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MARITIME PORTS AS ENGINES OF URBAN CHANGE AND ENVIRONMENTAL GOVERNANCE

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Abstract. Maritime ports have historically played a central role in the development of urban areas, serving as economic powerhouses and key nodes in global trade networks. However, beyond their economic function, ports also pose significant environmental challenges and are deeply involved in urban political dynamics. The expansion and modernisation of ports often lead to conflicts between economic growth and environmental sustainability, prompting regulatory interventions, urban planning adjustments, and public discourse on environmental justice. The article employs a qualitative literature review methodology to analyse the environmental changes in maritime ports. The study examines various academic sources, reports, and real-world examples to provide insights into port environmental governance. The data analysis employs a qualitative approach, exploring the interactions among various stakeholders in maritime ports. It focuses on how these interactions shape environmental practices and the socio-technical dynamics within port ecosystems. The article reveals how power dynamics, dependencies, and collaborations influence decision-making processes and environmental outcomes. For instance, the integration of Port Community Systems (PCS) facilitates communication among stakeholders, enhancing operational efficiency and sustainability. The literature review highlights best practices and identifies gaps in current research, particularly regarding the marginalisation of certain stakeholder groups. Specific case studies from various ports are analysed to illustrate the practical implications of the findings. The study tracks progress in sustainability efforts and identifies the key drivers influencing the environmental performance of ports. In conclusion, the article asserts the significance of maritime ports within urban settings, their environmental implications, the political processes that shape their governance and provides innovative insights into the networks and processes that shape successful environmental practices, contributing to the development of more sustainable port systems. It provides a distinctive approach to understanding interactions and negotiations between diverse actors, that influence environmental outcomes.

Keywords: Maritime Ports; Environment; Sustainability; Urban Politics.

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1. INTRODUCTION

Maritime ports have historically been central to urban development and global trade. Maritime ports have long been pivotal to the economic vitality of urban centres, serving as hubs for trade, transportation, and industry. Shipping is a key economic sector and over 80% of the volume of global trade in goods is carried by sea, and the percentage is even higher for most developing countries (UNCTAD, 2023). However, their significance extends beyond mere economic functions, encompassing environmental challenges and urban political dynamics. Maritime ports are not only economic hubs but also critical components of urban and environmental governance. The governance of these complex infrastructures requires multi-stakeholder engagement and adaptive policy measures. By examining best practices and identifying governance challenges, this research contributes to the broader discourse on sustainable urban development and environmental resilience in port cities. Ports operate at the intersection of economic growth, environmental sustainability, and governance frameworks, making them crucial sites for understanding urban political ecology (Hall and Jacobs, 2012). This article expands upon the research proposal by delving into the environmental impacts of maritime ports, the governance mechanisms in place, the role of stakeholders in shaping environmental practices, and case studies illustrating real-world applications. Adopting a nexus framework helps articulate the intertwined nature of port-related challenges. It enables a systemic understanding of how maritime logistics, urban planning, environmental policy, and social justice must co-evolve to create resilient and sustainable port cities. The nexus concept is often used to highlight how different systems (e.g., water, energy, food) are interdependent. In the case of maritime ports, we can construct a Port–City–Environment Nexus or Trade–Sustainability–Governance Nexus. This would emphasise:

1. Ports are at the nexus of trade and environmental change facilitating global commerce while contributing to pollution and land use challenges.
2. Urban governance and port planning are interlinked decisions made by city governments, port authorities, and global shipping networks have overlapping impacts.
3. Stakeholder power dynamics form a governance nexus in which governments, corporations, local communities, and ecological systems interact in complex ways.
4. The importance of stakeholder interaction lies in its ability to create value and guide organisational sustainability.

Figure 1. Maritime transport: a major player in the globalisation of the economy. (Source: Spring GDS)

This study frames maritime ports as central nodes within an urban environmental governance nexus where trade, infrastructure, ecological systems, and political decision-making converge. By adopting a nexus perspective, the research highlights the interdependence between economic growth, environmental regulation, and urban development. This article offers a nuanced analysis of port governance, environmental impacts, and sustainability practices, reinforcing the importance of policy and stakeholder collaboration in maritime urban settings. The study aims to:

- Analyse the environmental impact of maritime ports and their governance mechanisms.
- Explore the role of various stakeholders in shaping port environmental practices.
- Examine ports to illustrate real-world environmental governance in ports.
- Identify best practices in port sustainability efforts: Port of Rotterdam.

