploration (Figure 20). This is followed by an explanation of the ecological risks of scrubbers, supported by touching wildlife images and a simplified diagram to foster knowledge and risk perception without overwhelming the user (Figures 21 and 22). The page presents icon-based data that highlight the scale of the issue and guides users toward the interactive map, strengthening risk-perception, perceived usefulness, and ease of navigation (Figure 23). A final brief overview of solutions – such as alternative fuels and regulatory bans – improves users' self-efficacy by demonstrating viable responses to the problem, and a closing call to action links users to the tools available on the platform (Figures 24 and 25). This structure supports both public engagement and policy impact. Non-experts receive accessible and engaging content to build environmental awareness, while policymakers are introduced to a policy-relevant problem in a way that primes them to explore detailed data and simulation tools presented elsewhere on the site.

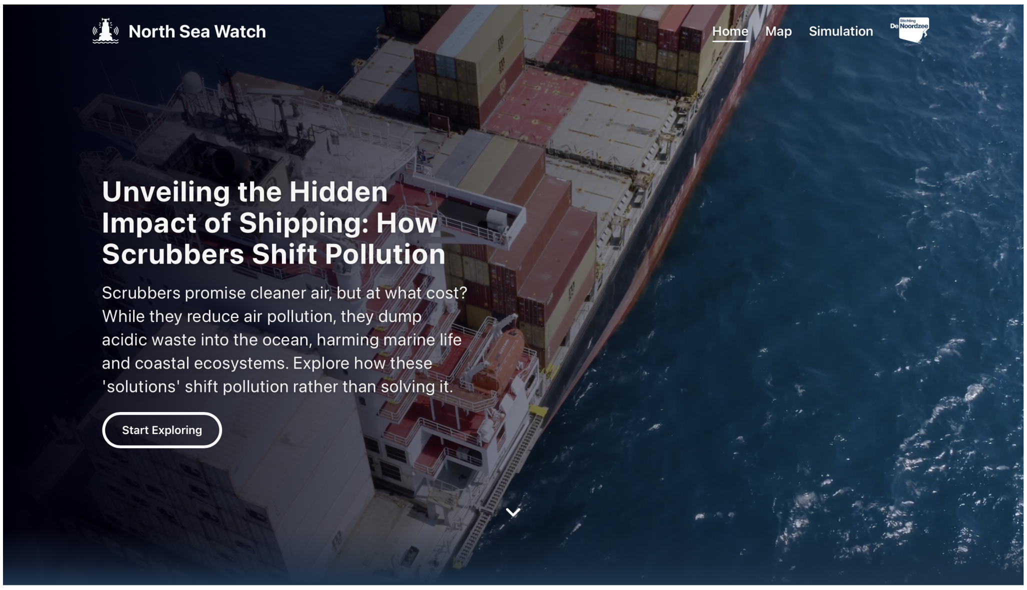

Figure 20: North Sea Watch Homepage Hero Section

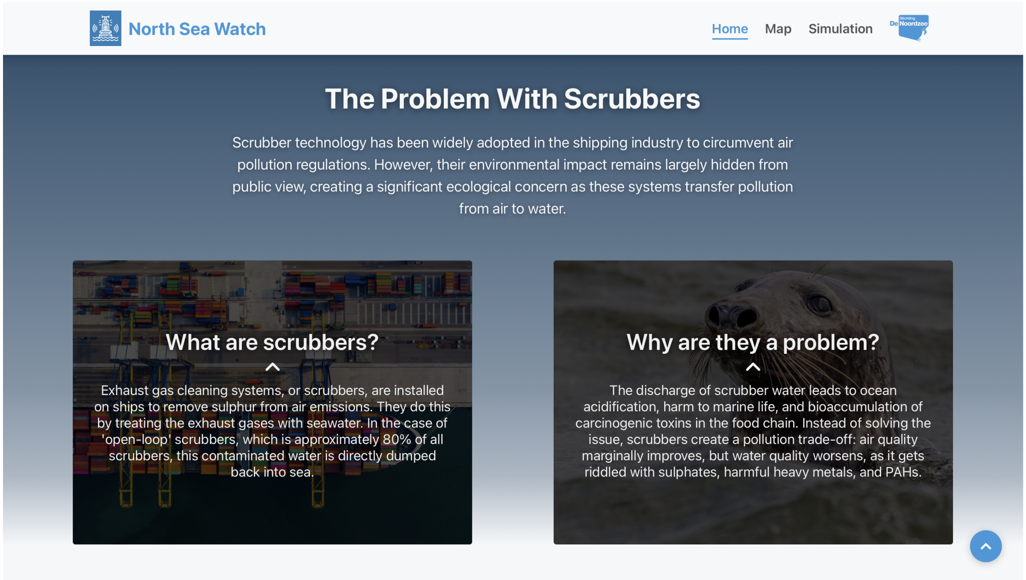

Figure 21: North Sea Watch Homepage Section – 'The Problem With Scrubbers'

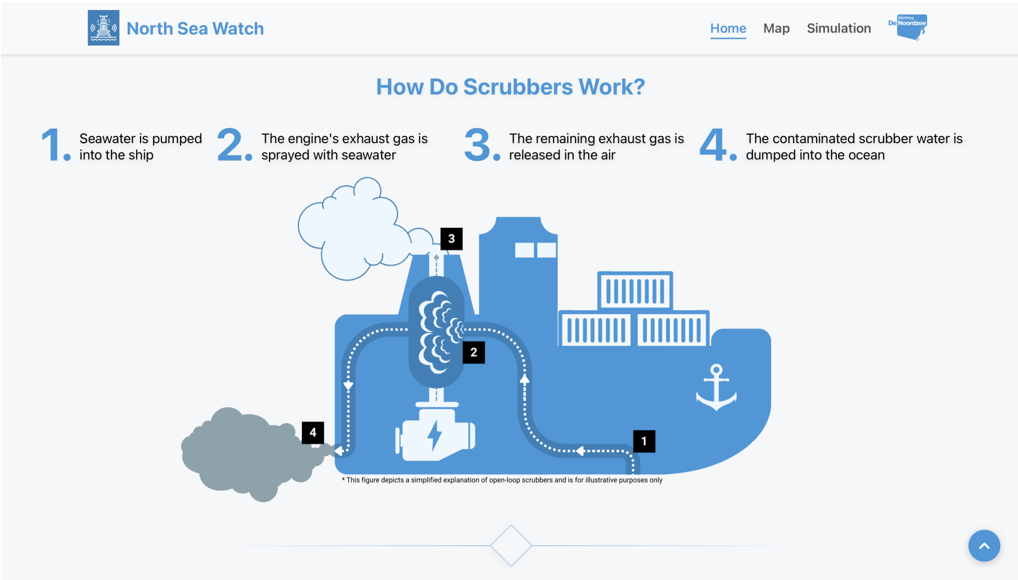

Figure 22: North Sea Watch Homepage Section – 'How Do Scrubbers Work?'

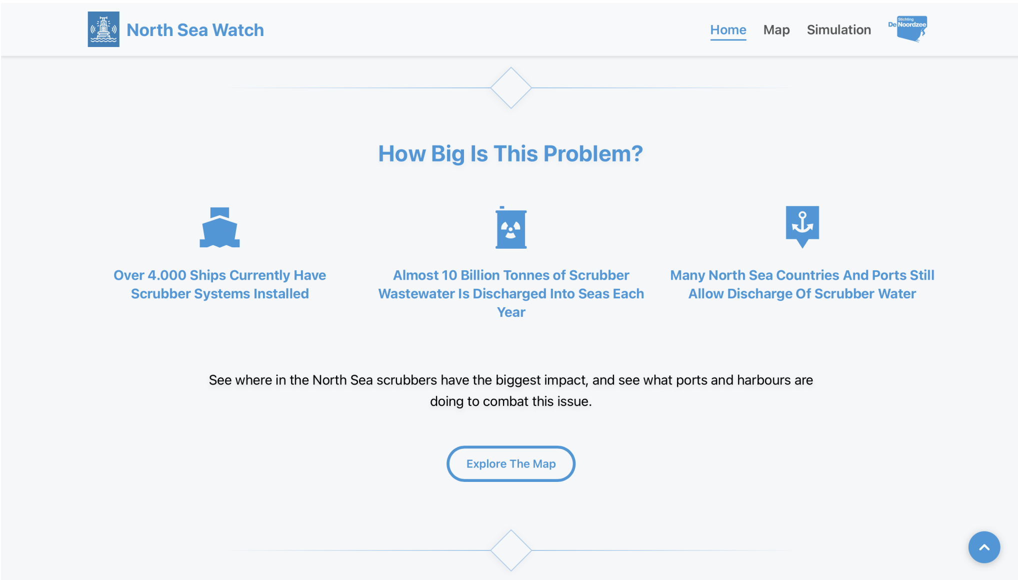

Figure 23: North Sea Watch Homepage Section – 'How Big Is This Problem'

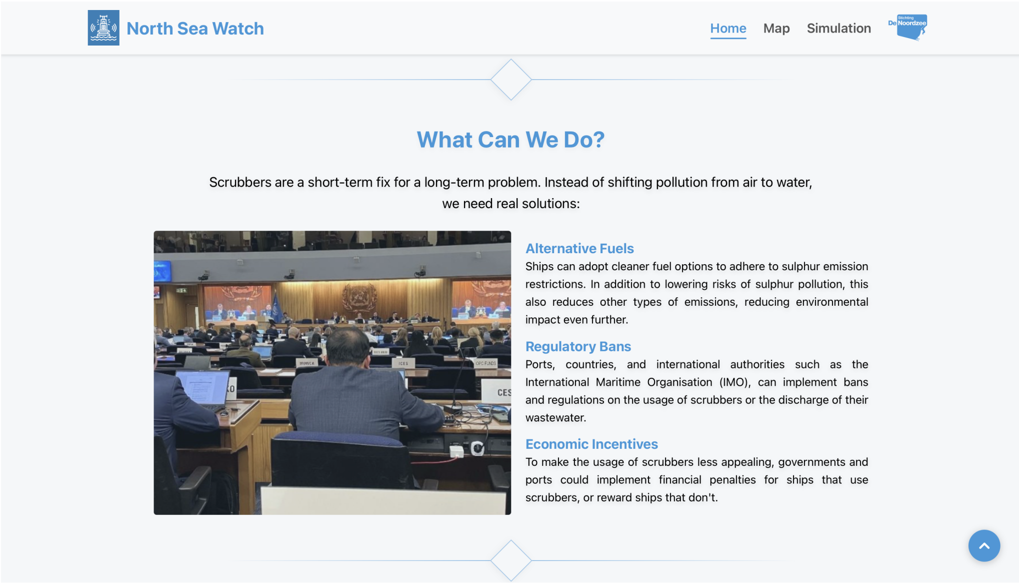

Figure 24: North Sea Watch Homepage Section – 'What Can We Do?'

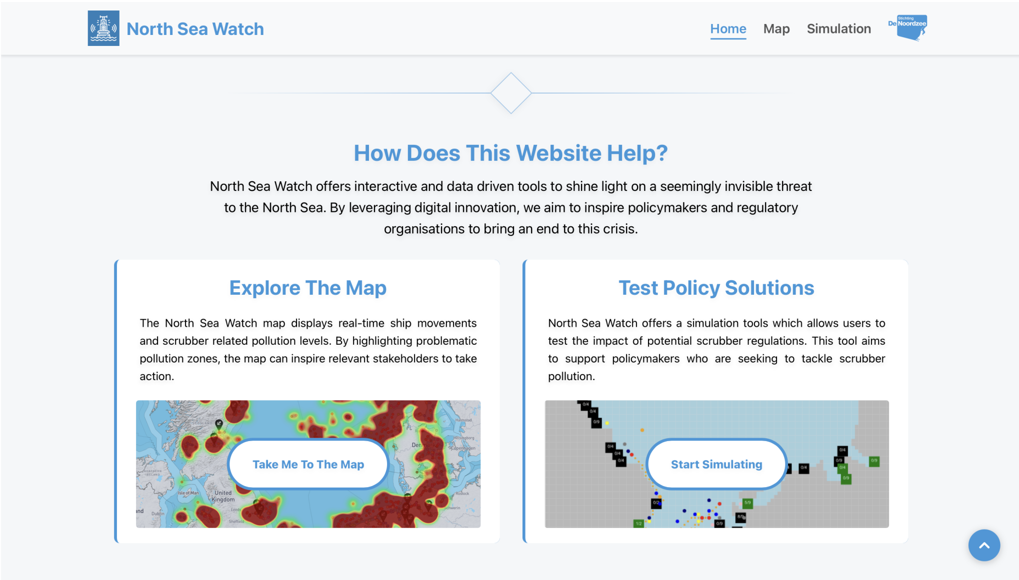

Figure 25: North Sea Watch Homepage Section – 'How Does This Website Help?'

4.1.2 Live Map

The live map is the core feature of the North Sea Watch platform, providing an interactive, real-time visualisation of maritime traffic and scrubber pollution within the North Sea. Built with Mapbox GL JS, this feature utilises data-driven visualisation to highlight pollution hotspots. It distinctively marks ships equipped with scrubbers and presents port-specific regulatory information, helping policymakers and environmental authorities identify regions requiring targeted intervention. It directly addresses stakeholders' needs for clear and accessible environmental data, encouraging informed policy decisions and promoting regulatory compliance. The map may be used by general users to identify local areas affected by scrubber discharge and compare policy differences, creating a more informed and environmentally aware public that can advocate for stricter regulations. As such, one of the core principles of the map is to present information clearly and efficiently using intuitive, interactive, real-time geospatial visualisation. This approach enhances usability and perceived usefulness, and is often more effective in engaging target audiences than conventional data communication methods – particularly in the context of environmental challenges (Patterson and Bickel 2016; Rist and Masoodian 2022).

An introductory pop-up window appears when users enter the page, presenting key features of the map and explaining their functionality (Figure 26). It also lists its data sources and provides a disclaimer regarding the accuracy of pollution estimates. To support user experience, the pop-up appears only once per device every 24 hours.

