WHY DON'T WE SEAWEED?

A research for seaweed cultivation as a nature-based solution, embracing the ecosystem services of seaweed, in the context of the Port of Rotterdam


Pictures by Nicholas Floch (Floch, 2016)

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PREFACE

This thesis is the final chapter of my academic journey at the AMS Institute, where I have had the privilege of exploring the intersection of sustainable development, industrial innovation, and nature-based solutions. The journey that led to this research has been both challenging and rewarding, but most forward, it has deepened my understanding of how nature-based solutions can be integrated into complex industrial ecosystems.

The topic of seaweed cultivation as a nature-based solution in the Port of Rotterdam has fascinated me from the beginning. I like to think outside the box and explore innovative solutions for challenging urban and industrial challenges, especially linked to my hometown, Rotterdam. Throughout this research, I have tried to uncover the potential of seaweed cultivation to not only mitigate climate change but also to contribute to the sustainability goals of the Port of Rotterdam.

ABSTRACT

This thesis explores the potential of seaweed cultivation as a nature-based solution (NbS) for achieving sustainability goals in the Port of Rotterdam. By integrating the ecosystem services framework and the Building with Nature (BwN) concept, the study investigates the enabling and constraining factors for implementing seaweed farming in an industrial port context. The Port of Rotterdam, Europe's largest port, is striving to become climate-neutral by 2050, aligning with several Sustainable Development Goals (SDGs). However, despite its ongoing sustainability initiatives, the port has yet to incorporate NbS into its strategy.

Through a combination of literature review and semi-structured interviews with experts, this research identifies the potential benefits of seaweed cultivation through ecosystem services, focusing on provisioning, regulating, supporting, and cultural services. The findings suggest that seaweed cultivation could contribute significantly to the port's environmental and economic objectives by providing ecosystem services and supporting the port's transition towards a circular and sustainable economy. However, some challenges need to be addressed before implementing seaweed cultivation, such as regulatory and policy barriers, spatial constraints, and stakeholder conflicts.

The findings suggest that seaweed cultivation in the Port of Rotterdam should primarily be pursued for research purposes at this stage. Stakeholders should be encouraged to form innovation clusters, which could serve as the starting point for integrating seaweed cultivation into the port's sustainability strategy and achieving broader SDGs. As knowledge and expertise in seaweed cultivation grow, these innovation clusters could help establish the necessary permits and frameworks and potentially identify a test site. By sharing knowledge on seaweed cultivation practices, the Port of Rotterdam can enhance its global position as a leader in sustainable port development.

The study concludes with recommendations for integrating seaweed cultivation into the Port of Rotterdam's sustainability vision, highlighting the importance of collaboration between industry, government, and academia to overcome existing barriers and maximize the ecological and economic potential of seaweed as a sustainable resource.

Keywords: *Seaweed Cultivation, Nature-based Solutions, Port of Rotterdam, Marine Ecosystem, Innovation Ecosystem, Ecosystem Services, Industrial Ecology, Sustainability Strategy, Building with Nature, Regulatory Barriers, Innovation Cluster*

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GLOSSARY

Aquaculture:	The breeding, raising, and harvesting of fish, shellfish, and aquatic plants.
Ecosystem:	A complex system consisting of biotic (living organisms) and abiotic (physical environment) components that interact and sustain each other. It can be a *natural* or *replicated* system and can be used to describe real (natural) systems and/or as a metaphor to understand and communicate complex interactions and processes of a system.
Ecosystem services:	The benefits that people receive from ecosystems. The concept highlights the interconnectedness of the environment and the economy, emphasizing the need for responsible management of natural resources to support both economic and human well-being.
Innovation ecosystem:	A network where various stakeholders, including economic players and non-economic factors, work together to innovate. It involves collaboration and shared resources among different actors to drive innovation and create value.
Marine ecosystem:	A natural ecosystem including seas and coastal zones, are vital habitats providing ecosystem services.
Nature-based solutions:	Nature-based solutions (NbS) are joint actions between humans and nature designed to address societal challenges, such as climate change while delivering benefits for people and biodiversity.
Natural ecosystem:	An ecosystem that interlinks biotic and abiotic factors that sustain each other, offering many benefits to different groups of people and helping protect natural resources.

1. INTRODUCTION

1.1 Nature-Based Solutions in Ports

There is a growing interest in the potential of nature-based solutions for mitigating climate change and addressing different sustainability challenges (Seddon, 2022; IUCN 2020; Frantzeskaki, 2019; Smith et al., 2021). Nature-based solutions (NbS) are collaborative efforts between humans and nature aimed at tackling societal challenges like climate change. They "provide benefits for both people and biodiversity by protecting, restoring, or managing natural and semi-natural ecosystems", as well as sustainably managing land and seascapes (SeaMark, 2023). They gained popularity as they serve as a powerful tool for addressing multiple challenges within the same solution and have been proposed to support the Sustainable Development Goals (Seddon, 2022; Nature-Based Solutions Initiative, 2024). According to Seddon (2022), there is an emerging need to improve our understanding of NbS, especially in marine and non-forest ecosystems as they exceed traditional technological approaches to solve issues (Rogers et al., 2013). Anthropogenic pressures like overfishing and eutrophication, which is the increase of excessive nutrients into the environment resulting in habitat degradation, are growing challenges to coastal ecosystems and communities depending on their resources (NOAA, 2024).

Ports are interesting sites to study the implementation of NbS a huge challenge to reach their sustainability targets. As key hubs in global supply chains, ports cause social and environmental externalities alongside economic growth. Their activities have significant environmental impacts, despite the crucial role oceans play in providing food, jobs, and recreation globally and nationally. Additionally, they damage the local marine ecosystem, including seas and coastal zones (Alamoush et al., 2021). Ports are some of the primary sources of pollution along the coastlines. Various industrial sources and numerous port activities cause this pollution in these marine ecosystems. As a result, concerns about the effects of ports on the environment have grown during the past few years (Lam & Notteboom, 2014). Since ports are durable coastal services, their environmental impact is long-lasting (Woo et al., 2018). These hubs for marine transport and international trading are important to our global economy and have a big social impact (Owusu-Mfum et al., 2023) and therefore carry a responsibility to mitigate their long-lasting negative impacts. To reduce harmful environmental effects, there are now stricter regulations that promote innovative designs to minimize impacts and encourage sustainable practices for the long term (Woo et al., 2018). The European Sea Port Organisation (ESPO) recognizes its global impact and the importance of mitigating climate change. As a result, ESPO publishes its *Top 10 Environmental Priorities of European ports* based on its environmental report each year (Espo, 2024). In the 2023 report, climate change, air quality, and water quality make the top five most important priorities for European ports. These environmental priorities align with various themes within the Sustainable Development Goals (SDGs). The United Nations' Sustainable Development Goals, as envisioned in the Paris Agreement 2015, are determined to protect the planet by taking rapid action on climate change by sustainably managing its natural resources (United Nations, 2015). This international agreement focuses on adaptation and mitigation methods to reduce the effects of climate change and wants to increase the resilience of vital ecosystems globally (Jansen, 2023). Altogether, ports make an interesting research area to study the implementation of NbS.

1.2 Seaweed as a Nature-Based Solution

Seaweed is a natural resource that is gaining popularity as it has recently found industrial applications such as biomaterials, fertilizers, and bioplastics, while also offering solutions for climate change mitigation and biodiversity improvement (O'Connor, 2017; WUR, 2024; Duarte et al., 2021), chapter 3 elaborates on the qualities and characteristics of seaweed. Additionally, multiple studies have shown the potential of seaweed cultivation to help achieve the SDGs (García-Poza et al., 2022; Sudhakar et al., 2023). Duarte et al. (2021) introduce seaweed cultivation as a unique, scalable, and sustainable solution for reaching climate targets and achieving the SDGs; "seaweed aquaculture generates multiple ecosystem services that lead to direct benefits in advancing several SDGs (SDGs 2,3,7,13,14), which, in turn, provide integrative benefits contributing to additional SDGs (SDGs 1,4,5,8-12,15)" (p.7).

1.3 The Port of Rotterdam's Road to Sustainability

The Port of Rotterdam (maps provided in Appendix 9.1), the largest in Europe and a leading global port has been chosen as the focus of this research due to its scale and ongoing efforts to become a model of sustainability and interest in sustainable port policies (HAVENVISIE, 2019; Statista, 2023; Lam & Notteboom, 2014). As a key industry player, the port has outlined an ambitious vision to reduce its environmental impact and achieve climate neutrality by 2050, promoting international collaboration and a commitment to global sustainability goals (Port of Rotterdam, 2023b). As detailed in different documents, its sustainability strategy emphasizes creating social value and minimizing negative external effects while the port continues to expand its activities. This ensures an additional complexity in meeting these sustainability targets (HAVENVISIE, 2019). The port's sustainability initiatives are closely aligned with several SDGs (Figure 1), including SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action) (HAVENVISIE, 2019; Corporate Social Responsibility, 2023).