1.1. Methodology

The research employs a qualitative literature review methodology, focusing on academic sources, reports, and real-world case studies. The key methodological steps include:

- An examination of existing studies on port environmental governance, urban sustainability, and stakeholder interactions.

Figure 2. Voyaging Toward a Greener Maritime Future. (Source: Boston Consulting Group)

- Identification of key actors (e.g., port authorities, environmental agencies, businesses, and communities) and their influence on decision-making.
- Examination of Rotterdam port to assess the practical implications of governance strategies and sustainability initiatives.
- Qualitative exploration of power dynamics, dependencies, and collaborations that shape environmental practices.

2. ENVIRONMENTAL IMPACT OF MARITIME PORTS

Ports contribute to economic prosperity but also pose significant environmental challenges, that affect both local communities and broader ecosystems including air, water pollution, soil contamination, habitat destruction, and greenhouse gas emissions (Notteboom and Rodrigue, 2021). These challenges are best understood through a nexus lens, where port operations act as intersections of energy consumption, waste production, and ecological disruption. The urban port environment nexus illustrates how single actions such as fuel choices or land development echo across ecological, social, and infrastructural domains. The transition to a greener future is gaining momentum as the maritime sector implements automation, digital systems, and healthier fuels.

The heavy reliance on fossil fuels for port operations and maritime transportation worsens the global carbon footprints. Additionally, waste disposal and ballast water discharge threaten marine biodiversity (OECD, 2018). Addressing these issues requires a comprehensive governance approach integrating sustainability principles into port management.

Ports are major sources of air pollution, as they facilitate heavy shipping traffic, industrial activity, and transportation emissions. Studies have shown that emissions from cargo ships, (VOC) volatile organic compounds; which are light components of crude oil, evaporate during loading operations port-based logistics, contribute to elevated levels of sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) in urban port cities (Bailey and Solomon, 2004). Maritime traffic contributes significantly to air pollution in port cities. While daily impacts from road traffic were more pronounced, the contribution of maritime activities to air quality degradation remains significant. A study focusing on Marseille revealed that cruise vessel arrivals substantially increased city-level concentrations of nitrogen dioxide, particulate matter, and sulphur dioxide. Emissions from ships, cargo-handling equipment, and port-related transportation are major contributors to air pollution. Pollutants such as sulphur dioxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) can cause severe health issues, including respiratory diseases. To mitigate these effects, many ports have implemented low-emission zones and alternative energy sources such as liquefied natural gas (LNG) and electrification of port operations (Zabrocki et al., 2021). Ports contribute to water and soil pollution through the discharge of pollutants, the accumulation of hazardous materials, heavy metals, and chemicals

from ship maintenance activities, accidental oil spills, and wastewater disposal. The improper handling of chemicals and industrial waste often leads to the contamination of coastal ecosystems, threatening marine biodiversity (Notteboom and Winkelmans, 2003). This contamination poses risks to marine life and can compromise the health of local communities. Additionally, ballast water from international vessels introduces invasive species, which can disrupt local ecosystems (Ng and Song, 2010). The adoption of ballast water treatment systems and strict regulations has been essential in addressing this issue. The discharge of ballast water containing pollutants, invasive species, and other contaminants into aquatic environments is known as "ballast water pollution," and it can have a number of negative impacts on the environment, human health, and economies. Numerous bacteria, larvae, and microscopic organisms that are collected in one place and released in another are frequently found in ballast water. Certain species have the potential to flourish in their new habitat, displace native species, disrupt regional ecosystems, and turn into annoyances. Ecological imbalances and a decline in biodiversity may result from this (BIO-UV Group, 2025).

In addition to bridging nations and continents, the marine sector has a big environmental duty. There are several broad categories into which maritime garbage can be divided. Food scraps, packaging, and other refuse produced by the workers and passengers are all considered galley and lodging waste. These materials must be disposed of properly to prevent pollution and pest attraction. One major issue facing the maritime industry is hazardous waste. It contains things like batteries, chemicals, and medical waste. These substances can present major risks to human health and the marine environment if improperly handled. The industry embarks on a cleaner, greener future as it embraces sustainable waste management techniques, such as cutting waste generation and utilising cutting-edge waste-to-energy technologies. Garbage tracking systems and sorting robots are examples of technologies that opens up new possibilities for effective garbage management. With the use of sensors and data analytics, waste tracking systems assist ships in monitoring the production and disposal of garbage, encouraging effective and ecologically friendly procedures. Ports are implementing sorting robots to expedite the recycling process. The efficiency of recycling is increased by these robots' ability to distinguish between different types of waste.