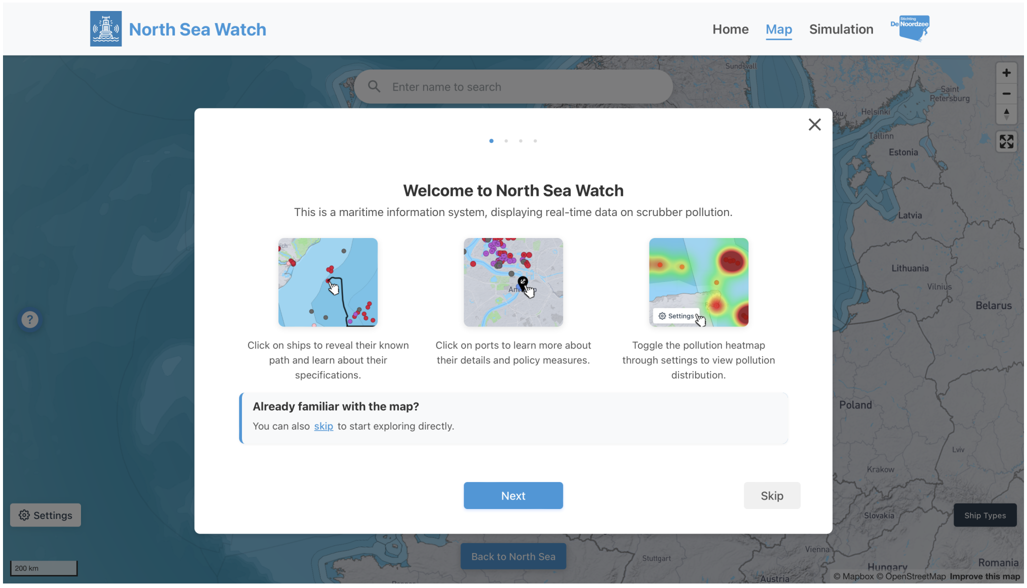

Figure 26: Introductory Map Pop-up – (Page 1)

As mentioned, the map itself presents an intuitive and interactive visualisation of shipping data in the North Sea. Interactive elements include clicking on individual vessels or ports, which triggers a sidebar to appear, revealing detailed information in the form of comprehensive tables. For vessels, this includes ship type, size, navigational status, and whether the vessel has a scrubber – and if so, its estimated discharge rate (Figure 27). Vessels that are clicked also display their known path, which represents pollution density for scrubber equipped vessels. For ports, the sidebar prominently displays a compact summary of scrubber-related policies that apply to the port (Figure 28) – which is also represented on the map through colour variations in port icons. Policymakers may be influenced by the prevalence of scrubber policies among North Sea ports, as they represent industry norms that can invoke pressure to adapt. This structured approach to displaying information ensures that users receive useful and relevant insights directly related to their immediate context on the map, which can facilitate informed decision making.

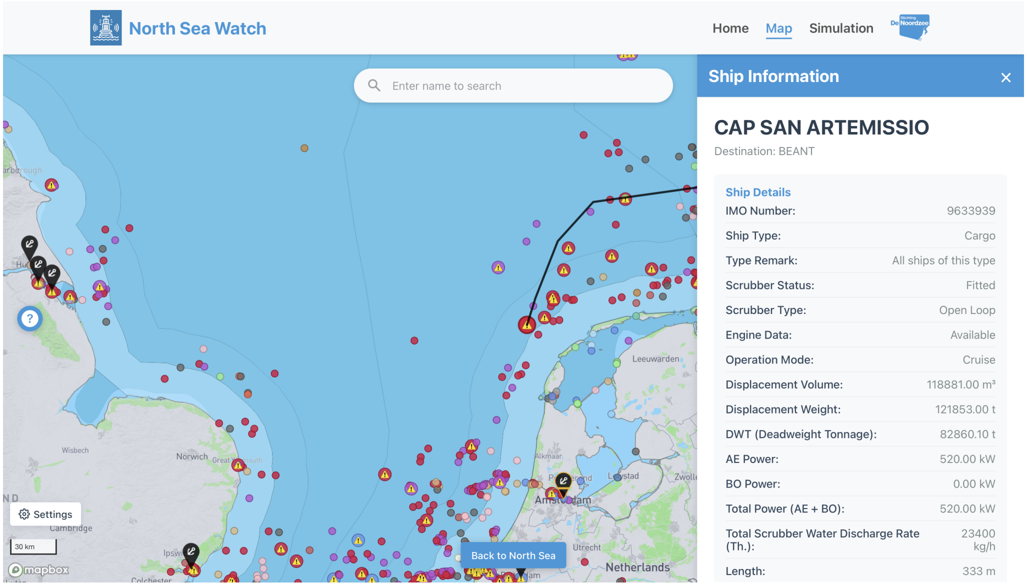

Figure 27: Map Page – Ship Information Sidebar

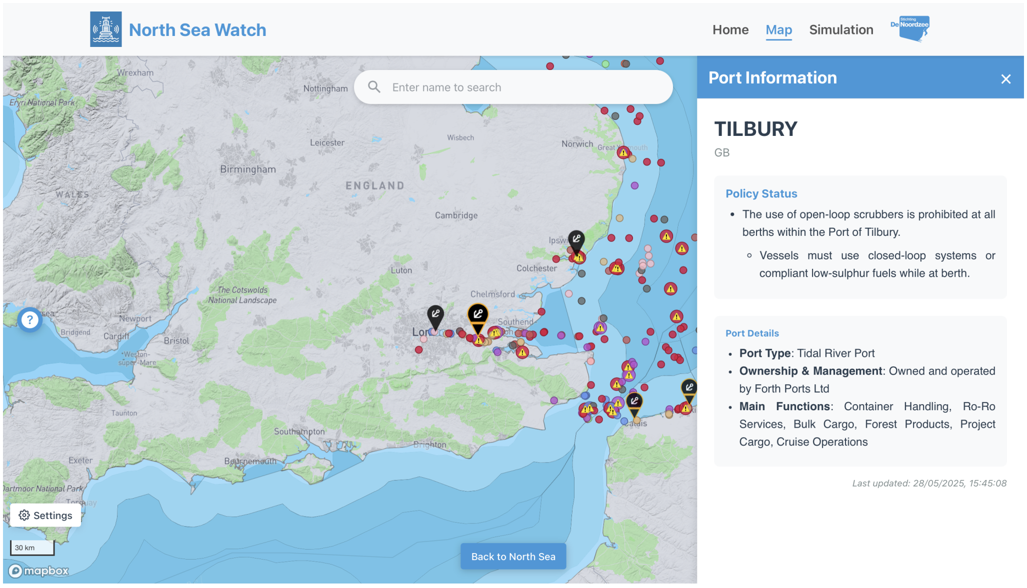

Figure 28: Map Page – Port Information Sidebar

Most interactive functions are integrated within a centralised settings panel, allowing users to conveniently control various map features in one accessible location (Figure 29). A heatmap visualisation can be toggled to reveal pollution hotspots clearly and effectively, minimising the need for complex interpretation (Figure 30). Scrubber-equipped vessels are distinctively marked with a commonly used warning symbol, leveraging risk perception and awareness of pollution sources with intuitive design. Furthermore, the settings panel provides advanced functionality through a playback mode to visualise scrubber pollution over a specified time period (Figure 31). Users can control this playback precisely with an intuitive slider, enabling detailed inspection of pollution patterns. A stand-alone control module featuring an easy-to-use interface and an integrated graph presenting pollution intensity ensures accessibility and user-friendliness.

Additional interactive elements include a search functionality for locating specific vessels or ports, a single click button to recentre on the North Sea region, a simplistic legend, and a question mark button which reopens the introductory pop-up when clicked, reinforcing accessibility and perceived ease of use of the map.

Lastly, the map design ensures responsiveness and functionality across different devices, encouraging greater accessibility. Overall, the map serves not only as an informational tool, but also actively engages users by guiding them toward understanding maritime pollution dynamics and encouraging informed policy decisions.

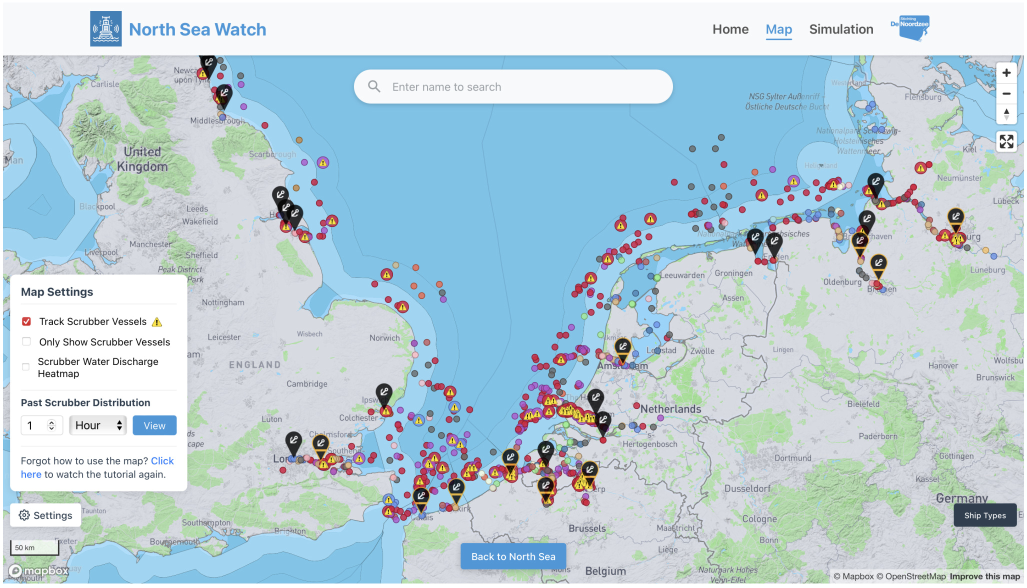

Figure 29: Map Page – Settings Panel

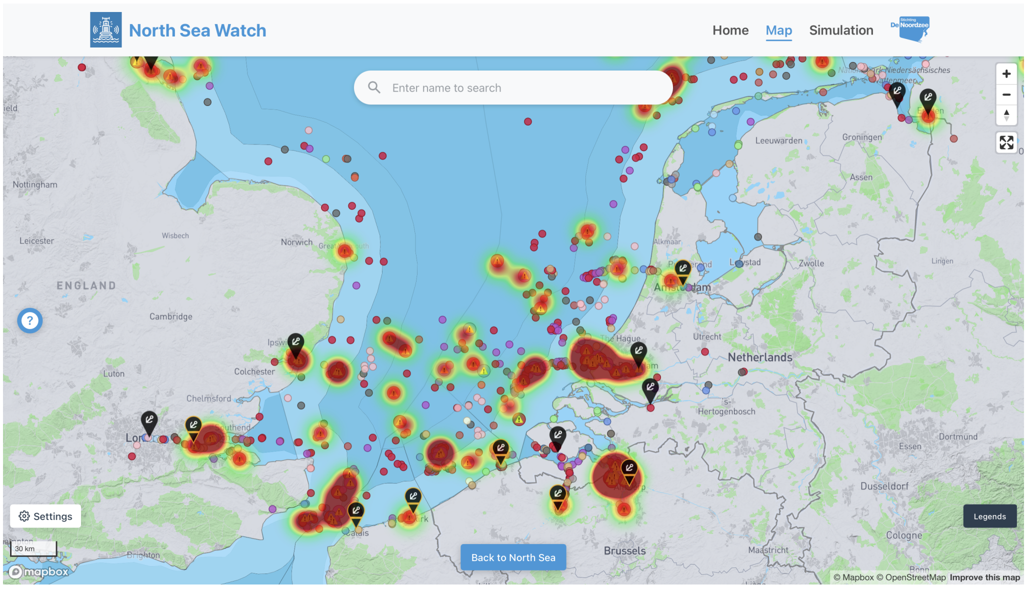

Figure 30: Map Page – Discharge Heatmap

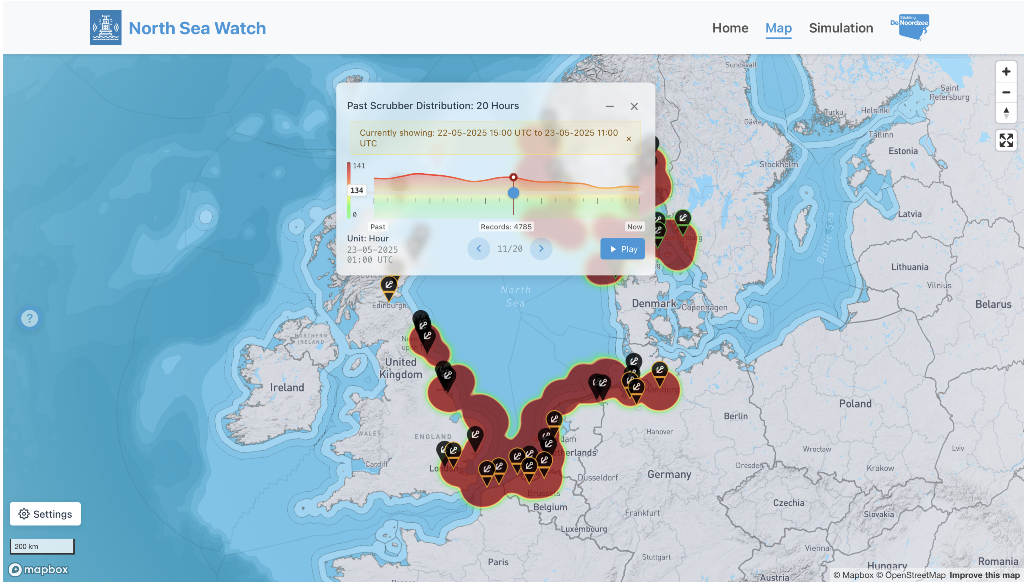

Figure 31: Map Page – Discharge Heatmap Playback Feature

4.1.3 Simulation Page

The simulation page incorporates an interactive version of the ABM described in Section 3.2 to simulate the effects of various regulatory scenarios on marine pollution (Figure 32). In short, users can modify policy-related simulation parameters and observe the outcomes in real-time. This powerful educational and analytical tool enables the visualisation of potential policy impacts, significantly contributing to stakeholders' understanding of complex maritime dynamics and encouraging proactive policymaking.

Similar to the live map, the simulation page visualises ship movements and scrubber pollution in the North Sea. Ports are colour-coded in a similar manner, and a legend is included to avoid confusion among users. Like on the live map, ports can be clicked to reveal more information, such as their name, docking capacity, and policy status (Figure 33). Furthermore, the simulation page contains a side panel displaying several summary statistics, such as ship routes, expected port revenue effects, and scrubber pollution volumes. The default simulation settings align with existing scrubber policies in North Sea ports and countries. Users can alter the simulation through the parameter dashboard to implement national bans or port-specific regulations (Figure 34). The default and national ban options provide accessibility to non-expert users. In contrast, the option to implement various port-specific regulations is intended for more informed users, such as environmental advocates and policymakers. As such, the simulation enables key stakeholders to assess the potential impact of their regulatory decisions, while providing an intuitive entry point for the public and educational users, enabling them to better understand the stakes of maritime policy and visualise how local or national actions could influence environmental impacts. This approach targets both public advocacy and top-down decision-making.

By providing a means of testing various policies at various scales and displaying potential outcomes of such policies on various fronts, the simulation page empowers users to make informed decisions when it comes to policy development. Focussing on consistent design and user interaction ensures that perceived ease of use and user friendliness of the platform remain sound, while the introduction of more complex features for policy testing has the potential to significantly improve user self-efficacy and perceived usefulness.