Figure 1: All 17 Sustainable Development Goals by the United Nations, and highlighted important SDGs for the Port of Rotterdam, own visualization.

The Port of Rotterdam translated these goals into three priorities: *economic transition, social transition,* and creating an *attractive region*. The port aims to work on these priorities through a variety of initiatives. To achieve the economic transition, the port focuses on digitalization, transitioning to new energy sources, and working towards a sustainable supply chain to remain competitive. To ensure a social transition, the port is focused on enhancing education, fostering the labor market, and promoting inclusivity. Lastly, the port is working to create an attractive region trying to balance urban development while improving the vitality of the port and industrial complex. This includes improving living conditions, safety, and environmental quality to attract investments and talent while maintaining a vibrant and healthy community (HAVENVISIE, 2019).

Economic progress is important, but according to the port, it must not come at the expense of nature, the environment, and the living conditions in the port industrial area. Besides being a hub for transportation, the port invests in facilities to process raw biomass, mostly brought in by ship, into biofuels and other outcomes (Ros et al., 2014). These efforts include implementing advanced logistics systems, new technologies, energy-efficient infrastructure, and renewable energy sources. Additionally, the "Natuurvisie Havenbedrijf Rotterdam" document highlights the port's commitment to integrating nature conservation with industrial development, ensuring that economic activities support and enhance the local and regional ecosystems. The port aims to create a resilient and biodiverse environment by 2030 through strategic planning, sustainable practices, and collaboration (Port of Rotterdam, n.d.-b). However, as shown in Figure 1. above, the Port of Rotterdam leaves SDG 14 (Life Below Water) out of its vision on sustainability, which is remarkable due to its connection to the surrounding water bodies. Collaborating partners working on the biodiversity in the port state that they want to focus more on what can be done below the water’s surface as even small measures can still achieve significant additional benefits (ARK Natuurontwikkeling, 2021).

The Port of Rotterdam's nature and future vision documents each emphasize different aspects of the port’s sustainable development. However, the sustainability plans outlined in the nature vision run parallel to the broader sustainability initiatives and do not seem integrated. Despite the port’s ambition to achieve comprehensive sustainability, including its goal of becoming a "bio-port," these efforts are not fully interconnected (Port of Rotterdam, n.d.-b; HAVENVISIE, 2019). Introducing NbS could help understand these complex interactions between humans and the ecosystems in the port and serve as innovative solutions to ensure sustainability. Considering the central role of the Maas River in the port's operations and identity, incorporating NbS into the port’s development plans seems both logical and beneficial.

1.4 Research Aim & Questions

1.4.1 Research Aim

This thesis focuses on the potential of cultivating seaweed as a NbS by exploring its enabling and and constraining factors in the industrial context of the Port of Rotterdam. While seaweed cultivation is gaining more popularity in the field of research, its application in port areas has not been investigated yet. Despite its prominent global position and ambition to become an innovation ecosystem, the Port of Rotterdam has not included NbS in its sustainability strategy yet. Therefore, this thesis seeks to bridge this knowledge gap and determine the viability of using seaweed cultivation as an innovative solution for meeting sustainability goals in port areas, as here the Port of Rotterdam. To address this knowledge gap multiple research questions have been formulated.

1.4.2 Main Research Question

What are the enabling and constraining factors for seaweed cultivation as a nature-based solution in the Port of Rotterdam and how can seaweed cultivation fit within the sustainability vision of the port?

1.4.3 Sub-Research Questions

1. *What are the most important sustainability goals of the Port of Rotterdam and how does it plan on contributing to the SDGs?*
2. *What are the possible functions of seaweed cultivation in the Port of Rotterdam?*
3. *What are the constraining and enabling factors for seaweed cultivation as NbS for the Port of Rotterdam?*

1.4.4 Scope

Within this research, there are several points of focus. First, I will assess the current sustainability efforts at the Port of Rotterdam and so create an understanding of the port's existing strategies to achieve its sustainability goals. I will do this by looking into how the port aims to maintain a healthy natural ecosystem, create good economic opportunities, and ensure a high quality of life for its (urban) residents. As the SDGs play an important role in the development of the Port of Rotterdam, I will also research how the port will achieve the SDGs as shown in Figure 1 to understand whether it is possible to cultivate seaweed in the Port of Rotterdam as an NbS, a clear overview of the current sustainability efforts is needed. Second, I will provide an understanding of what is possible in the Port of Rotterdam in terms of seaweed cultivation within its road to sustainability. Seaweed holds numerous qualities according to literature (O'Connor, 2017; WUR, 2024; Duarte et al., 2021; García-Poza et al., 2022; Sudhakar et al., 2023), but what can the function of seaweed cultivation be in an industrial ecosystem such as the port? Fourth, I will identify challenges and constraints, and analyze factors that may limit the implementation of seaweed cultivation. On the other side, I will also elaborate on the enabling factors for seaweed cultivation in the port. Finally, with the outcome of this research, I will substantiate recommendations for incorporating seaweed cultivation in the Port of Rotterdam. Overall, this thesis aims to follow a comprehensive approach and therefore reflect on the various aspects of nature-based solutions beyond only environmental impact.

There is also the possibility of downsides to the proposal of seaweed cultivation as the context of this research consists of a complex system with numerous stakeholders involved. Therefore I expect a conflict of interest between the different stakeholders of the Port of Rotterdam. Additionally, as the Port of Rotterdam is located within a highly urbanized area, I expect there to be issues regarding spatial justice within the waterbodies in the port.

The Port of Rotterdam speaks of additional sustainability goals besides those discussed in this research. However, to scope this research I have chosen to focus only on the sustainability goals as discussed in the research aim. As this research is qualitative, the sustainability goals are included and not the sustainability targets, as these require a quantitative data approach.

1.4.5 Structure

This paragraph outlines the structure of the thesis, beginning with an introduction that sets the stage by presenting nature-based solutions in port areas, specifically focusing on the Port of Rotterdam. In this section, the research questions are introduced, and the scope of the study is clearly defined. The theoretical framework then introduces the key concepts such as *ecosystems, ecosystem services, natural ecosystems, innovation ecosystems, industrial ecology,* and the "*Building with Nature*" approach. Following this, a background chapter on seaweed cultivation discusses its essential characteristics and requirements. It also examines current policies on seaweed aquaculture and provides an overview of commonly cultivated species in the Netherlands. These chapters lay the foundation by covering all relevant theories and concepts necessary for the thesis. Following this, the methodology is presented, which elaborates on the research process and leads to the results. In the results chapter, the discussed theories are revisited, and all the essential information needed to answer the main research question is provided. After that, the data provided in the results chapter is discussed according to the Building with Nature approach.

2. THEORETICAL FRAMEWORK

This chapter explains the theoretical framework of this thesis, which provides the foundation for understanding the complex interactions between industrial development and environmental sustainability within the context of the Port of Rotterdam.

Due to their coastal or river delta locations, ports are particularly vulnerable to the impacts of climate change. Their shift towards sustainability is supported by a growing emphasis worldwide on ecosystems and adopting an ecosystem services approach when it comes to planning and developing ports (Jansen & Erasmus University Rotterdam, 2020). Ecologists have used different metaphors to portray an ecosystem, such as a machine, system, or organism (Pickett & Cadenasso, 2022). Ecosystem services refer to the relationships between nature and human society. Humans depend on nature to maintain themselves and to provide resources and other necessities, such as nutrition and ecological benefits. Humans must co-produce these services using their abilities, expertise, and technologies (Bruckmeier, 2016). Thanks to ecosystem services, policymakers and stakeholders can "compare apples with apples" when evaluating the significance of a planned project concerning the ecosystems at the project site (René Kolman & International Association of Dredging Companies (IADC), 2014). It is argued that theories of ecosystem services could offer port officials new viewpoints on how the development of the surrounding natural and socio-economic systems affects them directly. In addition, the United Nations proposed that businesses and governments that use an ecosystem approach are more successful in adapting to new information and shifting demands (Jansen, 2020).

This chapter explains which theories are used in this thesis and how they connect. This thesis utilizes and shapes the Ecosystem Services framework and Building with Nature concept while focusing on the sustainability transition of the Port of Rotterdam. First, this chapter focuses on the theory of ecosystems and ecosystem services. Then, it narrows down to the context of the Port of Rotterdam and elaborates on the natural ecosystem, and the port's aim towards an innovative ecosystem and reaching an industrial ecology. After that, the Building with Nature concept is introduced and it is explained how this concept aligns with the innovative character of the Port of Rotterdam.

2.1 What is an Ecosystem?

An ecosystem is mostly described as a natural ecosystem that interlinks biotic and abiotic factors that sustain each other (Jansen & Hein, 2023). Ecosystems offer many benefits to different groups of people and help protect natural resources. Managing ecosystems is a great way to address societal challenges and ensure that biodiversity remains an important consideration in various sectors (IUCN, 2020). However, not all ecosystems are natural but replicate the interconnected workings of natural ecosystems. They consist of various factors that mutually influence each other, forming a complex and functioning system making them compatible with how natural ecosystems function (McManus, 2009). According to Pickett and Cadenasso (2002), an ecosystem is an ecological concept that holds more to itself than initially seems. They discuss three dimensions within the 'ecosystem' terminology: meaning, model, and metaphor. In this concept, the three dimensions are described as follows (Pickett & Cadenasso, 2022):

Meaning: This dimension refers to the definition of an ecosystem. An ecosystem is a biotic complex, including all living organisms, and its associated physical environment in a specific context. This definition emphasizes the connections between biotic and abiotic components and their interactions. The definition works for ecosystems of any scale, as long as they contain organisms, their physical surroundings, and their interactions.