The expansion and operation of port facilities often lead to the destruction of natural habitats, including wetlands and mangroves, which serve as crucial buffers against environmental hazards and support biodiversity. As ports expand, they require extensive land use, often encroaching on natural habitats and residential areas. Urban planners must balance economic benefits with environmental and social concerns, ensuring that port expansion projects incorporate green infrastructure and sustainable urban development practices. The continuous operation of ports results in increased noise levels and light pollution, which can disrupt local wildlife and affect the well-being of nearby residents.

3. URBAN & ENVIRONMENTAL POLITICS: STRATEGIES FOR SUSTAINABLE PORT DEVELOPMENT

Environmental governance in shipping and ports highlights the interaction of various regulations and planning regimes and indicates the influence of regulatory bodies in governing the complex global sector of maritime policy (Monios, 2019). Port governance under climate change suggests that mitigation and adaptation actions are partly linked to the commercial decisions of port actors but also driven by external actors, including government and regulators, thereby impacting decision-making (Monios, 2024). Port authorities play a significant role in decision-making processes for reducing and preventing negative environmental and energy effects from ports (Di Vaio et al., 2018; Di Vaio et al., 2019). The study on port environmental networks suggests that port authorities design policy measures and facilitate policy learning to improve environmental performance, indicating their influence on decision-making (Lawer, 2021). The environmental challenges posed by ports have led to increased public concern and political action. The relationship between ports and their surrounding communities is becoming increasingly conflictual, especially during periods of significant infrastructural development. Public environmental concerns can influence port sustainability, through the development of digital infrastructure which develops positive effects (Savoldi, 2024).

In response to environmental and political pressures, ports are adopting various strategies to enhance sustainability: Ports are redefining competitiveness to include ecological considerations, implementing measures that balance economic growth with environmental stewardship. This involves adopting cleaner technologies, enhancing energy efficiency, and reducing emissions. (Carter and Drouaud, 2022). The establishment of green shipping corridors aims to integrate renewable energy technologies, alternative fuels, and electrification in port operations. These

corridors have the potential to enhance urban sustainability, promote green logistics, and contribute to global decarbonization efforts (Akhavan, 2025).

Effective stakeholder management is crucial for the successful implementation of green strategies in ports. Engaging with local communities, environmental groups, and industry stakeholders ensures that diverse perspectives are considered, leading to more comprehensive and accepted sustainability initiatives (Satta et al., 2025). Stakeholder participation in a port expansion project emphasizes that if stakeholder participation is not properly implemented, it can lead to conflicts and become a 'post-political' tool, highlighting the challenges in managing stakeholder influence (Lawer, 2019). Policy-making in West and Central African ports highlights the challenges arising from discrepancies between regional environmental policies and those for the ports at sub-national level, indicating the complexity of managing stakeholder influence (Barnes-Dabban et al., 2018).

Based on the abstracts provided, it is evident that the key stakeholders involved in port environmental governance include terminal operators, local communities, regulatory bodies, and port authorities. These stakeholders exert influence over decision-making processes in port environmental governance, with their roles and influence varying based on the specific context and challenges faced. The challenges in managing stakeholder influence include discrepancies between regional environmental policies and those for the ports at sub-national level, as well as the potential for stakeholder participation leading to conflicts if not implemented effectively.

3.1. Governance Mechanisms and Stakeholder Roles

Maritime ports are integral to the fabric of urban environments, serving as economic engines while also posing significant environmental challenges. The interplay between port operations and urban environmental politics necessitates a balanced approach that addresses economic imperatives alongside ecological and social responsibilities. Through sustainable development strategies and proactive stakeholder engagement, ports can mitigate negative environmental impacts and contribute positively to the urban landscapes they inhabit.

This article emphasises the pivotal role of green strategies in meeting stakeholder expectations and strengthening corporate social responsibility initiatives, thereby influencing decision-making in ports. The primary stakeholders involved in port environmental governance include terminal operators and local communities, who have been identified as having a growing influence in port management decisions (Satta et al., 2025). The governance of maritime ports involves a complex interplay of global, national, and local institutions and regulations. The interplay of local, national, and international actors in maritime port governance presents several key challenges (De Oliveira et al., 2021). Overlapping jurisdictions and the reluctance to invest lead to challenges being under-addressed, such as emissions, noise, congestion, and climate change adaptation (Monios, 2020).