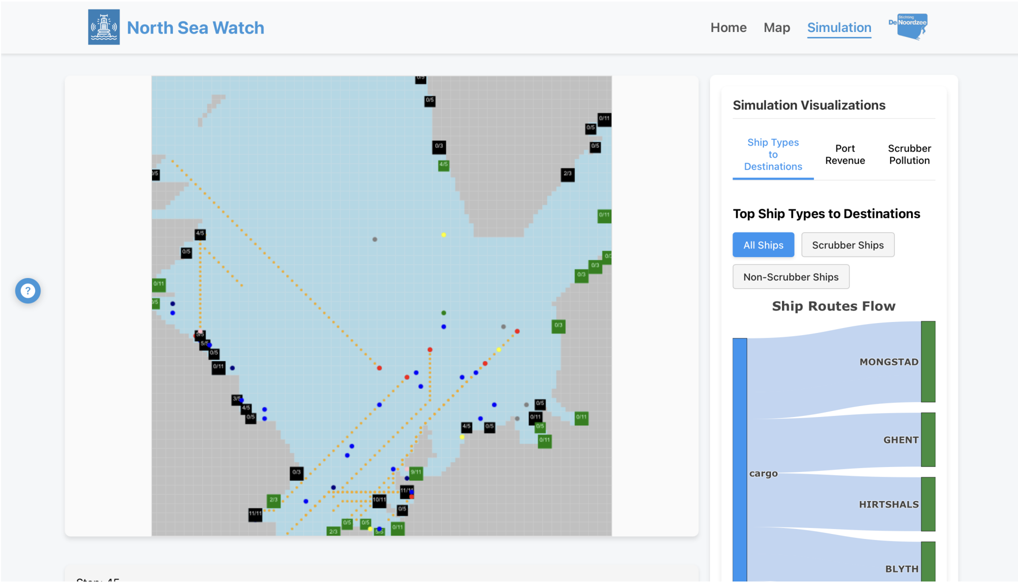

Figure 32: Simulation Page

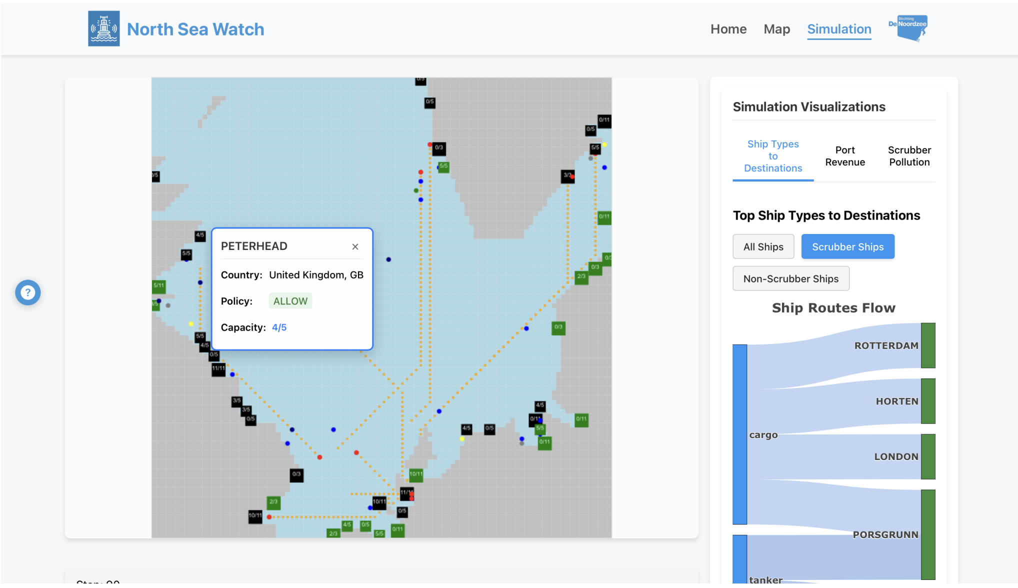

Figure 33: Simulation Page - Port Clickability

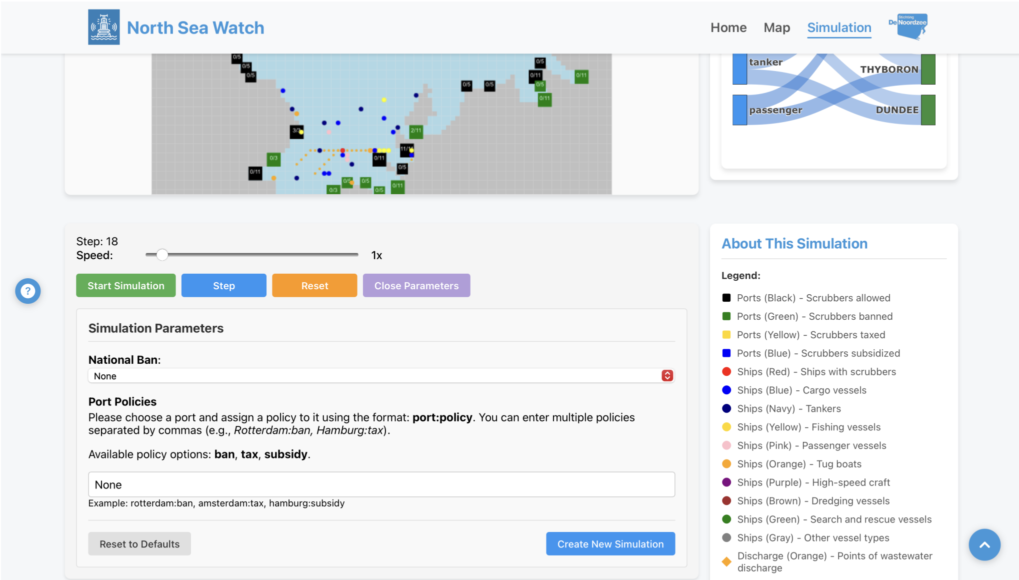

Figure 34: Simulation Page – Parameter Dashboard and Legend

5 Discussion

This project demonstrates that it is possible to transform complex research on scrubber water discharge into a digital intervention that is accessible and actionable to policymakers and the general public. By combining real-time shipping data, predictive modelling, and stakeholder insights, the North Sea Watch platform provides a clear answer to the central research question: it translates environmental evidence into an interactive decision support system that can inform regulatory action and raise public awareness.

What makes this possible is the platform's ability to link environmental data with the regulatory and political context in which it matters. Rather than simply showing where pollution occurs, it highlights how policy gaps and uneven enforcement allow the problem to persist. The simulation tool builds on this by giving users the ability to test different regulatory scenarios, revealing how coordinated or isolated policies affect pollution levels and port activity. This interactivity helps shift the platform from being just an informational tool to one that supports policy planning and advocacy.

Moreover, the platform fills a critical gap: Although scientific studies have established the risks of scrubber discharge and some policymakers have acted independently, there has been no shared, user-friendly space that links evidence, regulation, and action. North Sea Watch begins to fill that void. It offers policymakers a tool to test outcomes before implementing regulation, while offering environmental advocates a means to visualise and communicate the scale of the issue more effectively.

In this section, we reflect on these results, explore the implications for key stakeholders, and assess the ethical and practical challenges of building digital tools for environmental governance.

5.1 Implications

The North Sea Watch intervention can influence the three main stakeholder groups identified in Section 2.4 in different ways, depending on their use of the platform.

Environmental organisations, such as Stichting De Noordzee, will find the unified presentation of scrubber discharge data valuable for policy advocacy, as it consolidates information that was previously scattered across multiple sources. This could enhance their ability to demonstrate the scope and geographic distribution of the problem to policymakers, as one representative from One Planet Port stated:

> *"Nothing beats being able to, you know, meet someone in person and kind of talk it through. [...] having like online tools like this and using them in person can be really, really effective."*

Within the maritime industry, the intervention creates visibility around regulatory inconsistencies across North Sea ports and countries. Port authorities considering scrubber regulations can use the simulation tool to examine potential economic and environmental trade-offs before implementation, enhancing their ability to make informed decisions. For policymakers, the simulation tool has similar implications, but potentially at much larger scales. Furthermore, the website offers independent access to visual representations of pollution patterns and regulatory scenarios, which can be crucial in the initial communication of the scale of the problem, as a representative of the Danish Ministry of Environment stated:

> *"I think it could be very useful to have this kind of visualisation of probable discharges, especially when you are discussing with either governments or parties or stakeholders who don't really realise how big of a problem it is."*

The platform serves an awareness function for the general public by making visible an environmental issue that interview participants noted is largely unknown. However, the intervention's effectiveness ultimately depends on stakeholder engagement and utilisation rather than inherent transformative capabilities. As such, its true impact relies on Stichting De Noordzee's further efforts, using the North Sea Watch platform as a hybrid communication tool to reach influential stakeholders.

5.2 Ethical Considerations

Although vessel tracking and regulation assessments rely largely on publicly available data sources, this research was conducted with consideration of relevant ethical concerns, focussing primarily on data privacy, informed consent, and representation.

Despite its public availability, AIS data is handled securely to avoid potential misuse. Data collection and storage practices followed secure management principles. Data related to user activity are stored using Google Cloud SQL, only accessible to authorised researchers. The project adheres to the General Data Protection Regulation (GDPR), and details of data processing are clearly outlined in the North Sea Watch privacy policy. Qualitative data, such as recordings and transcripts, are also securely stored with access limited to authorised researchers.

To ensure informed consent for interviews, all participants received clear and comprehensive information on the research purpose, data usage, and their rights, including the right to withdraw at any time. Each participant signed a consent form confirming their understanding and agreement (see Appendix D). Furthermore, participants who were mentioned by name or position were done so according to their preferences.

AIS data does not cover most smaller or non-commercial vessels, and AISStream limits tracking data to land-based stations. As such, pollution analyses and real-time data visualisations may lack accuracy and reflect geographical biases due to limited coverage. Interview participant selection may also reflect certain biases. Most participants were contacted through Stichting De Noordzee's network, which could have limited the representation of diverse perspectives. To counteract this effect, efforts were made to consult individuals across all identified key stakeholder categories.

5.3 Limitations and Future Research Directions

The utilised approach to scrubber discharge analyses reveals several methodological constraints. Existing regulatory frameworks for monitoring scrubber discharge present significant detection challenges, as distinguishing scrubber wastewater from other vessel discharge sources requires sophisticated monitoring technologies. Endres et al. (2018) identify this as a persistent challenge in maritime pollution research, highlighting the insufficient measurement systems currently available for tracking pollutants along shipping routes and in port areas. Identification of fuel types and discharge origins remains problematic, particularly in conditional regulatory environments. These limitations could not be overcome within the scope of this study due to the substantial costs of comprehensive vessel monitoring systems and data. These constraints underscore a potential need for developing automated detection systems that could revolutionise compliance monitoring.

The complexity of environmental modelling represents another constraint in the current analytical framework. Although the study effectively quantifies discharge volume estimates, it does not account for environmental variables that influence pollutant behaviour and impact, as this would require advanced interdisciplinary expertise and resources beyond the project's scope. The absence of these factors limits the accuracy of pollution assessments, as recent research demonstrates that scrubber wastewater dispersion and pH neutralisation vary significantly depending on environmental conditions (Choi and Lim 2020). Further research incorporating environmental factors could enhance environmental impact assessments and support more targeted regulatory interventions.

The reliance on theoretical modelling rather than empirical water quality validation constitutes a fundamental limitation that simultaneously points toward the most critical research need in this field. Predictive models and visualisations, while valuable for policy communication, require validation through systematic water sampling to establish scientific credibility and regulatory utility. This empirical validation gap could not be addressed due to the specialised equipment, laboratory access, and field work required for comprehensive water quality assessment – resources that were not feasible within student project constraints. Research in monitoring marine pollution indicates that suitable analytical techniques and methodological approaches remain significant barriers to studying environmental pollutants and their ecological impacts (Bellas, Hylland, and Burgeot 2020). This limitation suggests that pollution hotspot predictions should be considered preliminary estimates rather than definitive environmental assessments. To address this gap, future studies should prioritise collecting physical water quality samples from areas predicted to have the highest concentrations of scrubber discharge, particularly major shipping hubs such as the Port of Rotterdam and the Port of Hamburg. Such empirical validation would not only strengthen the scientific foundation of discharge impact assessments, but also provide essential baseline data for measuring regulatory effectiveness, while adding a more ecologically precise layer to the research that could raise awareness of the broader environmental consequences of scrubber use in shipping.

Perhaps most importantly, the study's focus on discharge quantification rather than ecological impact assessment reveals the broader challenge of translating pollution metrics into meaningful environmental protection outcomes. This limitation affects the study's conclusions by providing pollution-based rather than ecosystem-health-based impact assessments. Although recent economic analyses demonstrate substantial theoretical environmental damage costs from scrubber discharge, estimated at more than €680 million in the Baltic Sea region alone between 2014-2022, these calculations represent modelling-based projections rather than field-measured ecosystem responses (Lunde Hermansson, Hassellöv, Grönholm, et al. 2024). Future research should adopt a more ecologically centred perspective by not only quantifying scrubber discharge but also directly examining its biological impacts on marine life. Based on empirical data on pollutant volumes, subsequent studies could investigate how contaminants from scrubber wastewater affect various marine species in identified pollution hotspots, at both individual and ecosystem levels, resulting in a comprehensive assessment of ecosystem-wide effects. Understanding marine ecosystem responses to chemical contamination requires essential interdisciplinary collaboration with marine biologists, where partnering with experts in marine ecology would enable the integration of biological insights and targeted field sampling programmes. Developing such comprehensive ecological assessment frameworks could transform the way maritime pollution regulations are designed and evaluated, shifting focus from discharge volume reduction to measurable improvements in ecosystem health.

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A Appendix: Data and Code

A.1 Database Schema

Below is the column composition and description of the two main data tables used for the data collection system, ships and ship_data:

Column name	**Data type**	**Description**
imo_number	bigint	International Maritime Organization (IMO) number uniquely identifying each vessel
mmsi	bigint	Maritime Mobile Service Identity (MMSI), an alternative international vessel identification number
length	integer	Length of the vessel
width	integer	Width of the vessel
max_draught	numeric	Maximum draught, depth below waterline of the vessel
ship_type	text	Vessel type code
type_name	text	Vessel type name
type_remark	text	Additional remarks on the vessel type
name	text	Vessel name

Table 2: 'ships' Data Table Schema

Column name	**Data type**	**Description**
id	integer	True heading of the vessel
imo_number	bigint	IMO number linking to the ships table
timestamp_collected	UTC timestamp	Timestamp when the data was collected by the system
timestamp_ais	UTC timestamp	Original timestamp from the AIS message
latitude	numeric	Latitude coordinate of the vessel
longitude	numeric	Longitude coordinate of the vessel
sog	numeric	Speed Over Ground, actual speed of the vessel

cog	numeric	Course Over Ground, actual movement direction of the vessel
true_heading	integer	True heading of the vessel
navigational _status_code	integer	Numeric code representing the vessel's navigational status
navifational_status	text	Text description of the vessel's navigational status
rate_of_turn	numeric	Rate of turn indicating how quickly the vessel is turning
destination	text	Current reported destination of the vessel

Table 3: 'ship_data' Data Table Schema

A.2 Code Repositories and Structure

This project worked with three main code repositories. Figures 35, 36, and 37, represent the file architecture of the North Sea Watch web platform, the AISStream data retrieval protocol, and the agent-based model, respectively.