Model: These models are conceptual tools to imitate and study how ecosystems behave under different conditions, they can be verbal, physical, quantitative, or graphical. Models are necessary because the definition of an ecosystem is neutral in scale and limitations.

Metaphor: The metaphorical dimension refers to the informal and symbolic use of the ecosystem concept in general parlance. Metaphors can describe ecosystems structurally (such as machines, organisms, or algorithms) or behaviorally (such as resilient or adaptable). These metaphors are used in scientific and social contexts to generate new ideas and communication. Metaphors can also help make scientific concepts accessible and relevant to the public and decision-makers by expressing complex ideas in more relatable terms.

These definitions highlight the complexity and adaptability of the ecosystem concept, showing how it can be used in various contexts to communicate different ideas and values (Pickett & Cadenasso, 2022). These dimensions provide a way to discuss the meaning of ecosystems beyond the initial 'natural ecosystem'. The original natural ecosystem consists of biotic and abiotic elements, the following figure shows the interconnection between different aspects of an ecosystem:

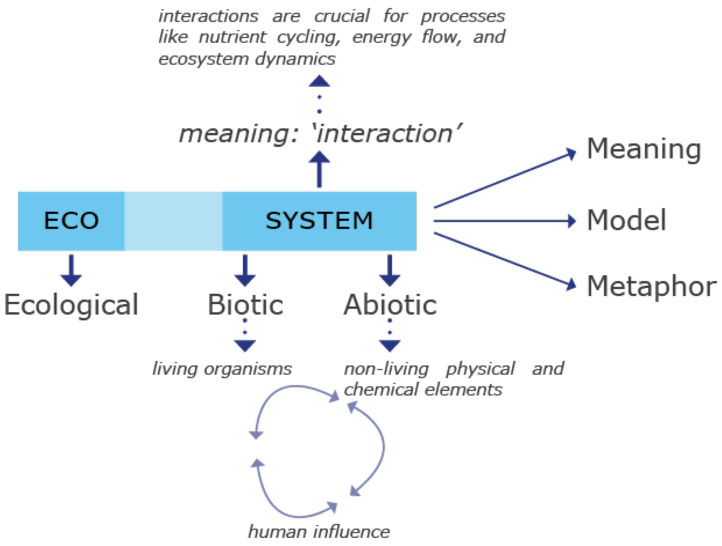

Figure 2: Explanation of an ecosystem's definition, dimensions, and components. The biotic and abiotic components are constantly interconnected and influenced by humans (Pickett & Cadenasso, 2022), own visualization.

Natural ecosystems consist of biotic and abiotic factors that form a "bubble of life" (National Geographic, n.d.). As stated before, not all ecosystems are natural but replicate the interconnected workings of natural ecosystems (McManus, 2009). Examples of these ecosystems found in the Port of Rotterdam are an industrial ecosystem, an innovative ecosystem, and an economic ecosystem. In these cases, the three dimensions of the ecosystem differ from the natural ecosystem, especially the 'metaphor' dimension. The

Port of Rotterdam is deeply connected to and depends on the natural ecosystem of the Maas River and Delta region.

2.2 What are Ecosystem Services?

Natural ecosystems provide ecosystem services and these are related but different concepts. Bennett et al. define ecosystem services as " benefits that people receive from ecosystems. They can usefully be conceived as part of a social-ecological system, for in the absence of people there are no services, and people often modify ecosystems to enhance the production of specific services…" (2009). Ecosystem services show that the environment and the economy are interconnected. This means it is needed to manage natural resources responsibly to support the economy and human well-being (Costanza, 2006). It's important to understand how ecosystems and their services interact because changes in one ecosystem can affect others, either positively or negatively (Bennett et al., 2009). *Provisioning* services refer to the ecosystem's products, such as raw materials, nutrients, and energy sources. The benefits obtained by the ecosystem to manage ecological processes can be described as *regulating* services, this includes climate regulation and bioremediation. *Supporting* services highlight the contribution of the ecosystem to other ecosystem services, such as habitat provision. *Cultural* services refer to the non-material benefits that people gain from the ecosystem, such as job opportunities, recreation, and commercial provision for communities (Clark et al., 2021).

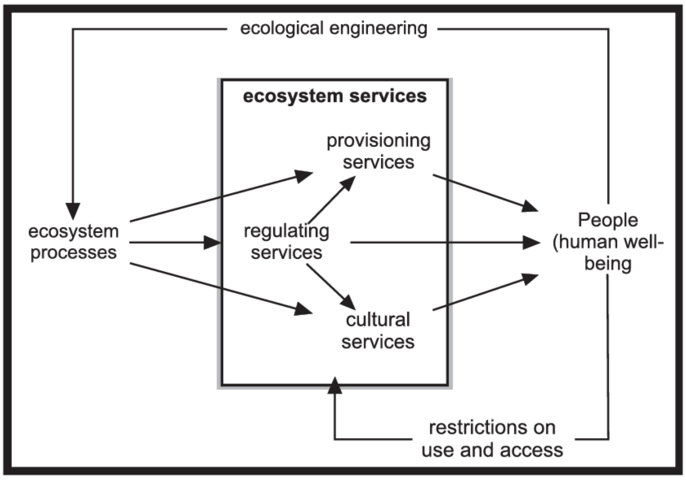

Figure 3: "Diagram representing ecosystem services" (Gupta & Nair, 2012).

Figure 3 represents ecosystem services and shows a direct link between ecosystems, the ecosystem processes, their services, ecological engineering, and the well-being of people. As 'supporting services' are not included in the diagram, they are equally important as the other services. Ecosystem processes include creating organic matter, exchanging nutrients and carbon, enhance soil formation have an important role in the provision of ecological services (US EPA, 2024). As seen in Figure 2, interactions within an ecosystem's biotic and abiotic elements are crucial for the ecosystem processes. These processes and services are influenced by natural factors, including seasonal and climate changes, as well as human actions such as the use of chemicals, waste production, changes in land use, and the management of water quality (US EPA, 2024).

2.3 The Ecosystem of the Port of Rotterdam

The ecosystem and ecosystem services concepts used in this research are explained in the previous paragraph. However, this is not specified in the context of the Rotterdam port. The following paragraphs elaborate on the context-related ecosystems that are present in the port. There are multiple ecosystems within the Port of Rotterdam, such as industrial, innovative, and natural ecosystems. As the ecosystems of a port are interrelated with the natural ecosystem, one always impacts the other (EcoShape, 2020).

2.3.1 Natural Ecosystem

The Port of Rotterdam is an industrial system built around the Maas River and delta region, using its natural resources to foster its growth (Hollen et al., 2014). The port consists of different water bodies, from sweet water from the Maas River to salt water at the Maasvlakte. The Nieuwe Maas is a delta river that flows into the sea, forming part of a unique freshwater-saltwater transition with a large brackish water zone (Van Herk et al., 2020). The *natural ecosystem* plays a crucial role in various aspects of the port's functioning, from facilitating the transportation and handling of goods to supporting the livelihoods of those who work there. The natural ecosystem in the Port of Rotterdam can also be defined as a *coastal ecosystem* because of the geographical context of the ecosystem. The port is part of a coastal ecosystem with many external factors. As the port is close to the port city of Rotterdam, the coastal ecosystem is vulnerable due to urbanization (Piccolo, 2021).

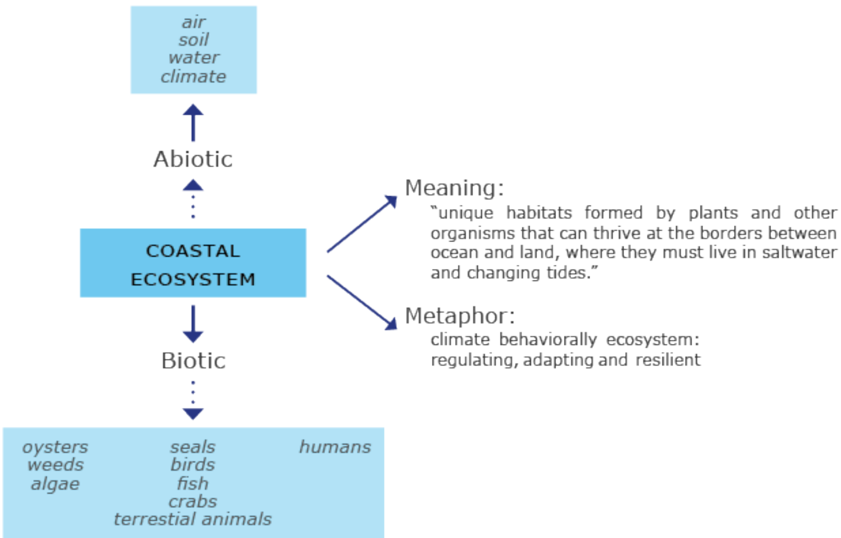

Figure 4: Coastal ecosystem in the Port of Rotterdam (Nepf et al., 2021)(Port of Rotterdam, 2022), own visualization

Within the port, there are more than 200 different flora and fauna species (Port of Rotterdam, 2022). The life under water is most interesting in the port area due to the different waterbodies and water flows. Because of the open connection between the hinterland and the sea, the port is not only an ideal migration route for migratory fish but also makes a perfect spawning and nursery area for thousands of fish (Port of Rotterdam, 2022). Originally, the coastal landscape is formed from the interaction between land and sea, making it a nutrient-rich and highly productive ecosystem. Nutrients and sediment are transported through wind, waves, tides, and water flow from hills to the ocean. Each habitat plays a unique role and provides specific functions.