Port authorities regulate port operations and implement sustainability initiatives. Port authorities play a central role on implementing sustainability initiatives and managing port operations. They are responsible for balancing economic growth with environmental protection and social progress (Fobbe and Hilletofth, 2021; Hiranandani, 2014). They often lead the development of sustainability strategies and frameworks, such as the Sustainability Plan 2015+ by North Queensland Bulk Ports Corporation, which targets specific operational issues and environmental settings (Duke, 2017). Government and environmental agencies enforce environmental regulations and set emission standards. Environmental agencies are crucial in setting regulations and standards for port operations to minimize environmental impacts. They work at various levels, from global (e.g. International Maritime Organization) to local, ensuring compliance and promoting sustainable practices (Monios, 2019; Barnes-Dabban and Karlsson-Vinkhuyzen, 2018). These agencies also collaborate with port authorities to implement green initiatives and monitor environmental performance (Acciaro et al., 2014). These groups advocate for stricter environmental regulations and monitor port activities (Ng and Song, 2010). Shipping companies' commitment to green shipping practices affects port sustainability. Businesses, including shipping companies and port users, are key stakeholders in port sustainability. They are often involved in adopting innovations and technologies to improve environmental performance, such as onshore power supply and alternative fuels. Their collaboration is essential for the successful implementation of sustainability strategies, as they provide the necessary resources and support (Acciaro et al., 2014). Local Communities, residents near ports experience environmental and health impacts, making their engagement crucial. Local communities are impacted by port operations and are increasingly involved in decision-making processes. Their concerns often include air and water quality, noise, and overall environmental health (Franchi and Vanelslander, 2021; Gambert, 2010). Community engagement is vital for fostering transparency and gaining support for sustainability initiatives. Ports like the Port of Brussels

have used sustainability reporting to address community concerns and demonstrate their commitment to sustainable development (Geerts and Dooms, 2021). Technology providers and simulation experts making innovations in digital technologies, including environmental monitoring systems, predictive modelling, and simulation tools, are crucial for sustainable port operations. These tools support scenario planning, emissions forecasting, and real-time decision-making, helping ports respond adaptively to environmental risks (Monios, 2020; Acciaro et al., 2014). Digital platforms like Port Information Systems (PIS) and Port Community Systems (PCS) are fundamental in improving operational transparency, coordination, and environmental performance. Port Information Systems centralize data on cargo movement, energy usage, emissions, and logistics flows, enabling stakeholders to monitor and optimize environmental impacts. Meanwhile, Port Community Systems facilitate communication and collaboration among port users including customs, shipping lines, freight forwarders, and regulators streamlining processes and reducing environmental footprints through data sharing and synchronisation. These systems foster integrated governance by creating a shared digital infrastructure that supports efficient, transparent, and sustainable port operations.

The interaction between these stakeholders forms a governance nexus, characterised by overlapping jurisdictions, competing interests, and shared responsibilities. Navigating this complex system requires integrative policies that align environmental regulation, port development, and community welfare. A nexus approach facilitates this integration by recognizing the mutual dependencies of actors across sectors. Collaborations between these stakeholders are vital in advancing sustainable port management, particularly in mitigating pollution and ensuring compliance with international environmental standards.

The contribution of the nexus approach to integrative policies can be seen in several ways: Sustainable Development Goals (SDGs) have prompted attempts to incorporate more sustainable practices in port governance models. The nexus approach aims to accommodate the role of sustainable ports in achieving economic growth, environmental protection, and social development simultaneously (Butt, 2021). The Integrated Maritime Policy (IMP) of the European Union seeks to provide coherence to the problems in the maritime sector through the coordination of all stakeholders, aiming to establish a structured, systematic collaboration framework (López-Bermúdez et al., 2020). Ports across the world are important catalysts for social change and governance reform in sustainable transport contexts, and they can become cornerstones for future decision making about climate change in local to international contexts (Nursey-Bray, 2015). The governance of port city regions requires collaborative approaches that focus on combined values to achieve long-term resilience and enable a sustainable and just coexistence of port and city actors within the same territory (Höller, 2021).

For example, when port owners, port managers, and market participants—who are typically profit-driven—aggressively pursue economic growth at the expense of environmental and social well-being, conflicts arise. As a result, they clash with neighbourhood organisations and port workers. Specifically, community organizations and port workers are typically not included in decision-making on port city development issues or policies, and their opinions may be ignored or underrepresented. Economic, social, and environmental factors should all be fairly balanced in a stakeholder management strategy (Lam and Yap, 2019).

In conclusion, the interplay of local, national, and international actors in maritime port governance presents challenges related to overlapping jurisdictions, emissions, noise, and climate change adaptation. The nexus approach contributes to integrative policies by accommodating the role of sustainable ports in achieving economic growth, environmental protection, and social development. The implications for sustainable development involve the need for collaborative approaches to achieve long-term resilience and coexistence of port and city actors.