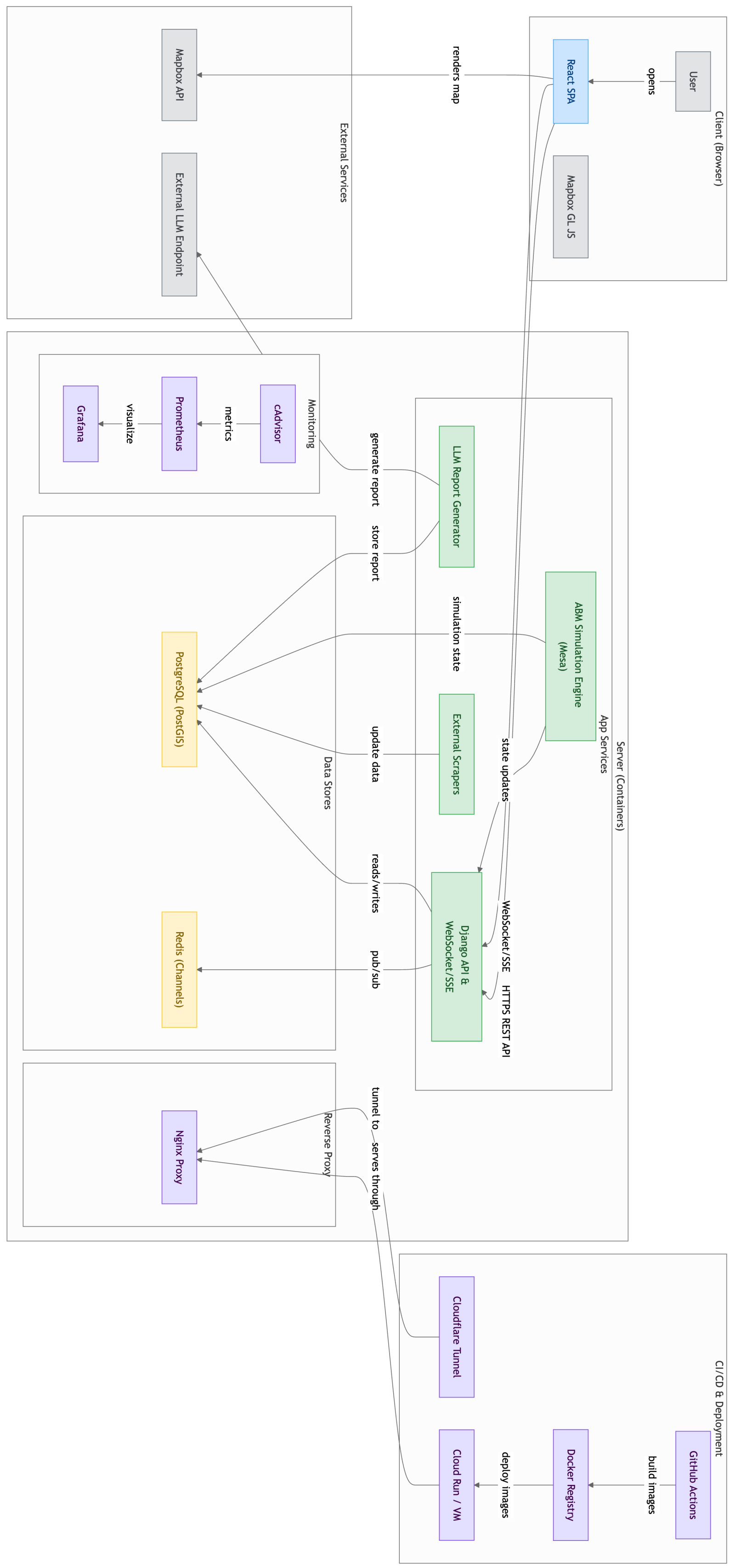


Figure 35: North Sea Watch Web Architecture

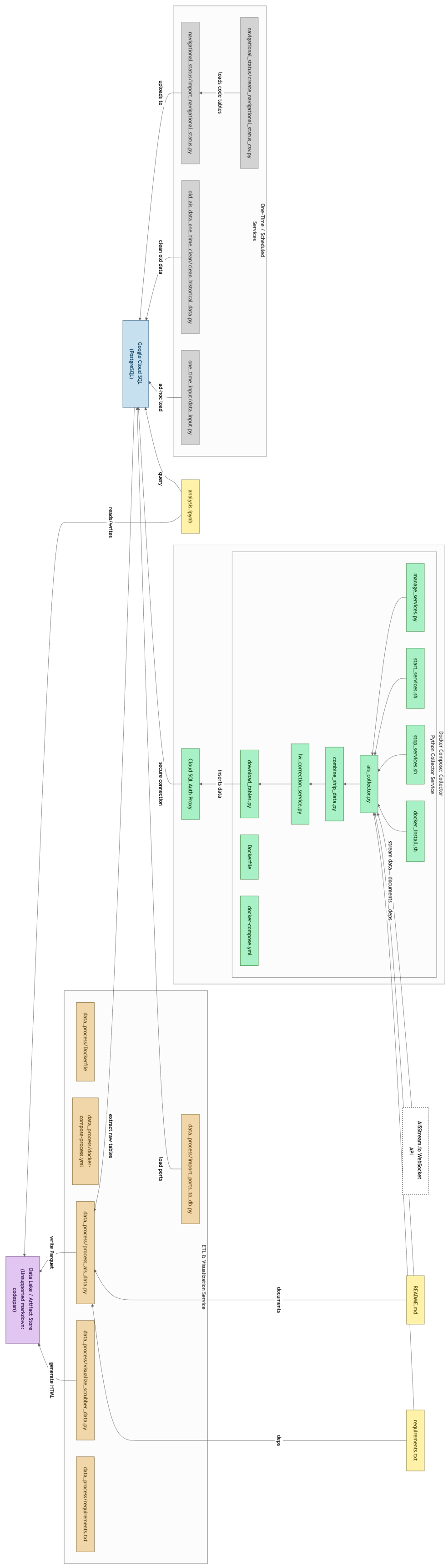


Figure 36: AISStream API Data Collection Architecture

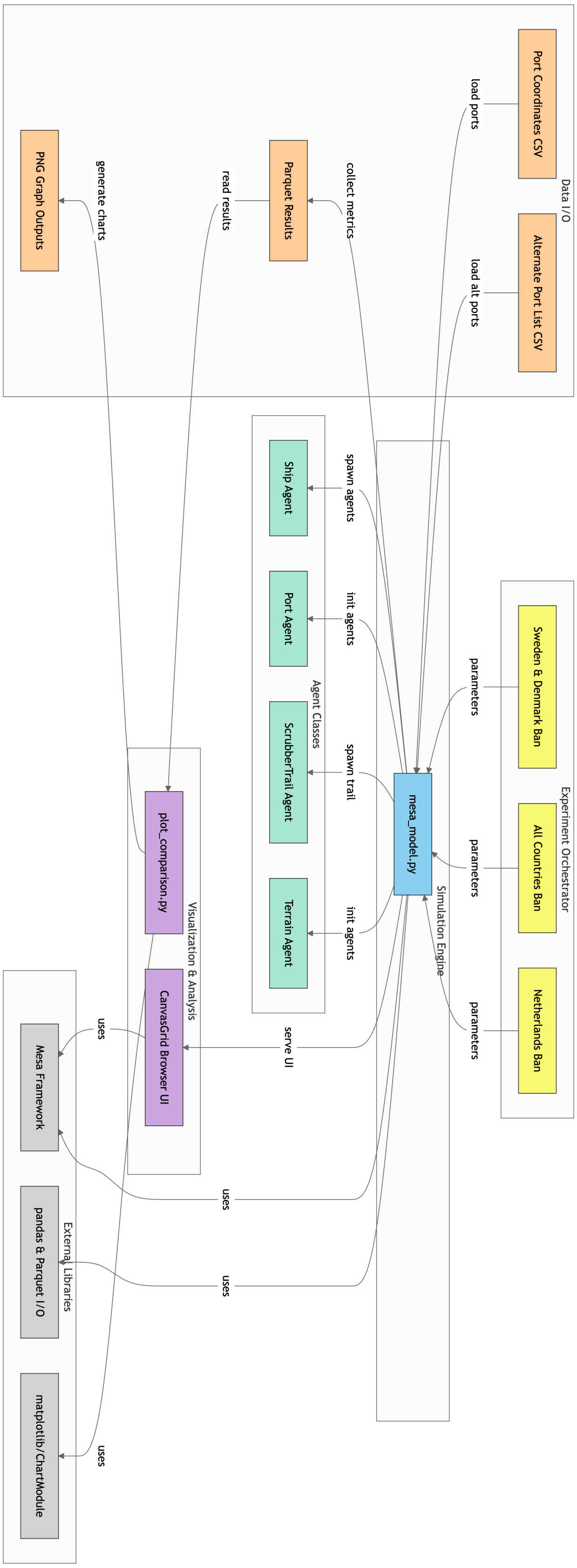


Figure 37: Agent-Based Modelling Architecture

As the original code repositories are directly linked to the North Sea Watch web platform, they must remain private to ensure that the platform can remain up and running. Instead, relevant repositories were cloned and stripped of sensitive information such as API keys and other credentials before being published. The repositories can be accessed through the following links:

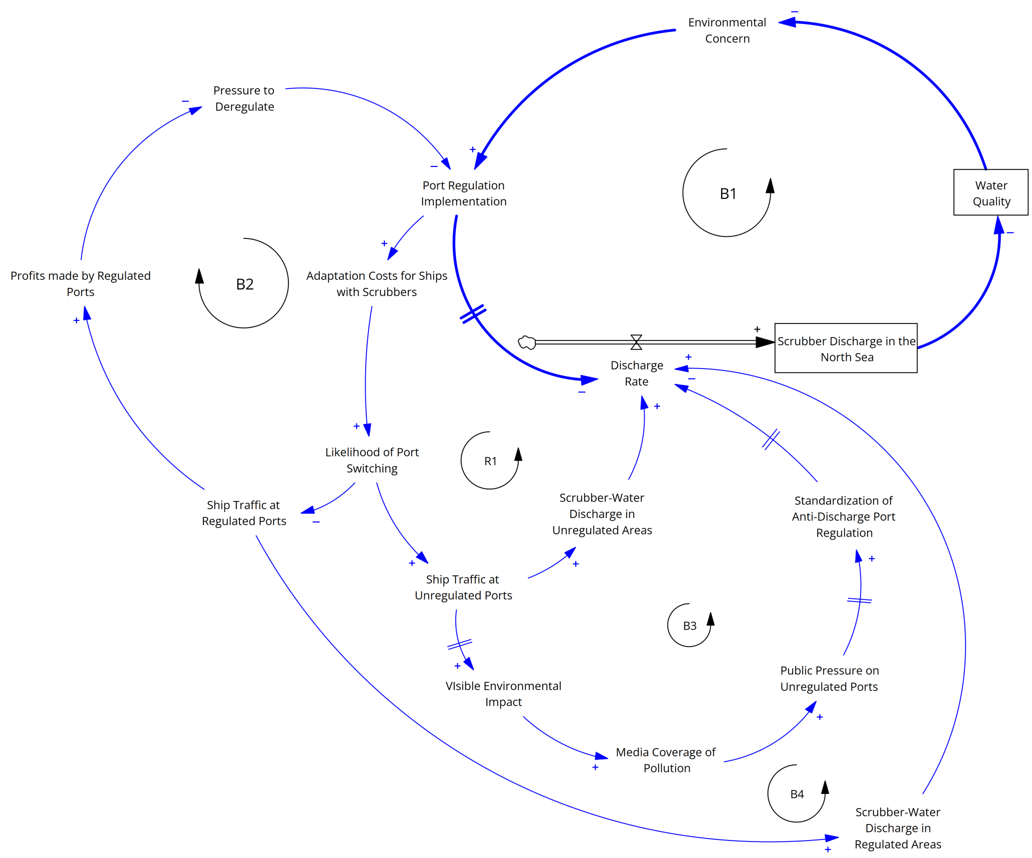
- North Sea Watch web repository (altered):
  - https://github.com/Aoyamaxx/public-north-sea-watch
- AISStream data collection repository (altered):
  - https://github.com/Aoyamaxx/public-ais-stream-api
- Agent-based model repository:
  - https://github.com/NorthSeaWatch/honors-abm
- Ship classification for scrubber discharge estimation repository:
  - https://github.com/NorthSeaWatch/discharge-calculation

A.3 Data Sources

The main data sources used for this project, as well as their origins and relevant links, are listed below.

- AISStream.io:
  - Used for collecting AIS vessel tracking data.
  - **Documentation:** https://aisstream.io/documentation
  - **GitHub:** https://github.com/aisstream
- ICCT Supplementary Data:
  - Used for identifying scrubber equipped vessels through IMO identification number.
  - **Confidentially Obtained**
- World Port Index:
  - Used for locating ports in the North Sea region.
  - Port selection was done in collaboration with Stichting De Noordzee.
  - **Managed by:** National Geospatial-Intelligence Agency
  - **Link:** https://msi.nga.mil/Publications/WPI
- ICCT SAVE Model Documentation:
  - Used to identify estimated power consumption based on DWT.
  - **Link:** https://theicct.github.io/SAVE-doc/versions/v2025.03.1/#11-ship-class-and-capacity-bin

B Appendix: Causal Loop Diagram



This guide explains the causal loop diagram depicting the complex system of maritime scrubber discharge regulation and its environmental and economic impacts. The diagram illustrates how various factors interact through feedback loops, creating dynamic patterns of behaviour in the system.

B.1 Understanding the Variables

Before exploring the feedback loops, it's helpful to understand the key variables in the system:

- **Stock Variables:** Accumulate over time (e.g., Scrubber Discharge in the North Sea, Water Quality)
- **Rate Variables:** Control the flow into or out of stocks (e.g., Discharge Rate)
- **Auxiliary Variables:** Influence the relationships between variables (e.g., Port Regulation Implementation)
- **Polarity Indicators**: The "+" and "-" signs on arrows indicate whether variables change in the same direction (+) or opposite directions (-)

B.2 Feedback Loops

The diagram contains five feedback loops (four balancing and one reinforcing) that together explain the dynamic behaviour of the system.