However, numerous coastal habitats are altered by human activities, especially ports. Therefore, ports can be fit under the term 'heavily modified water bodies', which are surface waters that are significantly altered by human activity, preventing them from achieving good ecological status (Ondiviela et al., 2013). The pollutants released in ports encompass greenhouse gases such as carbon dioxide (CO^2), oxides of nitrogen (NOx) and sulfur (SOx), methane (CH4), and particulate matter (PM) (United Nations, n.d.). However, air pollution is not the only pollution caused by port activities, the water quality is impacted as well. Port operations can significantly impact the quality of the water, and together with waste from the ships, marine life is harmed. This can lead to habitat loss or degradation (US EPA, 2023) and thus negatively impact the coastal ecosystem. Over the past 50 years, coastal ecosystems have undergone significant transformations due to natural and human activities, which have often altered multiple habitats and caused cascading effects. Human activities, driven by commercial interests in coastal development, have rapidly accelerated the degradation of these ecosystems (Gupta & Nair, 2012). In response, the ESPO has published its Top 10 Environmental Priorities for European ports (ESPO, 2024), which are linked to the SDGs (Jansen, 2023). These priorities aim to mitigate the impacts on heavily modified water bodies in ports and work towards creating sustainable ports. Future transformations in these areas are focused on restoring rather than compromising coastal habitats and natural ecosystems. Restoring heavily modified water bodies in ports is critical for achieving sustainability, as it enhances ecosystem services essential for mitigating environmental impacts and promoting long-term ecological health.

Ports play a crucial role in linking marine ecosystems with human economic activities. *Marine ecosystems*, including seas and coastal zones, are vital habitats providing essential human well-being services. Balancing economic and ecological interests in port development and operations will be one of the biggest challenges in the next decade. Sustainable interactions between human society and marine ecosystems are essential to maintain the continuous provision of ecosystem services, highlighting the need to protect these environments and promote sustainable practices (Bruckmeier, 2016). Thus, ports must integrate ecological considerations into their development plans to ensure that economic growth does not come at the expense of the invaluable services provided by marine and coastal ecosystems.

2.3.2 Towards an Innovation Ecosystem

From a historical point of view, the port and the city have had a symbiotic relationship, with the port relying on the city's resources for handling goods and passengers, and the city benefiting from the consumption and transportation of overseas goods. Although there were instances of resource exploitation and environmental degradation, they were widely accepted in exchange for economic growth (Jansen & Hein, 2023). However, the Port of Rotterdam now emphasizes that while economic progress is important, it should not come at the expense of nature, the environment, and the living conditions in the port industrial area (Port of Rotterdam, 2023).

The Port of Rotterdam sees its sustainability challenges as an opportunity and is actively positioning itself as a leading global maritime hub to flourish as an *innovation ecosystem,* which is seen as the evolution of a business and economic ecosystem (De Vasconcelos Gomes et al., 2018; Port of Rotterdam, n.d.-e). The definitions of an innovation ecosystem differ, however, they all emphasize the close relationship and interdependence between stakeholders (Andriamanantena et al., 2022). It is challenging to organize this ecosystem in the complexity of a port (Buitendijk & Buitendijk, 2019). An innovation ecosystem includes economic players and non-economic factors like technology, institutions, social interactions, and culture.

These non-economic elements support creating, introducing, and spreading ideas and innovations (Mercan & Göktas, 2011). Additionally, innovation ecosystems are closely related to innovation clusters (Witte et al., 2018) as multiple actors come together, develop collaborative relationships, and share resources and knowledge to create value (Andriamanantena et al., 2022). The Port of Rotterdam plays a central role in an innovation ecosystem by serving as a hub for economic activities, technological advancements, and collaborative efforts. As it is one of the world's largest and busiest ports, it is a key economic driver, attracting many businesses and industries. This creates a dynamic environment where innovation is crucial for maintaining competitiveness and efficiency (InnovationQuarter, 2016; Buitendijk & Buitendijk, 2019; Rodrigue, 2020). To stay ahead, the port invests in new technologies like automation, digitalization, and sustainable practices, fostering further innovation and development (Port of Rotterdam, 2023).

Additionally, the port encourages collaboration among stakeholders to facilitate the exchange of ideas, resources, and expertise necessary for innovation (InnovationQuarter, 2016; Buitendijk & Buitendijk, 2019). It hosts a culture of innovation and openness to new ideas at the port and promotes continuous improvement and adaptation (Port of Rotterdam, 2023). As a global trade hub, the port connects to international markets, spreading innovative practices and technologies, and enhancing its role in the global innovation ecosystem (Buitendijk & Buitendijk, 2019).

2.3.2 Towards an Industrial Ecology

With large industrial complexes and challenges regarding international competitiveness, the Port of Rotterdam is working towards meeting sustainability targets and improving its environmental performance (Hollen et al., 2014). As the Port of Rotterdam is working towards a sustainable system and aims for an innovation ecosystem, the industrial activities shift towards an *industrial ecology* (Port of Rotterdam, 2023). In this industrial ecosystem, the port's operations heavily depend on the availability of natural resources such as minerals, fossil fuels, and freshwater, which are essential for manufacturing and production. However, these industrial activities also produce emissions and waste that can negatively impact natural ecosystems (Gopalakrishnan et al., 2016). This mutual dependency highlights the need for ecosystem services, such as air and water quality regulation, to mitigate the environmental impact of industrial emissions. In urban contexts, this can be achieved by ecological engineering, which is defined as "the design of ecosystems for the mutual benefit of humans and nature" and can be met through NbS (*Ecological Engineering*, 2024). This concept is further elaborated on in the 'Building with Nature' paragraph. Within the industrial context of the port, a heavily modified water body, ecological engineering fits within the concept of an *industrial ecology*.

Industrial ecology focuses on achieving sustainable industrial development in specific geographic regions (Ashton, 2009). This is an approach to environmental management that seeks to make industrial processes and environmental sustainability work together without harming each other. It aims to reduce waste and pollution in industry. This concept looks at how industrial and natural systems interact and exchange resources over time. It focuses on how to balance human development with the environment, ensuring sustainable growth. The goal is to optimize the use of resources, energy, and capital throughout the entire lifecycle of a product, from raw materials to disposal, to achieve sustainability (Kapur & Graedel, 2004; Mitra et al., 2023; El-Haggar, 2007). As the Port of Rotterdam is moving towards a sustainable and circular industry in 2050 (Port of Rotterdam, n.d.-b), it can be said that the port aims to achieve an industrial ecology. Using this ecological metaphor, regional industrial ecosystems' development can resemble natural ecosystems' development (Ashton, 2009).

The innovative and industrial ecosystems differ in meaning and metaphor from the natural ecosystem in the Port, the following figure provides an overview of these metaphors:

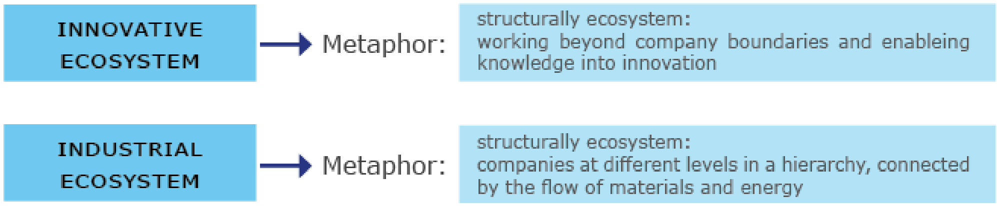

Figure 5: Innovative and industrial ecosystem metaphors (Auerswald & Dani, 2018)(Ashton, 2009). These ecosystems are an example of an ecosystem that is replicable to a natural ecosystem as it consists of various factors that mutually influence each other, forming a complex and functioning system.

2.4 Building with Nature Concept

As port industries are directly connected to natural ecosystems, emphasizing the importance of supporting the natural ecosystems is important. Ecological initiatives can maintain these ecosystems and their services as they provide quality and connectivity of coastal areas in urbanized land-seascapes (Aguilera et al., 2023). These initiatives in industrial and urban areas can be supported by ecological engineering with nature-based solutions.