Current research trends focus on understanding the economic principles underlying port policies, enhancing policy integration within integrated maritime policies, and further developing our understanding of maritime security issues. There is a need for further research to fully understand the economic principles underlying port policies and their relevance today (Brooks, 2019). Integrated maritime policies (IMPs) provide a comprehensive governance framework to support the sustainable use of seas and oceans, and there is an ongoing research on how IMP governance can be arranged to support more effective policy integration (Paridaens and Notteboom, 2021).

For example; port of Naples, Italy utilised information and communication technology (ICT) and Geographic Information Systems (GIS) to enhance stakeholder engagement and support deliberative decision-making for urban planning and port management. This approach facilitated better coordination between port and urban stakeholders (Ettorre

et al., 2023). Guangzhou and Shenzhen, China developed structured frameworks to balance economic, social, and environmental interests. These frameworks help policymakers manage diverse stakeholder interests and promote sustainable development (Lam and Yap,2019). Port of Long Beach, USA implemented various sustainable practices, including air and water quality management, waste disposal, and land/resource use. These practices are driven by public-private partnerships and stakeholder involvement (Hiranandani, 2014).

4. MAIN CHALLENGES FACED BY PORT AUTHORITIES IN IMPLEMENTING ENVIRONMENTAL REGULATIONS

Balancing economic growth with environmental protection, managing diverse stakeholder interests, and addressing the complexities of international, regional, and national regulations is very important (Hiranandani, 2014; Lam and Yap, 2019). Port authorities encounter several significant challenges when implementing environmental regulations. These challenges can be broadly categorized into institutional, financial, technical, and operational issues.

The existence of multiple regulatory bodies and overlapping jurisdictions complicates the enforcement of environmental regulations. This polycentric governance structure often leads to conflicts and inefficiencies (Monios, 2019). The financial burden of implementing green technologies and infrastructure is a major barrier. Many ports struggle with the high costs associated with renewable energy, electric port equipment, and other green initiatives (Roberts, 2023). Especially in developing regions, ports face financial constraints that hinder the adoption of comprehensive environmental management practices. This is evident in African ports, where financial limitations are a significant barrier to effective environmental management (Arabi, 2022). Effective environmental management requires robust data collection and analysis. However, ports often face challenges in gathering accurate data, which is crucial for implementing carbon management programmes and other environmental initiatives (Azarkamand et al., 2020). The integration of environmental agendas into port management is complex, requiring sophisticated decision-making models that consider various criteria such as resource optimisation, environmental impact minimisation, and operational safety (Argyriou et al., 2022). Ports are significant sources of pollution, including air and water emissions, noise, and waste generation. Managing these pollutants while maintaining operational efficiency is a persistent challenge (Roberts et al., 2023; Franchi and Vanelslander, 2021). The lack of adequate infrastructure, such as bunkering facilities for alternative fuels like LNG, hampers the adoption of environmentally friendly practices. This is a notable issue in the development of LNG bunkering facilities in North European ports (Wang and Notteboom, 2015). Ports like Hamburg face ongoing challenges with sediment contamination, which complicates dredging operations and compliance with environmental regulations (Röper and Netzband, 2007). Effective environmental management often necessitates collaboration among various stakeholders, including port authorities, regulatory bodies, and local communities. This collaborative approach can help address the multifaceted challenges of environmental governance (Azarkamand, 2020; Wooldridge et al., 2008).

Port authorities face the dual challenge of maintaining operational efficiency while adhering to strict environmental regulations. This balance is crucial for sustainable port operations and competitiveness. What are the key strategies and approaches? Ports implement environmental management systems to monitor and reduce greenhouse gas emissions and other pollutants. For instance, Italian ports use composite indicators to evaluate environmental quality and efforts towards pro-environmental paths, ensuring economic efficiency is maintained while minimising undesirable outputs (Castellano et al., 2020). Green port management practices involve adopting proactive green policies, pollution control measures, and automation. Ports like Singapore have been successful in implementing these practices, which significantly influence overall port efficiency and environmental sustainability (Mahmud et al., 2024). The integration of smart technologies, such as digital twins and automation, enhances operational efficiency and environmental sustainability. These technologies enable real-time data analysis, predictive maintenance, and optimized resource use, reducing emissions and operational costs. (Zeneli and Marinova, 2024; Tsolakis et al., 2022). Ports are increasingly adopting energy-efficient systems to comply with environmental regulations. These systems include sustainable energy generation, storage, and smart grid management, which help in reducing energy consumption and emissions (Le et al., 2023). Ports must comply with international and local environmental regulations. Implementing environmental incentives and penalty pricing can drive ports towards better environmental practices while maintaining operational efficiency (Mahmud et al., 2024).