B1: Environmental Regulation Response Loop

This balancing loop represents the basic regulatory response to environmental problems:

1. As Scrubber Discharge in the North Sea increases, Water Quality decreases (-)
2. Declining Water Quality leads to increased Environmental Concern (-)
3. Higher Environmental Concern strengthens Port Regulation Implementation (+)
4. Stricter Port Regulation Implementation reduces the Discharge Rate (-)
5. Lower Discharge Rate decreases Scrubber Discharge in the North Sea (+)

This creates a balancing effect where environmental degradation triggers regulatory responses that aim to reduce the pollution. The system seeks equilibrium through this negative feedback mechanism.

B2: Economic Pressure Loop

This balancing loop illustrates how economic forces can counteract environmental regulations:

1. Stronger Port Regulation Implementation increases Adaptation Costs for Ships with Scrubbers (+)
2. Higher Adaptation Costs increase the Likelihood of Port Switching (+)
3. Greater Likelihood of Port Switching reduces Ship Traffic at Regulated Ports (-)
4. Reduced Ship Traffic decreases Profits made by Regulated Ports (+)
5. Lower Profits increase Pressure to Deregulate (-)
6. Greater Pressure to Deregulate weakens Port Regulation Implementation (-)

This loop shows how economic pressures can undermine environmental regulations as ports face financial consequences from lost shipping traffic, creating push-back against strict environmental measures.

B3: Public Awareness and Standardisation Loop

This balancing loop demonstrates how public awareness can lead to broader regulatory standards:

1. Port Regulation Implementation increases Adaptation Costs for Ships with Scrubbers (+)
2. Higher Adaptation Costs increase the Likelihood of Port Switching (+)
3. Greater Likelihood of Port Switching increases Ship Traffic at Unregulated Ports (+)
4. More Ship Traffic at Unregulated Ports increases Visible Environmental Impacts (+)
5. Greater Visible Environmental Impacts increase Media Coverage of Pollution (+)
6. Increased Media Coverage strengthens Public Pressure on Unregulated Ports (+)
7. Stronger Public Pressure enhances Standardisation of Anti-Discharge Port Regulation (+)
8. Greater Standardisation reduces the Discharge Rate (-)
9. Lower Discharge Rate decreases Scrubber Discharge in the North Sea (+)
10. Reduced Scrubber Discharge improves Water Quality (-)
11. Better Water Quality reduces Environmental Concern (-)
12. Lower Environmental Concern weakens pressure for Port Regulation Implementation (+)

This loop shows how pollution visibility can create public pressure that leads to standardised regulations across different ports, potentially addressing the problem of pollution havens.

B4: Regulated Discharge Redistribution Loop

This balancing loop shows how regulations affect discharge patterns in regulated areas:

1. Port Regulation Implementation increases Adaptation Costs for Ships with Scrubbers (+)
2. Higher Adaptation Costs increase the Likelihood of Port Switching (+)
3. Greater Likelihood of Port Switching reduces Ship Traffic at Regulated Ports (-)
4. Reduced Ship Traffic decreases Scrubber-Water Discharge in Regulated Areas (+)
5. Lower Discharge in Regulated Areas reduces the overall Discharge Rate (+)
6. Reduced Discharge Rate decreases Scrubber Discharge in the North Sea (+)
7. Lower Scrubber Discharge improves Water Quality (-)
8. Better Water Quality reduces Environmental Concern (-)
9. Lower Environmental Concern weakens pressure for Port Regulation Implementation (+)

This loop demonstrates how regulations can successfully reduce pollution in regulated areas, potentially improving overall water quality if the reduction isn't completely offset by increases elsewhere.

R1: Regulatory Avoidance Reinforcing Loop

1. This reinforcing loop illustrates the potential for environmental regulations to create "pollution havens":
2. Port Regulation Implementation increases Adaptation Costs for Ships with Scrubbers (+)
3. Higher Adaptation Costs increase the Likelihood of Port Switching (+)
4. Greater Likelihood of Port Switching increases Ship Traffic at Unregulated Ports (+)
5. More Ship Traffic increases Scrubber-Water Discharge in Unregulated Areas (+)
6. Greater Discharge in Unregulated Areas increases the overall Discharge Rate (+)
7. Higher Discharge Rate increases Scrubber Discharge in the North Sea (+)
8. More Scrubber Discharge worsens Water Quality (-)
9. Lower Water Quality increases Environmental Concern (-)
10. Greater Environmental Concern strengthens Port Regulation Implementation (+)

This positive feedback loop can create a vicious cycle where stricter regulations in some areas actually worsen the overall environmental situation by shifting pollution to unregulated areas, potentially leading to even stricter regulations that further concentrate pollution in unregulated areas.

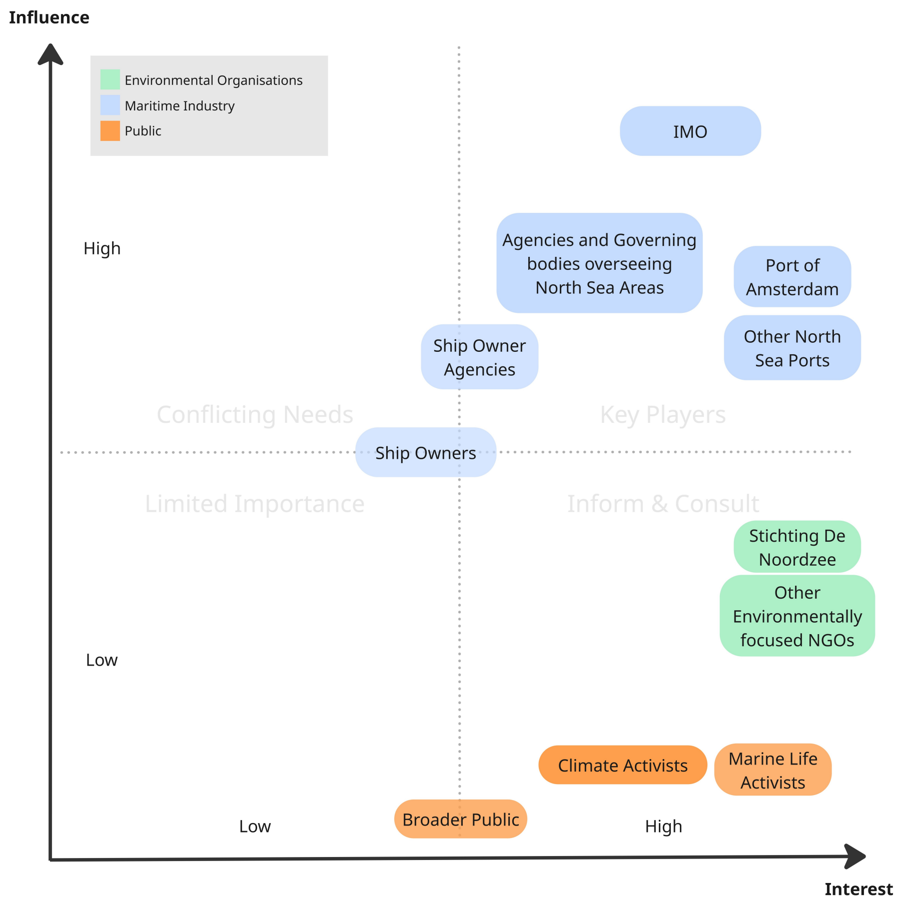
B.3 System Implications

The interaction of these five feedback loops creates complex system behaviour:

1. Short-term vs. Long-term Effects: Loop B1 may create immediate improvements, but loops B2 and R1 can undermine these gains over time.
2. Policy Resistance: Loop B2 shows how economic pressures can resist environmental policies.
3. Unintended Consequences: Loop R1 illustrates how well-intentioned regulations can create pollution havens.
4. Leverage Points: Loop B3 suggests that standardising regulations across ports may be more effective than strong regulations in isolated areas.
5. Tipping Points: If loop R1 dominates the system, environmental conditions could worsen despite increased regulation.

C Appendix: Stakeholder Analysis

C.1 Stakeholder Map



C.2 Decision Rule

We aim to create a digital intervention that visualises the effects of scrubber water discharge in the North Sea, designed both to inform the public and provide detailed information for policymakers. To systematically analyse the stakeholders involved in this issue, we employed Mendelow's Power-Interest Matrix, which positions stakeholders along two critical dimensions: 'Influence' and 'Interest' (Mendelow 1991).

The vertical 'Influence' axis represents the level of power and authority each stakeholder possesses to affect regulation, implementation, and practices related to scrubber discharge in the North Sea. Stakeholders positioned higher on this axis have greater capacity to directly impact policy decisions, enforcement mechanisms, or operational practices.

The horizontal 'Interest' axis indicates the degree to which stakeholders are concerned with or affected by water pollution issues, particularly scrubber discharge. This dimension reflects both their awareness of the environmental implications and the relevance of these issues to their organisational missions or personal values.

The matrix divides stakeholders into four strategic quadrants, each requiring a distinct engagement approach:

1. Key Players (High Influence, High Interest): These stakeholders are crucial partners for our initiative due to their combination of significant influence and strong interest. Attempts should be made for their active engagement throughout the project, as their support is essential for implementation success.
2. Conflicting Needs (High Influence, Low Interest): These stakeholders possess substantial influence but demonstrate limited or contradictory immediate interest in scrubber discharge issues. Understanding their operational behaviours may be of use, but is not a priority.
3. Inform & Consult (Low Influence, High Interest): These stakeholders show strong interest despite having less direct influence. They represent valuable allies for advocacy, research collaboration, and public awareness campaigns, requiring regular communication about project developments.
4. Limited Importance (Low Influence, Low Interest): Stakeholders in this quadrant demonstrate limited influence and interest regarding scrubber discharge. While requiring less intensive engagement, monitoring these stakeholders remains important as their positioning may shift with increased awareness or changing circumstances.

C.3 Stakeholder Descriptions

What? / Who?	**Position**	**Interests**	**Constraints**	**Insights**
Policy Makers and Agencies	Responsible for creating and enforcing maritime regulations. Some countries have banned scrubber discharge, while others have no regulations (Teuchies et al. 2020).	Balancing environmental protection with maritime economic interests. Seeking science-based policy decisions.	Political pressure from industry, limited enforcement resources, and regulatory fragmentation (Endres et al. 2018).	Policy makers recognise scrubber discharge impact but struggle with regulatory balance. The EU Water Framework Directive pushes for stricter measures (Lunde Hermansson, Hassellöv, Jalkanen, et al. 2023).
North Sea Ports	Some ports (e.g., Amsterdam) have bans, while others allow open-loop scrubbers. Ports weigh environmental concerns against competitive advantage.	Maintaining competitiveness while adhering to environmental standards. Avoiding loss of shipping traffic due to strict regulations.	Economic competition may lead to "race to the bottom" in environmental standards. Lack of standardised regulations (Hassellöv 2022).	Ports are critical gatekeepers. Amsterdam's 2025 discharge ban could lead to broader regulation shifts.
Stichting De Noordzee	Advocates against scrubbers, raising awareness of marine pollution and supporting stricter bans.	Protecting the North Sea ecosystem from contamination and acidification. Promoting sustainable shipping.	No direct regulatory power, relies on scientific evidence and public support for influence.	The NGO acts as a knowledge broker between research and policy makers, advocating for marine protection despite limited authority.
Ship Owners	Favour scrubbers as a cost-effective compliance method. Many have invested heavily in scrubber technology.	Maximising profit while meeting regulations. Recovering scrubber investments. Maintaining operational flexibility.	Economic concerns often outweigh environmental issues. High scrubber investment creates resistance to regulatory change (Zis and Cullinane 2020).	Scrubber adoption is financially attractive, with most ships breaking even within 3-5 years. By 2022, 51% of scrubber-equipped ships had profited €4.7 billion (Hermansson 2024).
Broader Public	Generally unaware of scrubber discharge but increasingly concerned about marine pollution and climate change.	Desire for clean seas, sustainable shipping, and transparency in environmental practices.	Limited knowledge about maritime operations and scrubber technology. Low awareness of shipping's role in pollution (Endres et al. 2018).	Public concern can drive policy change if informed. Awareness campaigns could improve engagement.
Insights	The scrubber issue is a classic case of economic vs. environmental interests. The challenge is balancing both.	Stakeholders share a long-term interest in the North Sea's health but differ on short-term priorities.	Regulatory fragmentation and knowledge gaps hinder progress. Better monitoring, standardised rules, and knowledge-sharing could help.	Effective regulation needs both scientific and economic considerations. Digital visualisation tools could improve stakeholder understanding.

D Appendix: Interview Consent Form

North Sea Watch Interview Consent Form

Aim of the study

This project is part of the educational program at the Computational Social Science bachelor of the University of Amsterdam. The results of this study will be used for educational purposes.

By the end of the project, students will develop a web-based interactive platform and comprehensive research report about the environmental impact of Exhaust Gas Cleaning Systems (EGCS) in the North Sea.

This study aims to understand stakeholder perspectives on scrubber water discharge in the North Sea, evaluate current regulatory approaches, and identify effective policy interventions to mitigate marine pollution from these systems.

This interview will include questions about your experience and expertise regarding maritime emissions regulations, the environmental impact of scrubber discharge, challenges in implementing port-based regulations, and potential solutions to address this emerging environmental concern.

As part of this research process, we may invite you to view and provide feedback on our website prototype during this interview or in a subsequent focus group session. Your insights will help us refine the usability and effectiveness of our digital intervention.

Confidentiality

Your privacy is protected as a participant in this study. Any reports generated might use paraphrased wording or quotes and can be attributed to your name. If you would not like your responses to be identifiable, you have a right to mention this to the interviewer. In this case, we will make your responses unidentifiable or adhere to a formatting of your choosing and use only paraphrased wording or quotes that cannot be used to identify you, unless indicated otherwise.

Withdrawal

Participation in this study is completely voluntary; it is entirely up to you to choose whether to participate or not to participate. You can withdraw at any time or refuse to answer any question without consequences of any kind. If you experience discomfort, you may discontinue the interview at any time.

Contact

The study is conducted by Al-fatihi Abdulmalik, Caleb Agoha, Andrey Bartashevich, Gonzalo Martinez Chavez, Kelt Paehlig, and Quanpu Xiao – all students at the University of Amsterdam. In case of questions, you may contact the group's primary contact person, Kelt Paehlig, via email at [redacted]. This project is supervised by Daniel Mayerhofffer, whom you may contact for additional questions or concerns about this research via [redacted].