NbS include innovative approaches while working with nature to find solutions for sustainability challenges, preserving biodiversity and ecosystem functioning (Martín et al., 2020; Xie et al., 2022; IUCN 2020). NbS have gained increasing popularity in European cities (Frantzeskaki, 2019; Smith et al., 2021) and serve as a powerful tool for addressing multiple challenges within the same solution (Smith et al., 2021). According to Seddon (2020), the success of nature-based solutions depends on the type and condition of the ecosystem where they are implemented, which interventions are used, how they are implemented, and who benefits from them. The availability of land and sea areas is important for NbS to flourish. Even if there is enough space for nature-based solutions, human activities can harm the health and resilience of ecosystems and their ability to deliver ecosystem services. However, using NbS builds gives room to innovate or adapt to changing conditions (Seddon, 2020), they represent a 'living innovation ecosystem' (Van Der Jagt et al., 2020).

Developing NbS for water-related infrastructures, such as sustainable development of ports and ecosystem restorations follows the *Building with Nature concept* (BwN). This is an innovative design approach that contributes to industrial ecology and aims to achieve an ecological balance and work with nature instead of against it. When it comes to water-related infrastructure and the environment, the focus should shift from reducing negative environmental impacts to creating positive effects through optimization, rather than just aiming for neutrality through compensation. (Wilms et al., 2020; EcoShape, 2021). Wilms et al. phrase the BwN concept as: "A paradigm shift: from 'building in nature', via 'building of nature', to 'building with nature'." (2020). The BwN approach, created by Ecoshape, proposes that NbS can be a sustainable and cost-efficient alternative to traditional engineering approaches (Taneja et al., 2020). The Netherlands is currently implementing the BwN method and ecological engineering concepts widely to manage its extensive coast and rivers (Wilms et al., 2020).

The concept of BwN can help address issues in port and delta cities by combining ecological, economic, and societal benefits. It involves solutions that can minimize the environmental impact of port infrastructures, promote the growth of marine life, mitigate flood risks, and enhance sediment management (EcoShape, 2020). Besides the physical and ecological conditions, it is also important to research the system of interest: human activities, and governance processes, to fully understand the ability to implement BwN solutions. Additionally, it is important to interact with the relevant stakeholders (EcoShape, 2020), especially in ports with numerous stakeholders involved.

The BwN concept has a five-step approach (EcoShape, 2020b) that needs to be taken when developing BwN designs, the steps are:

1. *Understand the system:* create a deep understanding of the physical, socio-economic, and governance systems involved. It is important to not only consider the most important goals, as this can limit the scope of the system. Conduct various sources when obtaining information about the system (EcoShape, 2020b), in this context the Port of Rotterdam.

2. *Identify alternatives:* Explore realistic, eco-friendly alternatives that offer win-win solutions. Include the ecosystem services that can strengthen the functioning of a system and explore if the locally active (natural) resources can be used. Within the BwN approach, solutions are transdisciplinary from the beginning. Therefore, include different stakeholders and experts on the system and potential BwN solutions.

3. *Evaluate alternatives:* Assess and select the best option that integrates all system dynamics. Search for creative and innovative ideas, these can be little investments as well. Small adjustments to an existing design or system may produce more value and involve stakeholders to shift perceptions from resistance to support.

4. Elaborate on the solution: Develop the selected solution, considering practical constraints. When elaborating on selected alternatives, consider practical constraints like project conditions, execution methods, and timing, ensuring ideas are feasible for construction. Engage stakeholders in the design and realisation process.

5. Prepare implementation: Address practical challenges to ensure successful implementation. To move a solution towards realization, address practical barriers by translating the idea into a design. Ensure funding and understand the permitting requirements early in the process. Collaborate with stakeholders throughout the process.

The following figure visualizes the interrelationships between the theories and concepts in this thesis:

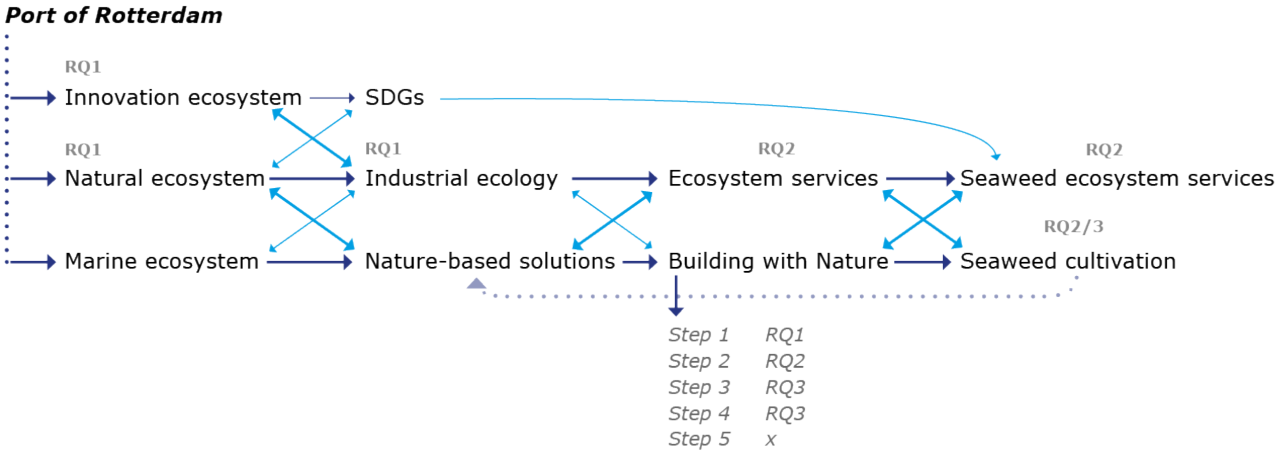

Figure 6: Interrelationship of the used theories and concepts in this research, own visualization

This thesis proposes seaweed cultivation as an exploratory nature-based solution in the Port of Rotterdam as it fits well in the theories of NbS and BwN. Seaweed cultivation is a concept that fits within the theories addressed as it is a nature-based solution that enhances ecosystem services, aligns with sustainable and innovative practices, integrates ecological and economic benefits, and offers adaptability to changing conditions, which are key principles of the NbS and BwN concepts.

3. THE ART OF SEAWEED CULTIVATION

3.1 The Characteristics of Seaweed

Societies have used seaweed as a service since the early days. Throughout history, coastal communities have been harvesting various types of seaweed from all algal groups. These communities used seaweed primarily for domestic purposes such as food and feed. However, in later years, seaweed also gained new purposes besides consumption. Currently, seaweed is a natural resource for industrial uses such as biomaterials, fertilizers, bioplastics, fuel material, and much more (O'Connor, 2017; WUR, 2024). Additionally, seaweed serves as a valuable source of food and natural products for several industries, offering a nature-based approach to mitigating and adapting to climate change and improving biodiversity loss. Additionally, seaweed holds the power to detoxify polluted aquatic habitats in industrial environments by absorbing metals (Duarte et al., 2021). These characteristics of seaweed make it an interesting natural resource for introducing innovative NbS in the Port of Rotterdam.

Farming seaweeds in marine environments for food, feed, or fuel has the potential to preserve significant amounts of natural land from being converted to managed land and release existing agricultural land for restoration efforts (Spillias et al., 2023). Additionally, dried or processed seaweed is valuable for insulation, fire-resistant materials, and furniture, supporting the increasing demand for natural, durable, and biodegradable materials (Duarte et al., 2021).

The benefits of seaweed cultivation are numerous and diverse and in addition, people use it to contribute to achieving several SDGs. It generates sustainable livelihoods for small-scale farmers and harvesters, which helps reduce poverty (SDG 1) and boost food and nutrition security (SDG 2). Additionally, seaweed cultivation helps overcome global environmental challenges regarding climate and biodiversity loss. (SDGs 7, 13, 14). Furthermore, seaweed cultivation creates new job opportunities, helps diversify income, and promotes local businesses (SDG 8). Moreover, seaweed can serve as a unique biomaterial for commercial use (SDG 12)(United Nations, 2024).