Port authorities must navigate a complex landscape of institutional, financial, technical, and operational challenges to implement environmental regulations

effectively. Addressing these challenges requires a combination of strategic investments, robust regulatory frameworks, and collaborative efforts among stakeholders. On the other hand, Innovations in technology and processes, stakeholder collaboration, and the development of comprehensive sustainability frameworks can drive significant improvements in port sustainability (Acciaro et al., 2014; Hall et al., 2013). Port environmental governance and urban sustainability require the active involvement of multiple stakeholders, including port authorities, environmental agencies, businesses, and communities. Effective governance strategies and sustainability initiatives must address the diverse interests of these stakeholders while promoting economic, social, and environmental goals. Case studies from ports demonstrate the practical implications of these strategies and highlight the importance of collaboration and innovation in achieving sustainable port development.

5. PORT OF ROTTERDAM AS A MODEL FOR URBAN SUSTAINABILITY

Historically, Rotterdam's development has been closely tied to its port. Post-WWII reconstruction emphasised modernist planning and rapid rebuilding. Over time, the city transitioned from an industrial hub focused on petrochemicals and containerisation (1960s–1980s) to a post-industrial global city emphasizing services, knowledge economies, and sustainability, innovation, international trade, focusing on climate resilience, digital transformation, and green urbanism (2000s – present) (Hajer and Dassen, 2014).

Port of Rotterdam, Netherlands: *"We are actively striving to enhance our good influence as the port of Rotterdam's developer, which will ultimately raise the economic and social value for all of our stakeholders."* It highlights the collective power of everyone who is involved in the port of Rotterdam. Additional, illustrative stories, provide an insight into the intentions and initiatives: from sustainability and innovation to security and social engagement (Port of Rotterdam Authority, 2024).

This illustrates how a nexus-based approach has been applied to port sustainability balancing technological innovation, stakeholder coordination, and environmental responsibility. The port has adopted innovative sustainability strategies and is known for its green initiatives and has invested in shore power systems, allowing ships to use renewable energy while docked, reducing emissions (Van der Lugt et al., 2015).

Rotterdam, Europe's largest port city, has undergone significant urban transformation, shaped by a combination of economic shifts, sustainability efforts, and governance innovations. In recent years, its governance model has evolved towards collaborative, multi-actor strategies that emphasize sustainability, resilience, and digitalisation. The Port of Rotterdam is Europe's largest port and a key gateway to the European continent. Its economic impact is substantial, contributing approximately 6% of the Netherlands' GDP (OECD, 2019).

Figure 3. Terminals. (Source: Port of Rotterdam)

Rotterdam has been at the forefront of port innovation, leading initiatives in digitalisation, automation, and green shipping. The port has also invested in sustainable energy, such as hydrogen production and carbon capture projects, to reduce its environmental impact. The Port of Rotterdam Authority is committed to creating both economic and social value by fostering sustainable growth in collaboration with stakeholders. Its CSR (Corporate Social Responsibility) efforts focus on key areas such as safety, health, climate and energy, and employment, aiming to set an example for others and contribute to the UN Sustainable Development Goals. In 2021, the port updated its CSR statement to emphasise a balance between economic development and environmental sustainability, aligning with the Paris Agreement through Science Based Targets for CO_2 reduction (Port of Rotterdam Authority, 2021).

Despite these advancements, the port faces significant environmental challenges. Rotterdam remains a major source of carbon emissions due to industrial activities and shipping traffic, and expansion projects like Maasvlakte 2 have raised concerns over habitat destruction and biodiversity loss (OECD, 2019; Port of Rotterdam Authority, 2021).

Situated in a low-lying delta, Rotterdam is highly vulnerable to sea-level rise and climate events. To address these risks, the city has pioneered urban resilience strategies, such as the "Room for the River" programme, which creates floodable spaces to manage overflow. Maasvlakte 2, a climate adaptive port extension, integrates sustainable logistics and renewable energy use (Port of Rotterdam Authority, 2021). Floating infrastructure projects like the Floating Pavilion and Floating Farm demonstrate innovative water based urban design (Koop and Van Leeuwen, 2017).