Please indicate in what way you wish to be mentioned in any reports written following this interview:

- ☐ Full name and job title
- ☐ Initials and job title
- ☐ Job title
- ☐ Full anonymity (please note that your place of employment may still be mentioned)

Other: ____

Signature: ____________________________ Date: [DATE OF INTERVIEW]

E Appendix: Interview Guides

E.1 Henri van der Weide – Advisor Clean Shipping at Port of Amsterdam

Briefly explain the following to the interviewee: **What our project is about and the goal of the interview:** We are a team of students from the University of Amsterdam working on a project called 'North Sea Watch' in collaboration with Stichting De Noordzee, a Dutch non-profit environmental organisation. Our project focuses on the environmental impact of exhaust gas cleaning systems (EGCS), commonly known as scrubbers, in the North Sea. **What We're Developing:** We are creating: • An interactive web platform that visualises scrubber water discharge in the North Sea • Tools to help policymakers understand the environmental impacts of different regulatory approaches • Educational content to raise public awareness about this issue **Purpose of This Interview:** • This interview with you, as a policy advisor at the Port of Amsterdam, is crucial for our project because: – **We want to understand the decision-making process that led to Amsterdam's scrubber discharge ban** – **We're interested in how you balance economic considerations with environmental protection** – **We hope to learn about practical challenges in monitoring and enforcing such regulations** – **Your insights will help us develop our digital platform to be most useful for policymakers** **Briefly go through the key points of the Consent Form** **Ask permission for recording the interview**

Subtheme 1: Port of Amsterdam's Scrubber Discharge Ban **Goal:** Understand the decision-making process, implementation, and challenges of the recent ban	**Introduction:** We'd like to start by understanding the Port of Amsterdam's recent ban on scrubber discharge from January 2025. **Initial question:** Could you walk us through the process that led to the Port of Amsterdam's decision to ban scrubber water discharge from moored vessels? **Potential follow-up questions and probes:** • What were the key factors that influenced this decision? • What stakeholders were involved in this decision-making process? • Why focus on moored vessels specifically rather than all vessels in port waters? • What has been the response from shipping companies? • How are you monitoring and enforcing this new regulation?

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Subtheme 2: Balancing Economic and Environmental Concerns **Goal:** Explore the ethical considerations and policy trade-offs in scrubber regulation	**Introduction:** We're interested in understanding how ports navigate the trade-offs between economic interests and environmental protection. **Initial question:** How does the Port of Amsterdam balance maintaining economic competitiveness with environmental protection concerns related to scrubber discharge? **Potential follow-up questions and probes:** • Has there been concern about ships diverting to other ports without discharge bans? • What economic analyses were conducted before implementing the ban? • Who do you believe should bear the financial responsibility for mitigating environmental damage from scrubber discharge? • How do you weigh short-term economic benefits against long-term environmental consequences?
Subtheme 3: Coordination and Future Policy Development **Goal:** Understand inter-port coordination, challenges in implementation, and future policy directions	**Introduction:** We'd like to understand how port authorities coordinate with each other and what you see as the future of scrubber discharge regulation. **Initial question:** How does the Port of Amsterdam coordinate with other North Sea ports regarding scrubber discharge regulations? **Potential follow-up questions and probes:** • What are the most significant challenges you face in effectively monitoring scrubber discharge? • What jurisdictional issues arise when attempting to enforce regulations across different territorial waters? • Do you think there should be a unified approach across all North Sea ports? • What role do you see for international bodies like the IMO in this issue? • What resources would significantly improve your ability to monitor and enforce scrubber discharge regulations?
Subtheme 4: Public Awareness and Digital Solutions **Goal:** Gather insights for our digital platform development and feedback on our prototype	**Introduction:** As we develop our web platform, we're interested in your perspective on how digital tools might support policy implementation and public awareness. **Initial question:** Based on your experience, what is the current level of public knowledge about scrubber systems and their environmental effects? Do you find that the general public, or even maritime stakeholders outside the industry, understand this issue? **Potential follow-up questions and probes:** • What kind of data visualisation would be most helpful for policymakers like yourself? • What information gaps exist that our platform could help address? • Would a simulation showing potential impacts of different policy scenarios be useful for decision-makers? • (If time permits) We'd like to show you a prototype of our web platform. Could you provide feedback on what you find most useful and what could be improved?
Wrapping up the interview. Thank the interviewee for their time.	

E.2 Dr Lucy Gilliam, Co-Executive Director, One Planet Port and Tanner Tuttle, MSc, One Planet Port

<table>
<tr><td colspan="2">Briefly explain the following to the interviewee:
What our project is about and the goal of the interview:
We are a team of students from the University of Amsterdam working on a project called 'North Sea Watch' in collaboration with Stichting De Noordzee, a Dutch non-profit environmental organisation. Our project focuses on the environmental impact of exhaust gas cleaning systems (EGCS), commonly known as scrubbers, in the North Sea.
What We're Developing:
We are creating:
• An interactive web platform that visualises scrubber water discharge in the North Sea
• Tools to help policymakers understand the environmental impacts of different regulatory approaches
• Educational content to raise public awareness about this issue
Purpose of This Interview:
• To get your feedback on our digital prototype.
• To hear your expert opinion on digital behavioural change and engagement strategies.
• To explore additional features that could make our intervention more effective in reaching both policymakers and the general public.
• Your insights will directly contribute to creating a more impactful digital intervention.
Briefly go through the key points of the Consent Form
Ask permission for recording the interview</td></tr>
<tr><td>Subtheme 1: Prototype introduction and feedback
Goal: First impressions and detailed feedback on the prototype.</td><td>Introduction: We'd like to start by showing you our current digital prototype and gathering your first impressions.
Initial question: Could you please take a look at our prototype and share your initial thoughts — both positive and negative?
Potential follow-up questions and probes:
• Is the environmental issue clearly described on the website?
• Does the structure (Home / Map / Simulation) make sense to you?
• Currently, the map displays all vessels. Do you think it would make more sense to show only scrubber-related vessels?
• Regarding visualisation: Should the scrubber discharge be shown only as a heat circle around the ship, or should we also display a trail/line behind the vessel?
• For the simulation feature, do you think it should be more interactive (user-driven) or based on predetermined scenarios?</td></tr>
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Subtheme 2: Main stakeholder outreach **Goal:** Learn how to better target policymakers.	**Introduction:** We'd now like to discuss how we could improve our platform to be more impactful for policymakers, who are one of our key target audiences. **Initial question:** During your time at One Planet Port, do you feel that you have learned important strategies for engaging policymakers in the maritime sector? **Potential follow-up questions and probes:** • Do you know if such strategies can also be applied through an online platform such as our project? • In your experience, what factors contribute to the effectiveness of a web application dealing with environmental issues? • Do you feel that online platforms have the potential to bring about systemic change? How should such platforms be constructed to be effective? • How could we track or measure the effectiveness of our platform with this audience? • Having seen our prototype, do you have any thoughts as to how a meaningful long-term evaluation strategy for our application could look like?
Subtheme 3: Public awareness **Goal:** Explore how to effectively engage the general public.	**Introduction:** We're also very interested in reaching a broader audience and raising general public awareness about scrubber discharge. **Initial question:** As someone with experience in online engagement, do you feel that increasing public awareness on the scrubber issue has the potential to bring about meaningful change? **Potential follow-up questions and probes:** • What steps should we consider when designing for public engagement? • Do you have suggestions as to what sections of our website could be refined to better engage the general public? • What are some obstacles you've encountered in previous public engagement projects that we should try to avoid? • Could you share examples of successful web platforms or digital campaigns that managed to effectively engage the public?
Subtheme 4: Theoretical concepts **Goal:** Gather ideas about relevant theoretical frameworks for our research.	**Introduction:** Beyond the platform itself, we are also researching the social science concepts behind digital behavioural change. Currently, the website aims to leverage motivational and pre-motivational factors for behaviour change, such as knowledge and risk assessment. We'd love to hear your thoughts on this. **Initial question:** Do you have any experience applying scientific concepts and frameworks regarding behaviour change? **Potential follow-up questions and probes:** • Are there specific social theories or behavioural models that you recommend we explore? • Which theoretical approaches do you think are most effective when trying to invoke environmental awareness and action online?
Wrapping up the interview. Thank the interviewee for taking time to sit down with you.	

E.3 Two individuals positioned as Head of Section, Department for Marine Nature and Environment, Danish Ministry of Environment and Gender Equality

<table>
<tr><td colspan="2">
Briefly explain the following to the interviewee:
What our project is about and the goal of the interview:
We are a team of students from the University of Amsterdam working on a project called ‘North Sea Watch’ in collaboration with Stichting De Noordzee, a Dutch non-profit environmental organisation. Our project focuses on the environmental impact of exhaust gas cleaning systems (EGCS), commonly known as scrubbers, in the North Sea.
What We’re Developing:
We are creating:
• An interactive web platform that visualises scrubber water discharge in the North Sea
• Tools to help policymakers understand the environmental impacts of different regulatory approaches
• Educational content to raise public awareness about this issue
Purpose of This Interview:
• This interview with you, as representatives from the Danish Ministry of Environment and Gender Equality, is crucial for our project because:
– We want to understand Denmark’s policy development process regarding maritime environmental regulations
– We’re interested in what factors influence successful environmental policy implementation
– We hope to learn about cross-border coordination in the North Sea region
– Your insights will help us develop our digital platform to support policy development processes better
Briefly go through the key points of the Consent Form
Ask permission for recording the interview
</td></tr>
<tr><td>
Subtheme 1: Danish Maritime Environmental Policy Development
Goal: Understand the policy development process that led to Denmark’s approach to scrubber discharge regulation
</td><td>
Introduction: We’d like to start by understanding Denmark’s phased approach to scrubber discharge regulation that will ban open-loop systems from July 2025 and closed-loop systems from July 2029.
Initial question: Could you explain the reasoning behind Denmark’s decision to implement a phased approach with different timelines for open-loop versus closed-loop scrubber systems?
Potential follow-up questions and probes:
• What scientific evidence informed this differentiated approach?
• Why was a 4-year gap chosen between the two implementation dates?
• Were there differing views among stakeholders about treating the two systems differently?
• What considerations went into determining the 12 nautical mile boundary for regulation?
• How does this phased approach compare to other regulatory strategies you considered?
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Subtheme 2: Policy Development Process **Goal:** Understand the policy development journey that led to Denmark's scrubber discharge regulations	**Introduction:** We're interested in learning about the process that led to Denmark's current regulatory position on scrubber discharge. **Initial question:** Could you walk us through the key stages in developing Denmark's scrubber discharge regulation, from initial concerns to final policy formulation? **Potential follow-up questions and probes:** • Which stakeholders were most actively involved in the policy development process? • What role did environmental organisations play in shaping the policy? • How did shipping industry representatives respond to the proposed regulations? • Were there significant revisions to the policy during its development? • What economic impact assessments were conducted, and how did they influence the final policy?
Subtheme 3: Implementation and Enforcement Strategies **Goal:** Understand how Denmark plans to implement and enforce its scrubber regulations	**Introduction:** We'd like to understand how Denmark plans to implement and enforce these new regulations effectively. **Initial question:** What strategies and mechanisms will Denmark employ to monitor compliance and enforce the scrubber discharge bans once they take effect? **Potential follow-up questions and probes:** • What technologies or monitoring systems will be used to detect violations? • How will enforcement differ between coastal areas and busy shipping routes? • What penalties or consequences will non-compliant vessels face? • How will you address challenges with vessels that transit through Danish waters? • What resources have been allocated for implementation and enforcement?

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Subtheme 4: Cross-Border Coordination **Goal:** Understand international cooperation dynamics in North Sea environmental protection	**Introduction:** The North Sea is shared by multiple countries with varying approaches to scrubber regulation. We'd like to understand how Denmark coordinates with its neighbors. **Initial question:** Did Denmark work with or inform neighboring countries? If yes, how has Denmark worked with other North Sea countries regarding maritime scrubber regulations, and what challenges have you encountered in harmonising approaches? **Potential follow-up questions and probes:** • What forums or mechanisms have been most effective for international coordination? • How do you address regulatory inconsistencies between neighboring countries? • What role have EU frameworks played in shaping Denmark's approach? • Do you foresee greater regulatory alignment across North Sea countries in the future?
Subtheme 5: Digital Tools for Policy Support **Goal:** Gather insights for our digital platform development to better support policy processes	**Introduction:** As we develop our web platform, we're interested in your perspective on how digital tools might support environmental policy development and implementation. **Initial question:** What kind of digital tools or data visualisations would be most valuable to support environmental policy development and implementation in your work? From our website, what do we need to improve or change to be in a better position to help out? **Potential follow-up questions and probes:** • What information gaps currently exist that better data visualisation could address? • From your experience with environmental advocacy and policy communication, what elements make a website most effective at conveying complex environmental issues like scrubber pollution to policymakers and driving actual policy change? • How important is the presentation of scientific evidence versus economic impact data in persuading policymakers? • What types of simulations or scenario modeling would be most persuasive in policy discussions? • What approaches have you found most effective for communicating technical environmental issues to non-specialist policymakers? • (If time permits) We'd like to show you a prototype of our web platform. Could you provide feedback on what you find most useful and what could be improved from a policy development perspective?

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Subtheme 6: Measuring Policy Success **Goal:** Understand how Denmark will evaluate the effectiveness of its scrubber regulations	**Introduction:** We're interested in understanding how Denmark plans to measure the success of its scrubber regulations. Potentially helping us know how to measure the effectiveness of our digital intervention. **Initial question:** What indicators or methods will Denmark use to evaluate whether the scrubber discharge regulations are achieving their intended environmental benefits? **Potential follow-up questions and probes:** • What baseline measurements are being established prior to implementation? • How will you distinguish the effects of these regulations from other environmental policies? • What timeline do you expect for measurable improvements in water quality? • How will you communicate the outcomes to the public and stakeholders? • How might evaluation results inform future policy adjustments?
Wrapping up the interview. Thank the interviewee for taking time to sit down with you.	