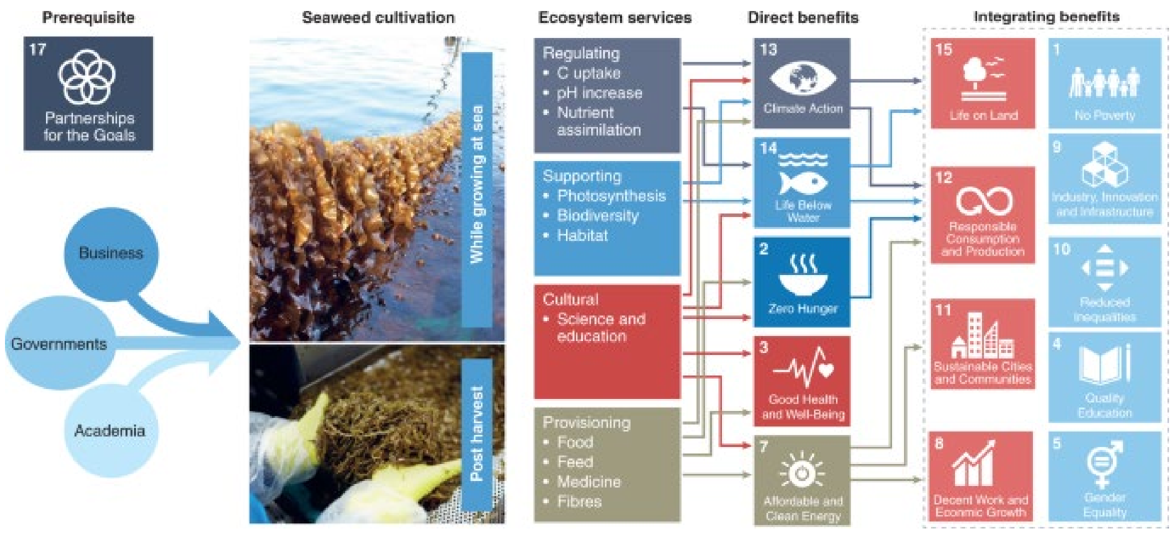

Figure 7: "Direct and Indirect Benefits of Seaweed Cultivation" (Duarte et al., 2021)

Figure 7 shows the direct and indirect benefits of seaweed cultivation. Additionally, according to this figure, the prerequisite for seaweed cultivation as a means of ecosystem services is a partnership between businesses, governments, and academia. This shows that the success of seaweed cultivation as a means of providing ecosystem services depends on the collaboration and interconnected efforts of these stakeholders, functioning as an ecosystem where different components mutually influence each other (McManus, 2009). "Partnerships are crucial for overcoming barriers in seaweed cultivation. There are misunderstandings about the benefits of seaweed farming and its impact on coastal ecosystems. Therefore, it is essential to form partnerships among various stakeholders to expand awareness and promote the sustainable use of seaweed cultivation (Duarte et al., 2021).

3.2 Seaweed ecosystem services

This research studies the possibility of seaweed cultivation as NbS in the Port of Rotterdam. Therefore, it is important to understand the ecosystem services of seaweed. Generally, the primary purpose of seaweed aquaculture is to deliver provisioning services. In the past, the focus on provisioning services only contributed to the decline of other ecosystem services. However, the benefits of seaweed cultivation enhance all categories within the ecosystem services framework. Cultural services are the hardest to define due to their place-specific nature (Clark et al., 2021). The educational values within cultural services and education-related projects on marine ecosystems are becoming more popular within the European Union. (Cotas et al., 2023). Additionally, as shown in Figure 7 in the second chapter, involving academia is a prerequisite when using seaweed to reach certain SDGs.

The ecosystem services provided by seaweed aquaculture according to literature are summarized in the following table, together with other literature on seaweed ecosystem services:

Table 1: Ecosystem services of seaweed cultivation (Clark et al., 2021; Cotas et al., 2023; SeaMark, 2023)

Seaweed ecosystem services	
Provisioning	Regulating
Food: For human consumption *Raw materials* *Biomass:* Fertilizer, biofuel, biogas, medicine, and biomedical products	*Bioremediation of waste:* Removing pollutants from waters through storing, burial, and recycling *Soil formation:* Increase environment quality for aquatic plants *Gas and climate regulation:* Carbon sequestration, carbon storage, pH regulation, coastal protection *Nutrient and water cycling* Water purification, seawater balance, improving water quality *Eutrophication mitigation* *Production of oxygen by photosynthesis*

Supporting	Cultural
Habitat provision: Habitat provided by marine organisms and farm structures *Resilience and resistance:* The extent to which ecosystems can work with disruptions and recover without degrading or changing drastically. *Coastal protection:* Farm structures and marine organisms defend the coastal zone	*Tourism and recreation* *Cognitive development:* Science, education, research, pilot-scale experiments *Non-use benefits* *Sense of place and livelihood:* employment opportunities, alternative income

3.3 What is Needed for Seaweed Cultivation?

3.3.1 Environment

There are environmental conditions that need to be taken into account when choosing a site for seaweed cultivation, such as light, water quality, salinity, and water temperature (Clark et al., 2021). Light is essential for the photosynthesis process of seaweed which is important for its growth. Deeper water with high turbidity can negatively influence growth and productivity, such as a fluctuating salinity (Clark et al., 2021). Seaweed can absorb nutrients from the water, such as nitrogen and phosphorus. Increased quantities of nutrients have the potential to accelerate growth, making on-land cultivation more attractive in coastal regions with modest nutrient levels (Clark et al., 2021). Additionally, different seaweed species thrive in different temperatures, it can impact the growth and overall health of the seaweed (Cai et al., 2021).

3.3.2 Policy for Seaweed Cultivation

To start cultivating seaweed a permit or license needs to be granted by the public authorities. The use of space at sea is regulated by laws for marine planning from the EU Maritime Spatial Planning Directive or similar laws. However, the development of shore-based farms and support facilities for offshore farms are controlled nationally (Genialg, 2021). Overall, the European Union does not have clear regulations on seaweed cultivation yet. However, its potential does not stay unseen (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). The document '*Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030'* states that seaweed cultivation can provide climate mitigation and adaptation services besides commercial purposes, such as nature-based coastal protection, when subject to the right framework. The European Commission & Directorate-General for Maritime Affairs and Fisheries want to promote new types of aquaculture as this sector "is still far from reaching its full potential" (2021). The strategic guidelines document highlights the importance of different types of aquaculture that can preserve natural ecosystems and provide protective services against climate change, such as seaweed. It calls for new legislation to meet the opportunities of the aquaculture sector (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). The Maritime Spatial Planning Directive also states that maritime development and seaweed aquaculture should be based on an ecosystem approach. They emphasize that regulations on the EU level are missing and that this is one of the main obstacles to the rise of seaweed aquaculture (Camarena Gómez et al., 2024).

There currently are different certificates that are applicable for seaweed farmers. The most prominent is the ASC-ASM Seaweed Standard certification which validates seaweed sustainable efforts all around the world. It is the first international standard that certificates for good social and environmental practice and is a key certificate to prove sustainability (CBI, 2022; European Climate, Infrastructure and Environment Executive Agency & Directorate-General for Maritime Affairs and Fisheries, 2017). Second, the IFA standard is a global standard that covers the entire production chain of seaweed cultivation and ensures responsible farming practices (European Climate, Infrastructure and Environment Executive Agency & Directorate-General for Maritime Affairs and Fisheries, 2020). In the EU, there are strict regulations for using seaweed as a resource for human products regarding contamination. To enter the market it is necessary to comply with the safety requirements (CBI, 2022).

Figure 8 below visualizes the steps of aquaculture policies from 2013. The EU aims to address the policy gap caused by differences within the EU in obtaining aquaculture farming licenses and so level the playing field for aquaculture activities (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021).