To mitigate emissions, the Port of Rotterdam has launched ambitious carbon reduction initiatives aiming for climate neutrality by 2050 through electrification, hydrogen, and circular economy strategies. The Porthos carbon capture and storage (CCS) project, which stores CO_2 under the North Sea, exemplifies this effort (Port of Rotterdam Authority, 2023). Additionally, Rotterdam aims to become a central hub for green hydrogen in Europe. Rotterdam has integrated sustainable urban planning into its transformation. Smart & green mobility projects expanding cycling infrastructure, electric public transport, and car-free zones. High-rise developments with integrated greenery, like the Timmerhuis and Depot Boijmans Van Beuningen. Circular economy pilot projects are encouraging reuse of materials in construction and urban design (EUKN, 2020). Rotterdam's governance structure balances public interests with private-sector innovation, forming coalitions between local government, businesses, and civil society. For example; the Municipality of Rotterdam leads urban planning, sustainability policies, and housing initiatives. Port of Rotterdam Authority (a semi-public entity) manages port operations, logistics, and environmental strategies. The Dutch government and the EU support policies on energy transition and climate adaptation (OECD, 2019).

Rotterdam's governance structure aligns with urban regime theory, wherein coalitions between state, market, and civil society shape urban policy. Public-private partnerships (PPPs), such as the Porthos project, showcase joint efforts towards decarbonisation (Stone, 1989; Bulkeley and Betsill, 2005). The Port of Rotterdam's 2023 annual report, titled "Connecting the world. Building tomorrow's sustainable port," highlights the port's commitment to sustainability in the middle of a challenging geopolitical and economic landscape. The report emphasizes the challenges and strategic priorities shaping the port's future: For example; sustainability investments such as expansion of carbon capture (Porthos Project), green hydrogen infrastructure, and circular economy initiatives. Technological and digital innovations such as increased reliance on AI-driven logistics, automation, and data-sharing platforms. Major milestones were achieved in the transition to a sustainable port, including the final investment decision for the CO_2 transport and storage project, Porthos, and the commencement of construction on the national hydrogen network.

On the other hand, Actor-Network Theory, offers another analytical lens, emphasising the relational dynamics between human and non-human actors (Latour, 2005). In the Port of Rotterdam, entities like the Port Authority, shipping companies, AI platforms (e.g., PortXchange), and infrastructure all act as "actors" co-producing governance outcomes. The Port Authority functions as an "obligatory passage point," mediating interactions between stakeholders (Callon, 1986). Actor-Network Theory views technological, human, and organisational entities as interconnected "actors" forming networks that influence each other's actions. In the context of the Port of Rotterdam, ANT can be applied to understand how diverse actors such as the Port Authority, shipping companies, environmental agencies, local communities, and technological systems interact to shape port operations and governance. Actor-Network Theory suggests that humans, organizations, and technology are all "actors" that form dynamic networks influencing governance and policy. Applying ANT to Rotterdam's port transformation highlights how different actors both human and non-human interact to shape sustainability and innovation.

5.1. Key Actors in the Port Network

Actor	Role & Influence	Strategy
Port of Rotterdam Authority	Semi-public entity managing port operations, infrastructure, and sustainability projects.	Acts as a central coordinator, advancing green logistics, digitalisation (e.g., PortXchange), and climate neutrality goals (e.g., Porthos project).
Municipality of Rotterdam	Responsible for urban planning, economic policies, and social inclusion.	Integrates urban resilience, circular economy initiatives, and participatory planning into port-city development.
Shipping & Logistics Companies	Large firms like Maersk and MSC influence decarbonisation efforts and digitalisation.	Invest in green shipping technologies, automated logistics, and compliance with emissions targets.
Regulatory Bodies & Environmental Organizations (IMO, EU, EPA, PSC)	Drive stricter regulations on emissions and sustainability targets.	Push for enforcement of international and regional standards (e.g., IMO, EU Green Deal) and ecological accountability.
Technology & Innovation Hubs	Develop smart port solutions, AI logistics, and automation.	Create digital platforms (e.g., digital twins, predictive logistics) to optimise efficiency and reduce emissions.
Local Communities & Workers	Engage in urban co-production, pushing for equitable development.	Advocate for inclusive development, environmental health, and climate justice in port expansion decisions.

In ANT terms, the Port of Rotterdam Authority functions as an "obligatory passage point", meaning all actors must interact with it to achieve their goals (e.g., sustainability, trade, employment). The Porthos CO_2 storage project is a prime example—bringing together government agencies, energy companies, and environmental regulators in a tightly connected network.