E.4 Project Manager & Team Lead, UvA Green Office

Briefly explain the following to the interviewee: **What our project is about and the goal of the interview:** We are a team of students from the University of Amsterdam working on a project called 'North Sea Watch' in collaboration with Stichting De Noordzee, a Dutch non-profit environmental organisation. Our project focuses on the environmental impact of exhaust gas cleaning systems (EGCS), commonly known as scrubbers, in the North Sea. **What We're Developing:** We are creating: • An interactive web platform that visualises scrubber water discharge in the North Sea • Tools to help policymakers understand the environmental impacts of different regulatory approaches • Educational content to raise public awareness about this issue **Purpose of This Interview:** • To get your feedback on our digital prototype. • To hear the opinions of non-experts. • To explore what can be the weaknesses and potential obstacles in reaching the general public • Your insights will directly contribute to creating a more impactful digital intervention. **Briefly go through the key points of the Consent Form** **Ask permission for recording the interview**

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(Continued)

Subtheme 1: Prototype introduction and feedback **Goal:** First impressions and detailed feedback on the prototype.	**Introduction:** We'd like to start by showing you our current digital prototype and gathering your first impressions. **Initial question:** After looking at our prototype what are your first thoughts about it, both positive and negative? **Potential follow-up questions and probes:** • Does the structure (Home / Map / Simulation) make sense to you? • Do you like the design of the pages or is there something that triggers you? • Currently, the map displays all vessels. Do you think that displaying only marine vessels that are polluting will make more sense? • For the simulation feature, do you think it should be more interactive (user-driven) or based on predetermined scenarios?
Subtheme 2: General Public outreach **Goal:** Learn how to better target general public	**Introduction:** We'd now like to discuss how we could improve our platform to be more impactful for the general public. **Initial question:** Do you think the web application we developed has the necessary features to catch your attention and encourage you to explore it further? **Potential follow-up questions and probes:** • Is the issue of scrubber discharge clearly explained to you? • Do you understand what the potential solutions to the issue are? • Do you have suggestions as to what sections of our website could be refined to better engage the general public? • In your opinion, what is the most efficient way to reach the general public through in-person advertising, online advertising, or a combination of both?
Wrapping up the interview. Thank the interviewee for taking time to sit down with you.	

F Appendix: Interview Analyses

F.1 Henri van der Weide – Advisor Clean Shipping at Port of Amsterdam

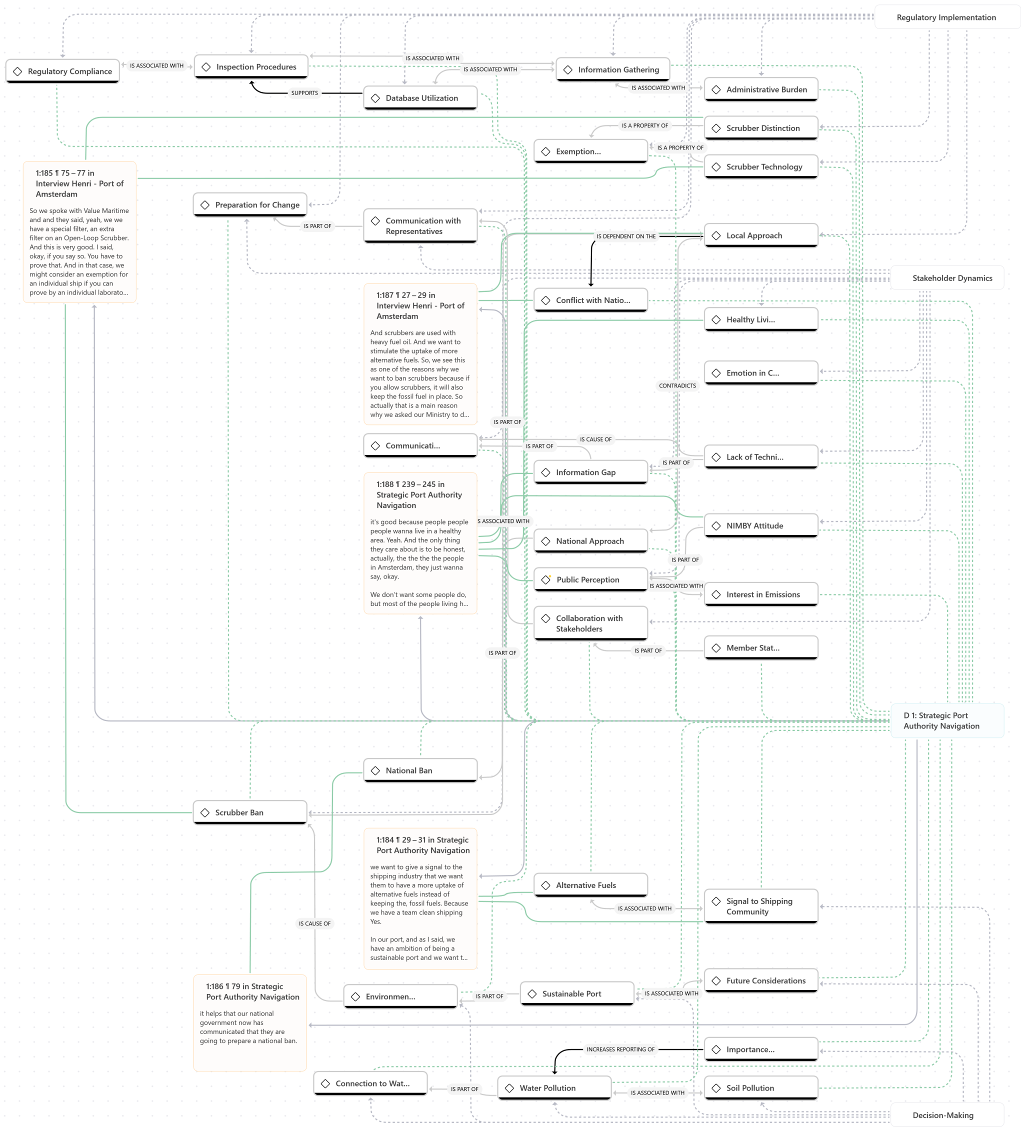

Figure 38: Interview Code Network

F.1.1 Main Themes from Code Network

Regulatory Implementation

- Local approach vs. national ban represents different regulatory strategies
- Port-level regulations can serve as forerunners to broader national policies
- Exemption possibilities exist for ships with proven pollution reduction technologies
- Implementation requires clear distinction between scrubber types (open vs. closed loop)

Decision-Making Factors

- Environmental sustainability serves as primary motivation for policy
- Soil pollution concerns provided legal justification for local regulations
- Port authorities acted despite inconclusive scientific evidence
- Strategic signal to shipping industry about future regulatory direction

Stakeholder Dynamics

- Communication with representatives from shipping industry essential before implementation
- Conflict exists between national legislation and local port by-laws
- Industry stakeholders prefer regulatory clarity over fragmented approaches
- Shipping community's economic concerns must be addressed through clear communication

Enforcement Mechanisms

- Database utilisation supports monitoring of vessel compliance
- Inspection procedures target ships with known scrubber installations
- Administrative burden is considered manageable for port authorities
- Distinguishing between different scrubber technologies presents practical challenges

Public Perception

- NIMBY attitude ("Not In My Backyard") influences local community perspectives
- Public generally lacks technical understanding of maritime pollution issues
- Information gap exists between industry expertise and general awareness
- Healthy living environment prioritised over shipping industry concerns

Strategic Port Authority Navigation

- Sustainable port vision drives policy decisions despite uncertain evidence
- Signal to shipping community about cleaner fuel adoption
- Port of Amsterdam positioned as environmental leader
- Future considerations include broader national regulations

F.1.2 Key Insights

1. Precautionary Principle: Despite inconclusive scientific evidence, the port chose to implement regulations based on a "care principle": "The policy report said something about 'well, it doesn't help but it's not so bad'... but in Antwerp they had another study and in Sweden they had another study and that was completely 180 degrees the other way around... so we said okay then we go for [taking] care of our future."

2. Legal Adaptation: The port found an innovative legal approach: "We had to find another argument to come up with a scrubber ban and we found it in soil pollution... It's more or less a kind of economical reason how we sold it." This demonstrates strategic navigation of regulatory frameworks.

3. Signal to Industry: The ban serves as a broader message: "We want to give a signal to the shipping industry that we want them to have a more uptake of alternative fuels instead of keeping the fossil fuels... we have a team clean shipping."

4. Limited Economic Impact: The port determined economic consequences were manageable: "For instance 9 million in, I don't remember what the name is, but it's like a one-time cost... then it's 19 million after that. Each year." They concluded this was "peanuts" compared to overall shipping costs.

5. Enforcement Strategy: The port developed practical monitoring approaches: "We have patrol vessels... We have inspectors, dangerous cargos driving around. And they know which vessels are coming into our port. We have a kind of small database which said, 'okay, these vessels have a scrubber.'"

6. Public Awareness Gap: Local communities lack understanding of scrubber issues: "They really don't know what it is... People in Amsterdam... just look at a ship and say, 'hey, this ship is sailing.' And they really have no clue or idea what fuel they are burning or what emissions they have."

F.1.3 Using This Network for Analysis

When analysing port-level scrubber regulations using this network map:

1. Identify legal pathways - Port of Amsterdam found creative legal justification through soil pollution concerns

2. Consider enforcement practicalities - Successful implementation requires database systems and inspection protocols

3. Evaluate economic impacts - Assess relative costs compared to overall shipping operations

4. Map stakeholder communications - Early engagement with industry representatives minimises resistance

5. Recognise public perception challenges - Technical complexity of maritime pollution creates awareness gaps

This network reveals that port authorities can implement meaningful environmental regulations even without national mandates or conclusive scientific consensus. The Port of Amsterdam case demonstrates a strategic approach that balances environmental leadership with practical implementation concerns.

Their approach highlights the value of the precautionary principle in environmental governance and shows how local initiatives can eventually influence broader national policies. The port's decision to act as an environmental forerunner, despite potential conflicts with national legislation and shipping industry preferences, provides a model for other ports considering similar regulations.

F.2 Dr Lucy Gilliam, Co-Executive Director, One Planet Port and Tanner Tuttle, MSc, One Planet Port

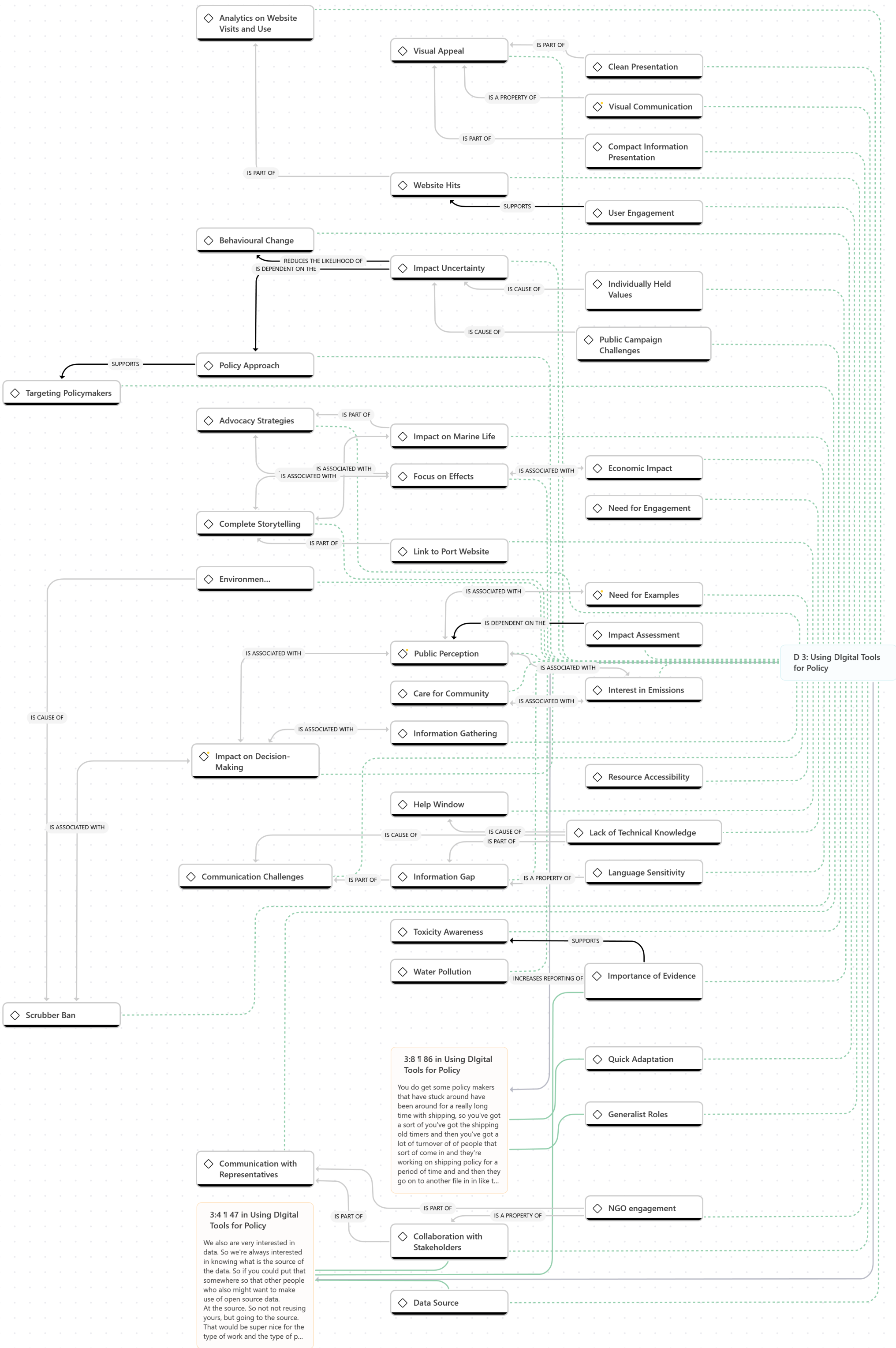

Figure 39: Interview Code Network

F.2.1 Main Themes from Code Network

Visual Communication Strategy

- Clean, engaging presentation is essential for conveying complex maritime pollution data
- Visual elements (maps, infographics) are more effective than text-heavy explanations
- The platform's design successfully balances technical detail with accessibility
- Consider adapting terminology to avoid industry language that might mislead the public

Data Transparency & Credibility

- Prominently display data sources to build trust and enable further research
- Include attribution for AIS tracking and pollution calculation methodologies
- The platform's credibility depends on users understanding where information comes from
- Technical users value the ability to access source data beyond the visualisation layer

Targeted Advocacy Approach

- Focus on influencing policymakers rather than general public campaigns
- The platform serves as a storytelling tool for in-person advocacy meetings
- Policy change is more likely through direct engagement with decision-makers
- Visualisations provide compelling evidence that verbal arguments alone cannot

Environmental Impact Visualisation

- Connect scrubber discharge data to specific marine habitats and sensitive areas
- Show proximity of pollution to nature reserves, fisheries, and other valued ecosystems
- Quantify discharge in ways that make the scale of the problem immediately apparent
- Use heat maps to highlight pollution concentration in critical areas

Stakeholder Network Development

- Connect with established environmental groups focused on North Sea issues
- Share the platform with organisations like Ocean Rebellion and Extinction Rebellion
- Consider port authorities and maritime agencies as both targets and potential collaborators
- Leverage existing advocacy networks rather than building audience from scratch

Action-Oriented Engagement

- Provide clear pathways for different user types to take meaningful action
- For policymakers: offer simulation tools to model regulatory impacts
- For advocates: supply shareable visualisations and data points for campaigns
- For general users: include links to relevant petitions or advocacy groups

F.2.2 Using This Network for Analysis

When analysing the interview using this network map:

1. Identify priority audiences - The map shows stronger connections to policymaker engagement than general public awareness
2. Evaluate communication approaches - Note the emphasis on visual communication over text-heavy content
3. Consider implementation pathways - Look at how different stakeholders might use the platform for different purposes
4. Assess impact measures - The network connects website hits to behavioural change through reduced uncertainty
5. Plan stakeholder engagement - Use the collaboration nodes to identify key relationships to develop

This network reveals that One Planet Port views the platform primarily as a specialised tool for policy advocacy rather than a mass public awareness campaign. Their feedback emphasises using data visualisation to tell compelling stories about marine pollution while maintaining technical credibility through transparent sourcing and accurate representation of the issues.