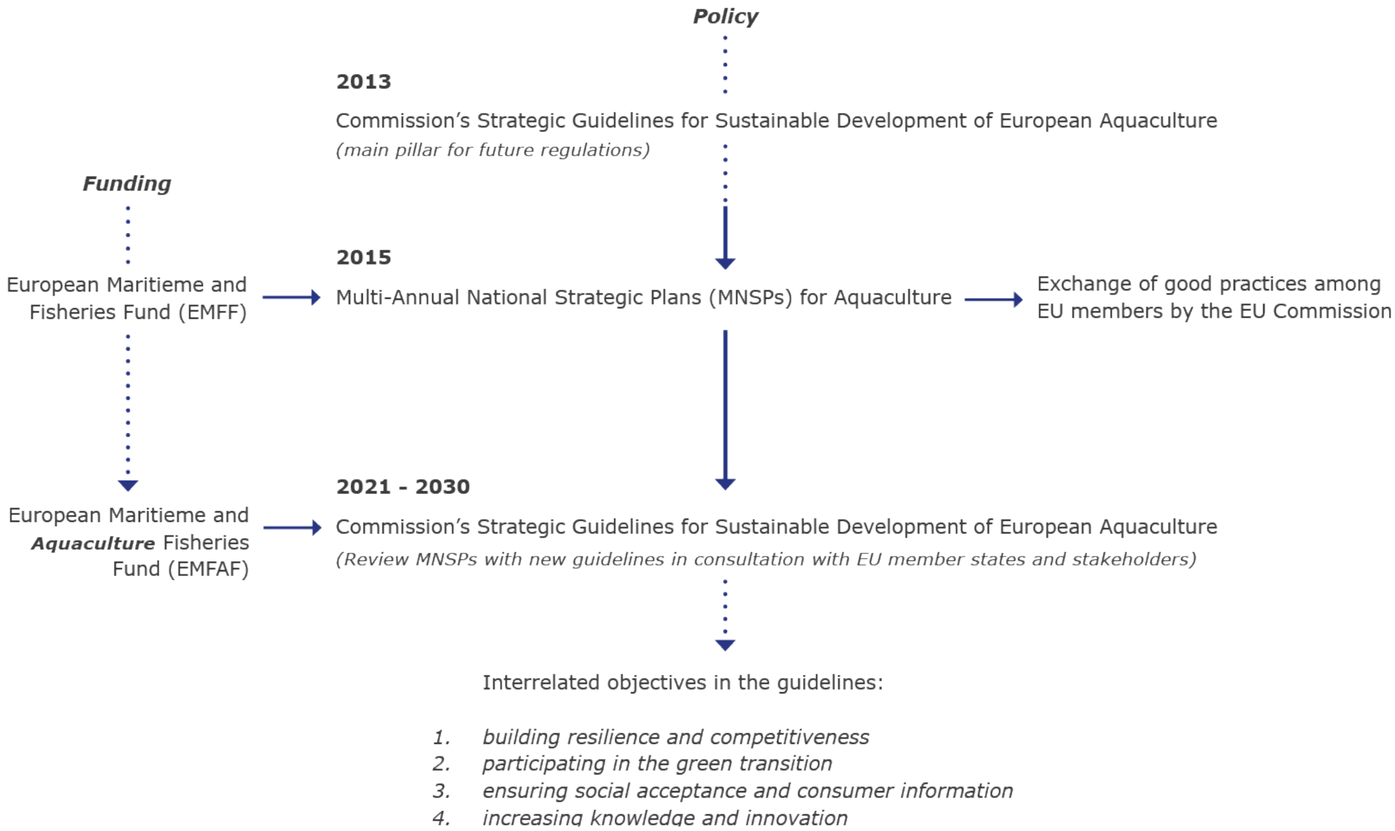

Figure 8: Policy and regulations European aquaculture. This figure shows the timeline of the different policy documents in the European Union regarding aquaculture and how it is funded. The most recent document highlights the interrelated objectives included in the guidelines that need to be followed to achieve the Commission's vision.

There are four key interrelated objectives in the EU Commission's strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. The first objective, *building resilience and competitiveness,* focuses on strengthening the sector's ability against economic and environmental challenges while improving its market position. The second objective, *participating in the* *green transition,* involves adopting sustainable practices, mitigating environmental challenges, and aligning with the European sustainability goals. The third objective, *ensuring social acceptance and consumer information*, is about being transparent and gaining the public's trust by ensuring that the consumers are well-informed about products and services. The final objective, *increasing knowledge and innovation*, emphasizes the importance of research and creating a framework that brings different disciplines and stakeholders together for the continuous improvement of practices. In this framework, the development of innovation clusters for sustainable aquaculture should be included (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021).

Narrowing down to the Dutch aquaculture sector, seaweed is relatively new and when cultivated, it is for food purposes only. Commercially cultivated seaweed has been on the Dutch market since 2013 (European Climate, Infrastructure and Environment Executive Agency & Directorate-General for Maritime Affairs and Fisheries, 2023). However, the North Sea Farmers is a Dutch company that recently has been invited by the members of the House of Representatives to discuss innovations regarding aquaculture and to show the benefits of seaweed cultivation. The possibilities of scaling up seaweed cultivation in Europe were also discussed (North Sea Farmers, 2024), this shows a growing interest within governmental organizations.

3.3.3 Process of Cultivating Seaweed

Seaweed can be cultivated onshore, offshore, or integrated with other aquaculture practices. Onshore cultivation utilizes tanks and ponds with pumped coastal seawater (Ould & Caldwell, 2022). Offshore cultivation, involving floating nets or ropes with seaweed at the surface (off-bottom) or anchored to the sea bottom, is more vulnerable to environmental changes and has a higher risk of loss due to storms. In deeper waters, 'off-bottom' cultivation is more common as it keeps the seaweeds near the surface where they are subject to more light (Theuerkauf et al., 2021). These offshore methods are primarily used for biomass and food production (Ould & Caldwell, 2022). Offshore structures are more vulnerable to environmental changes, have a higher risk of loss due to storms, and are primarily used for biomass and food production. Additionally, the logistics, costs, and infrastructure make it a challenging cultivation method (Brandenburg, 2016).

After cultivating seaweed, the next step involves harvesting the biomass and processing it in a refinery. In the refinery, the harvested biomass transforms various bioproducts. These bioproducts could include many valuable and sustainable materials, such as bioplastics, biochemicals, and even food products. Additionally, the possibility of using seaweed as a biofilter is becoming more popular. However, the Dutch seaweed market is still exploring different uses of seaweed's biomass besides the food industry. (Brandenburg, 2016; Ministry of Agriculture, Fisheries, Food Security and Nature, 2020). This process chain is visualized in Figure 9 below.

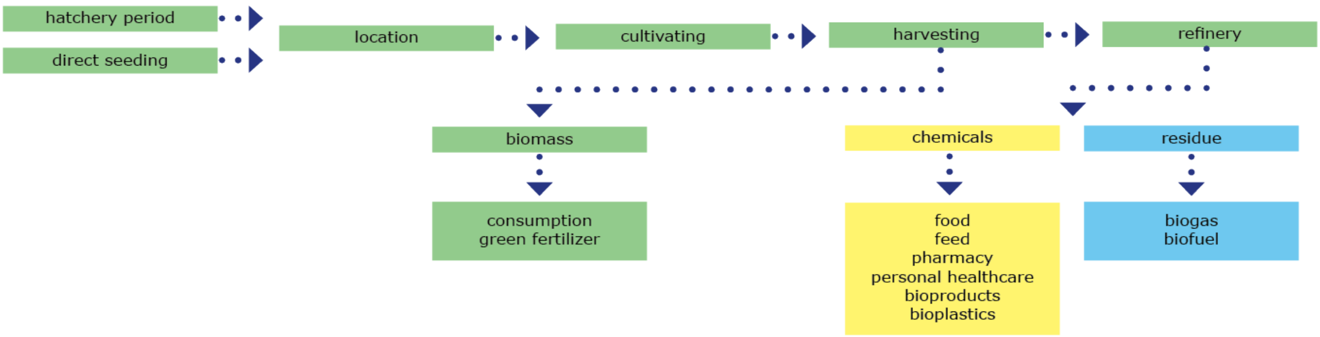

Figure 9: Chain of seaweed cultivation from seeding to bioproduct, data from Brandenburg (2016), own visualization

3.3.4 Stakeholders

There are numerous stakeholders involved in the process of seaweed cultivation, it begins with obtaining a license, having the right resources to cultivate and eventually processing the biomass. The power/interest stakeholder matrix in Figure 10 visualizes how stakeholders in the seaweed cultivation sector relate to each other in the context of power and interest. *Stakeholders* can be defined as a person, group, or organization with some interest in a project. This can be from a partitioning, supportive, or influencing role. Additionally, they can bring value and sometimes carry responsibilities towards the project. For each project, different stakeholders are involved and their role differs (Pirozzi, 2019).

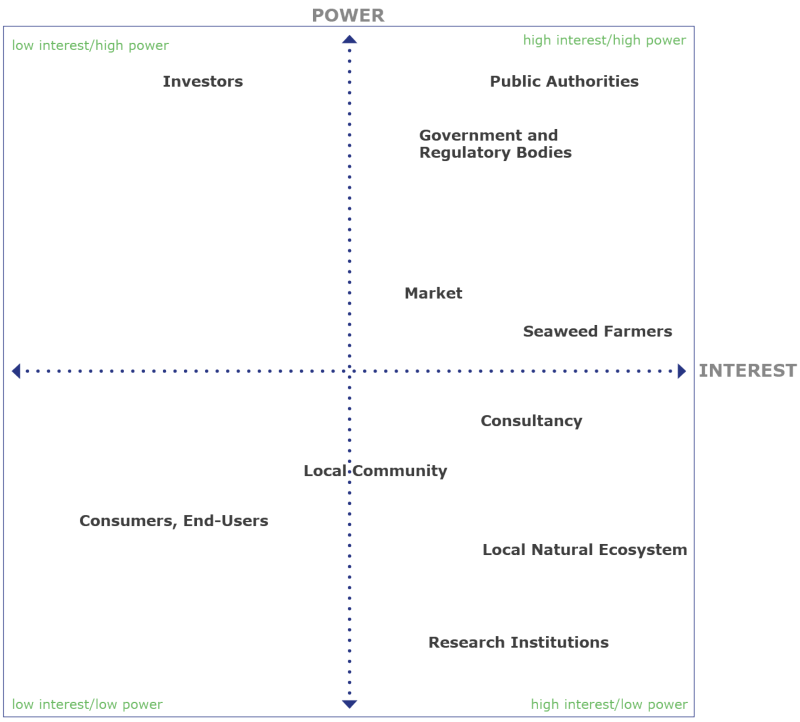

Figure 10: Power/interest matrix of the stakeholders involved in the seaweed cultivation process

3.4 Seaweed Species in the Netherlands

The most common and promising seaweed species in Europe and (the Netherlands) include Ulva Lactuca (*Sea Lettuce),* Laminaria digitata (*Oarweed)*, Palmaria (*Dulse)*, and Saccharina latissima (*Sugar Kelp*). The table on the next page elaborates on the different qualities of the species.