Regime theory on the other hand focuses on the coalitions between public and private sectors that govern urban areas. In Rotterdam, the Port Authority also collaborates with various stakeholders, including municipal and national governments, private enterprises, and civil society organisations, to drive sustainable initiatives. For instance, the Porthos project exemplifies a public-private partnership aimed at reducing CO_2 emissions through collaborative efforts. By integrating ANT and Regime Theory, we can analyse how the Port of Rotterdam's governance model facilitates sustainability. The Port Authority acts as a central node, aligning the interests of diverse actors towards common goals. This networked approach enables the port to adapt to economic challenges while advancing environmental objectives, reflecting a dynamic and inclusive governance model. In conclusion, the Port of Rotterdam's initiatives demonstrate how collaborative networks and strategic governance can drive sustainable transformation in complex infrastructural settings. Rotterdam's governance model aligns with urban regime theory, where coalitions between government, private actors, and civil society shape decision-making.

Co-production also refers to collaborative decision-making and project implementation between government institutions, private firms, and local communities. In Rotterdam, co-production is evident. Citizens and businesses contribute to projects like floating urban farms, green roofs, and energy-efficient housing. The Blue City initiative repurposes old industrial buildings into circular economy hubs with community involvement. The "Room for the River" programme integrates public participation in flood resilience planning. Floating architecture (e.g., Floating Pavilion, Floating Farm) showcases how bottom-up innovation meets government planning. Open-access platforms allow stakeholders to share real-time shipping data, CO_2 emissions metrics, and logistics flows. PortXchange (Digital Twin Initiative) enables co-produced AI-driven solutions for optimising cargo flows. Co-production ensures that Rotterdam's transformation is not just top-down but actively shaped by businesses, researchers, and citizens.

Rotterdam's urban and port transformation showcases how a port city can integrate ANT-driven networks, regime coalitions, and co-production strategies to achieve sustainability goals. This hybrid governance approach balances economic competitiveness with environmental responsibility. The hybrid governance model reflects co-production, where citizens and businesses engage in initiatives like floating farms, green roofs, and participatory climate adaptation projects. This multi-layered governance approach makes Rotterdam a global leader in green port transformation, balancing economic growth, climate resilience, and participatory governance.

Ports must find a balance between economic growth and environmental sustainability. This involves investing in green technologies and practices that may have higher initial costs but result in long-term savings and compliance benefits (Le et al., 2023; Quintano et al., 2021). Effective collaboration among port authorities, policymakers, and local communities is essential for developing and implementing sustainable port practices. This ensures that all stakeholders' interests are considered and addressed (Di Vaio et al., 2018; Sepehri et al., 2024). Ports should continuously monitor and improve their environmental and operational performance through regular assessments and updates to their management systems and technologies (Kuznetsov et al., 2015). By adopting these strategies, port authorities can achieve a sustainable balance between operational efficiency and environmental compliance, ensuring long-term viability and competitiveness in the global maritime industry.

On the other hand despite progress, significant challenges remain in achieving comprehensive port sustainability. The role of digitalization and automation in reducing environmental impacts. Strategies for balancing economic competitiveness with strict environmental policies. Studies assessing the long-term effectiveness of sustainability measures. The development of circular economy principles within port operations, such as waste-to-energy projects. Social equity concerns related to port expansion, particularly in terms of displacement and public health.

6. CONCLUSIONS

Maritime ports remain critical components of urban economies, yet their expansion raises significant environmental and political challenges. From an urban and environmental political perspective, regulatory interventions and community activism play essential roles in mitigating the negative impacts of ports. Meanwhile, a Science and Technology Studies (STS) perspective particularly through Actor Network Theory, offers deeper insights into how technological, regulatory, and social elements interact to shape port dynamics. Actor Network Theory provides a useful framework for analysing the complex interactions between human and non-human actors in port governance. According to Latour, ANT conceptualises networks where human actors (such as policymakers, shipping companies, activists) and non-human entities (like pollution levels, technological infrastructure, environmental laws) influence each other. Future studies should explore the evolving role of digital technologies, equity considerations, and innovative economic models to further advance sustainable port management.

In conclusion, to enhance sustainability, policymakers and port authorities should consider the following strategies: Encourage collaboration between governments, private companies, and local communities to drive sustainability initiatives. Strengthen international regulations: Enhancing compliance with global agreements such as the International Maritime Organization's (IMO) environmental standards. Implement strict emission controls and incentivise the use of cleaner fuels. Investment in renewable energy; increasing reliance on solar, wind, and hydrogen energy sources for port operations.

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