F.3 Two individuals positioned as Head of Section, Department for Marine Nature and Environment, Danish Ministry of Environment and Gender Equality

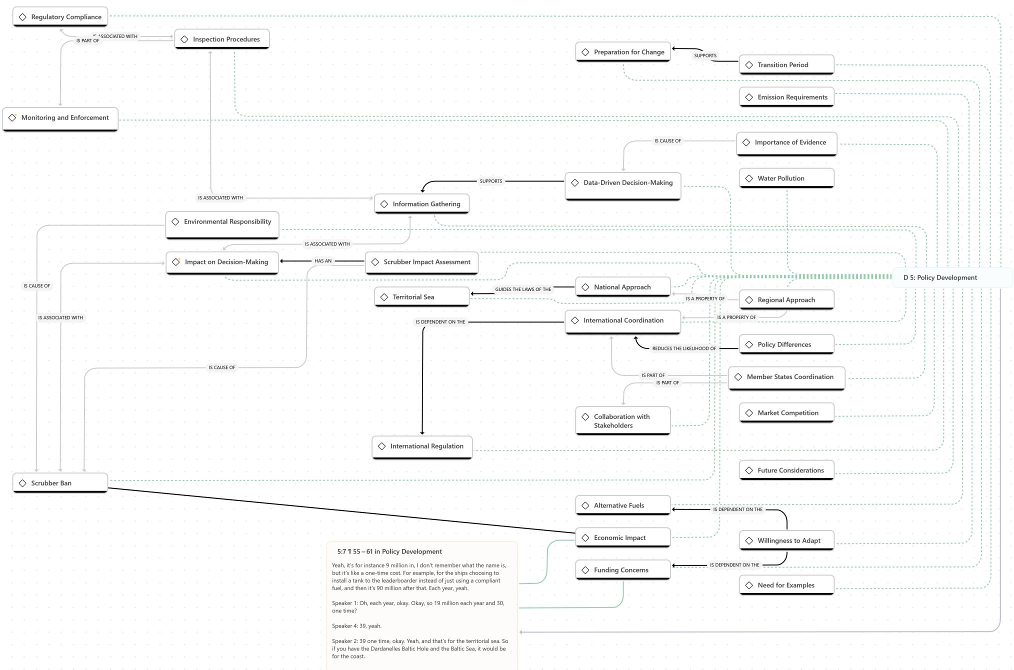

Figure 40: Interview Code Network

F.3.1 Main Themes from Code Network

Policy Development Process

- Evidence-based decision making guided the implementation of the Danish scrubber ban
- Scientific studies (particularly from OSPAR) provided critical foundation for policy decisions
- Economic impact assessment balanced environmental concerns with industry considerations
- Policy development involved multiple stakeholders and political negotiations

Regulatory Implementation

- Monitoring and enforcement mechanisms are essential components of the ban
- Inspection procedures must be practical and consistent across territorial waters
- Regulatory compliance requires clear guidelines for ship operators
- Transition periods allow industry adaptation while ensuring environmental protection

Territorial Jurisdiction

- 12 nautical mile territorial sea limit defines the scope of national regulation
- International waters require different regulatory approaches and coordination
- Jurisdictional boundaries create enforcement challenges for maritime regulations
- Regional coordination with neighbouring countries strengthens effectiveness
-

International Coordination

- Alignment with neighbouring countries (Sweden, Finland) enhances regulatory effectiveness
- Member states coordination through OSPAR and other conventions supports regional approaches
- International regulation at IMO level faces greater challenges but remains a long-term goal
- Policy differences between countries can create regulatory gaps

Economic Considerations

- Economic impact assessment showed manageable costs to shipping industry
- One-time costs (39 million) and annual costs (19 million) were quantified
- Alternative fuels and technology options provide compliance pathways
- Funding concerns were addressed through transition periods for different scrubber types

Environmental Responsibility

- Water pollution prevention was a primary driver for the policy
- Data showed significant contribution of scrubbers to marine pollution (e.g., 20% of nickel)
- Environmental responsibility outweighed industry objections in political decisions
- All political parties ultimately supported the ban despite initial industry resistance

F.3.2 Key Insights

1. Scientific Evidence as Foundation: The ministry representative noted that scientific studies showing pollution levels were crucial: "Our agency looked at that and they published like a table on how much of those substances are in the environment... for example, nickel is 20% of the substance that's coming from the scrubbers."

2. Balanced Policy Approach: The economic impact was carefully assessed: "It's 39 million for the ship owners to change their ships... and then it's 19 million from the years after that." This was deemed "not a huge amount compared to the environmental effect."

3. Tiered Implementation Strategy: Different timelines were established for different scrubber types: "We decided to have a transition period [for closed-loop systems] because it's not as much as the open loop systems." This phased approach (open-loop ban in 2025, closed-loop in 2029) balances immediate action with practical transition.

4. Cross-Border Coordination: The timing of implementation was coordinated with neighbouring countries: "It's not a coincidence that Sweden and Finland and Denmark, that our regulation is going to enter into force at almost the same time. It's also a way to make it easier for the ships to navigate in the regional regulation."

5. Jurisdictional Limits: The 12 nautical mile limit was based on international law: "We also investigated the option of doing it in the exclusive economic zone. But due to the nautical sea, you can't do that without international regulation."

6. Broad Political Support: The ministry emphasised the cross-party consensus: "All of the banks ended up supporting the competition in the parliament, even though the industry is not always that happy about it."

F.3.3 Using This Network for Analysis

When analysing maritime environmental policy using this network map:

1. Evaluate evidence base - Danish policy was built on specific scientific findings showing significant pollution contribution

2. Consider jurisdictional frameworks - Territorial sea boundaries define the scope of national regulatory authority

3. Assess economic impacts - Quantify both one-time and ongoing costs to industry to demonstrate feasibility

4. Identify coordination opportunities - Regional alignment with neighbouring countries enhances effectiveness

5. Recognise implementation challenges - Monitoring and enforcement require practical inspection procedures

This network reveals that successful scrubber discharge regulation requires a multi-faceted approach combining scientific evidence, economic analysis, political consensus-building, and cross-border coordination. The Danish case demonstrates that environmental protection can achieve broad political support when properly framed and implemented with reasonable transition periods.

The ministry's experience provides valuable insights for other countries considering similar regulations, highlighting the importance of clear jurisdictional understanding, stakeholder engagement, and evidence-based policy development. Their coordinated approach with Sweden and Finland creates a regional standard that could serve as a model for North Sea-wide regulation.

F.4 Project Manager & Team Lead, UvA Green Office

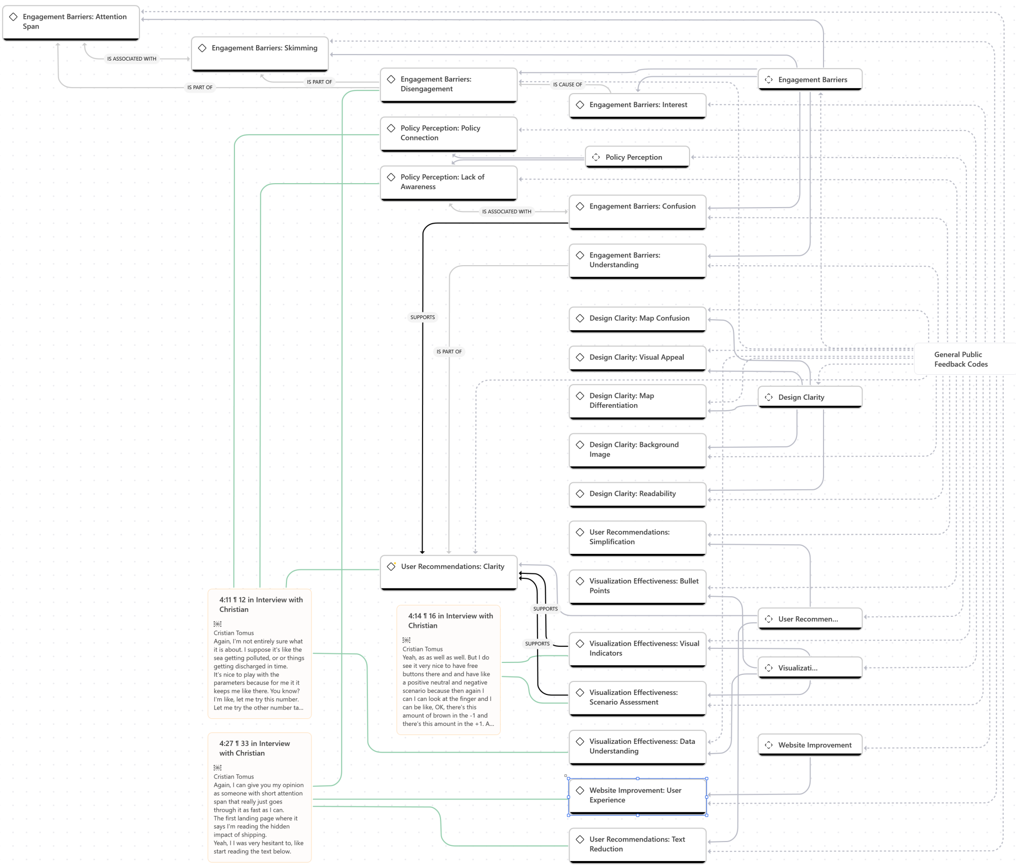

Figure 41: Interview Code Network

F.4.1 Main Themes from Code Network

Engagement Barriers

- Attention span challenges are a significant obstacle for general users
- Text-heavy content triggers immediate disengagement or skimming behaviour
- Users quickly scan rather than read detailed explanations
- Information overload creates barriers to understanding key concepts

Design Clarity Requirements

- Visual elements must be immediately understandable without extensive explanation
- Map interfaces need clear differentiation between ship types and pollution indicators
- Background imagery supports engagement but shouldn't distract from core content
- Readability is prioritised over comprehensive information

User Recommendations for Simplification

- Bullet points and concise statements are more effective than paragraphs
- Information should be layered, with essential facts presented first
- Interactive elements capture attention longer than static text
- Visual indicators and icons communicate more effectively than descriptions

Visualisation Effectiveness

- Visual indicators like heat maps require clear explanation of what they represent
- Scenario-based presentations help users understand complex environmental impacts
- Users respond positively to predetermined scenarios (positive/neutral/negative)
- Data presentation must balance simplicity with meaningful information

Website Improvement Priorities

- Landing page should minimise text and immediately present visual engagement
- Interactive elements should be self-explanatory or include minimal guidance
- Users appreciate the ability to manipulate simulation parameters but need context
- Clear navigation between different sections supports extended engagement

F.4.2 Key Insights

1. Initial Impressions Matter: Interviewee immediately noted text overload on the landing page, saying "I saw a lot of text on the first page... I'm not gonna read through all of this." This indicates the critical importance of first impressions in capturing user attention.
2. Bullet Points Over Paragraphs: Interviewee specifically mentioned stopping at bullet points: "I stopped when I saw a page with bullet points and some one-sentence facts... that part actually stopped and read." This confirms that condensed, scannable information is more effective.
3. Interactive Elements Sustain Engagement: The simulation was described as "fun to play around with" even without full understanding of the parameters, showing that interactive elements can maintain interest beyond static content.

4. Need for Clear Explanations: Interviewee expressed confusion about the heat map: "I'm not entirely sure what's displayed there... I suppose it's like how much they discharge in what regions of the sea." This highlights the need for clear legends and explanations for data visualisations.
5. Predefined Scenarios Aid Understanding: When asked about simulation features, interviewee suggested: "I do see it very nice to have free buttons there and have like a positive neutral and negative scenario... this is how I know it's bad or good."

F.4.3 Using This Network for Analysis

When analysing public engagement using this network map:

1. Evaluate content hierarchy - Prioritise visual elements and bullet points over detailed text explanations
2. Consider attention patterns - Design for users who will only engage for 2-5 minutes initially
3. Balance flexibility with guidance - Provide both open exploration and predetermined scenarios
4. Focus on immediate clarity - Ensure visualisations are immediately comprehensible without extensive reading
5. Optimise landing page - Reduce text content and highlight interactive features immediately

This network reveals that general public users approach environmental websites with limited attention resources, making quick judgments about engagement value. The platform should front-load visual elements, interactive features, and concise information points to maximise the likelihood of meaningful engagement with the scrubber discharge issue.

G Appendix: Project Timeline

Week	**Programme Deadlines**	**Project Milestones**
Week 9		Project Kickoff (February 25th)
Week 10	Progress Check: Project Proposal (March 5th)	Finish Project Proposal (March 3rd) Finish Honours Proposal (March 4th) Preliminary Web Architecture Setup Initialisation of ABM Strategy
Week 11		Pursue WFR Data Implement Primary Website Features Implement Preliminary ABM
Week 12	Final Submission: Project Proposal (March 19th)	Pursue WFR Data Web Implementation ABM Development Online Partner Meeting (March 20th) Contact Interview Subjects
Week 13	Progress Check: Final Product (March 28th)	In Person Partner Meeting (March 27th) Start Final Report
Week 14		Integrate ABM on Website Compile Web Content Perform Policy Analysis
Week 15		Prototype Presentation (April 9th) Perform Policy Analysis Compile CLD Plan Interviews

Week 16		ABM experimentation + analysis
Week 17	Progress Check: Final Report (April 25th)	Perform Interviews Interview Analysis Finish Final Report Draft Plan Further Interviews (if necessary) Perform Web Improvements
Week 18		Implement Feedback Perform Interviews Interview Analysis Plan Focus Group Re-evaluate Analyses
Week 19		Implement Feedback Perform Web Improvements
Week 20		Analyse Interviews Implement Results
Week 21		Finish Final Product Finish Final Report
Week 22		Implement Report Improvements Implement Web Improvements Finalise Report and Product
Week 23	Final Submission: Final Product (June 5th) Final Submission: Final Report (June 6th)	Transfer Report To Overleaf Create Website Video Recording Final Proofreadings Submit Project (June 5th)
Week 24		Prepare Presentation Material
Week 25		Presentation Event (June 18th)

Table 4: Project Timeline Overview