Table 2: Different qualities of the species Ulva Lactuca, Laminaria digitata, Palmaria, and Saccharina latissimi (Lubsch & Timmermans, 2019; Reith et al., 2005)

Species	**Characteristics**	**Growth Conditions**	**Temperature in degrees**	**Nutrient uptake**	**Cultivation method**	**Common use**
Ulva Lactuca *(Sea Lettuce)*	Green macroalgae with thin, sheet-like fronds Rapid growth in nutrient-rich waters	Nutrient-rich waters Marine and brackish environments Moderate to high light conditions	10-20 °C	High phosphate and nitrate	Ropes or nets hanging on the water column	Human consumption Animal feed Bioremediation Biofuel production
Laminaria digitata *(Oarweed)*	Brown macroalgae with long, leathery fronds Prefers cold, nutrient-rich waters	Nutrient-rich waters	5-18 °C	Moderate nitrate	Lines anchored to the seabed/ floating at the surface	Food industry Animal feed Fertilizers Cosmetics Biofuel production
Palmaria *(Dulse)*	Red macroalgae with fan-like fronds	Rocky substrates and strong water movements Moderate to high light conditions	5-15 °C	Moderate nutrient uptake	Attached to nets or ropes for cultivation	Food industry
Saccharina latissimi *(Sugar Kelp)*	Brown macroalgae with long, broad fronds	Grows sheltered, medium wave exposure	5-15 °C	High nitrate	Grows on lines or ropes	Food industry Supplements Biofuel production Fertilizer

4. METHODOLOGY

The methodology chapter outlines the research approach and techniques employed to investigate the potential of seaweed cultivation as an NbS within the Port of Rotterdam. This research, grounded in an ecosystem services framework and the Building with Nature concept, provides a recommendation for the Port of Rotterdam about the feasibility of integrating seaweed cultivation in the port, motivated by a literature review and interviews with experts. This thesis employs a qualitative research methodology integrating a comprehensive literature review and semi-structured interviews. This study provides a strong base for further investigation and incorporation of cultivating seaweed in the Port of Rotterdam. The outcomes of the RQs offer a thorough understanding of the potential of seaweed cultivation as a nature-based solution in the port, and how this is feasible by outlining the enabling and constraining factors.

To evaluate the sustainability of the port's ecosystems comprehensively, the study consistently uses the ecosystem services framework and the Building with Nature concept to answer the research questions. Therefore, the research questions aim to answer the different BwN steps as outlined in the theoretical framework. Altogether, the RQs aim to provide a comprehensive overview of the feasibility of seaweed cultivation as an NbS within a BwN approach in the context of the Port of Rotterdam.

This thesis emphasizes the Port of Rotterdam as a case area. The Port of Rotterdam is the largest in Europe and is focusing on becoming climate-neutral by 2050. Its strategy aligns with several SDGs and is outlined around three priorities: economic transition, social transition, and creating an attractive region. The port emphasizes the need for economic progress that does not harm the environment, integrating nature conservation with industrial development to create a resilient ecosystem by 2030.

4.1 Data collection methods

Figure 11 below visualizes the research steps. All sub-research questions are addressed by the same approach: a combination of literature review and semi-structured interviews with experts. Following the literature review and semi-structured interviews, a qualitative comparative study is conducted that outlines the findings of RQ1, RQ2, and RQ3. This creates an understanding of how seaweed cultivation can serve as NbS in the sustainability strategy of the Port of Rotterdam.

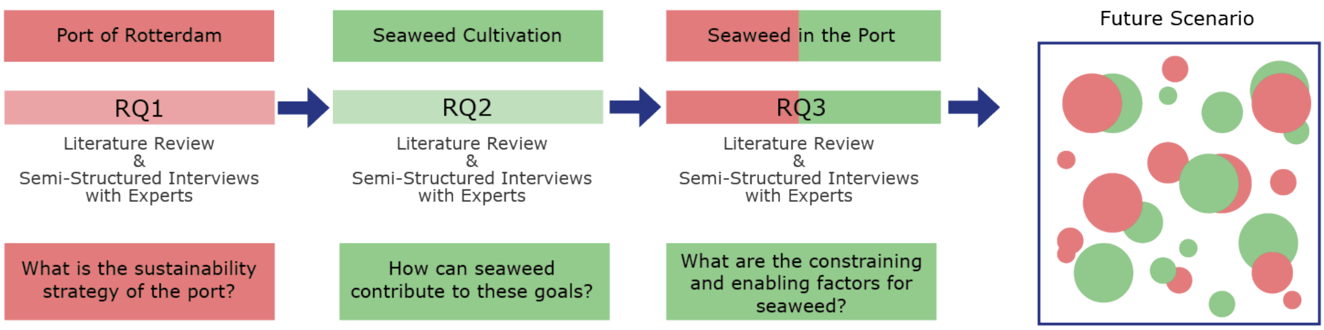

Figure 11: Research Roadmap, own visualization

4.1.1 Semi-structured interviews

The research questions were answered by literature review and semi-structured interviews, these interviews were online and on-site. Researchers can gain insights into individual experiences through interviews that might not have been possible with different research approaches (ATLAS.ti, 2024). The experts introduced in this research are different stakeholders who are affiliated with seaweed cultivation or the Port of Rotterdam. As shown on page X, there are different stakeholders involved in the process of cultivating seaweed. A total of 43 connections were made which led to 12 interviews with different parties through the snowball sampling method. This is a qualitative method that relies on networks and connections within a certain research theme and helps the researcher find potential participants (Stewart, 2024). During the process of interviewing, more connections were established by the 'snowballing' effect, this created a strong group of experts relevant to this research. The length of the interviews was between 30-50 minutes, all interviews were recorded with consent and were sent official consent forms before publishing this thesis. The following table describes the interviews and interviewees:

Table 3: List of interviews with a description of the interviewees' background

Expert #	Date	Company	Company description	Function/Expertise
Expert 1	11-04-2024	Hortimare	Breeding and propagating seaweed, supply of starting material and expertise in seeding methods and hatchery technology	Sales Manager
Expert 2	16-04-2024	SINTEF	One of Europe's largest independent research organisations	Ocean Researcher
Expert 3	11-04-2024	Dutch Seaweed Group	Innovative partner in seaweed	Operations and Cultivation
Expert 4	15-05-2024	WUR	Wageningen University	Projectmanager / Researcher
Expert 5	22-04-2024	Holdfast and Stipe	Specialize in the refining power of seaweed	Owner
Expert 6	29-05-2024	Port of Rotterdam	Company Port of Rotterdam, largest port in Europe	Nature and Environmental advisor
Expert 7	17-06-2024	Port of Rotterdam	Company Port of Rotterdam, largest port in Europe	Social Innovation
Expert 8	15-04-2024	Port of Rotterdam	Company Port of Rotterdam, largest port in Europe	Electrification & Hydrogen
Expert 9	15-04-2024	Port of Rotterdam	Company Port of Rotterdam, largest port in Europe	Business Manager Circular Economy
Expert 10	26-06-2024	DCMR	Environmental protection agency	Wastewater
Expert 11	24-06-2024	DCMR	Environmental protection agency	Senior Policy Advisor in sustainable development and circular economy
Expert 12	24-06-2024	DCMR	Environmental protection agency	Policy Advisor

The interviews are coded with the software ATLAS.ti, a tool that easily organizes and analyses qualitative data. The qualitative interviews result in unstructured data, which needs to be systematically organized to facilitate relevant insights in this research (ATLAS.ti, 2024). This thesis works with thematic analysis coding, which is about finding themes within data revolving around different concepts and finding patterns. Within a theme, there are multiple occurrences or similar results that seem important. (ATLAS.ti, 2024). This thesis focuses on different themes when coding the data, the overarching themes are *sustainability in the Port of Rotterdam, qualities of seaweed*, *SDGs Port of Rotterdam, innovation ecosystem, and key elements for cultivating seaweed.*

4.1.2 Literature review and data analyses

A literature review helps identify the scope of what has been studied and is essential for answering research questions since it places a study in the context of existing knowledge and highlights gaps for further research (Hart, 1998; Machi & McEvoy, 2016). It helps design better research, adds credibility, and ensures the study builds on previous work instead of repeating it (Ridley, 2012). This research partly answers all RQs through a literature and policy review. The academic search engine Google Scholar was used to find the right literature and grey literature was considered to complement the insights gained from academic papers.

The terms used in Google Scholar were *seaweed cultivation, seaweed species Netherlands, seaweed ecosystem (services), seaweed and SDGs, marine ecosystem, innovation ecosystem (port), ecosystem services framework, potential of nature-based solutions, nature-based solutions in ports, nature-based solutions innovation ecosystem, building with nature concept, (future of) coastal ecosystems, human impact coastal ecosystem, ports and natural ecosystem, sustainable industrial development, ecosystem services (port), carbon sequestration seaweed, Port of Rotterdam innovation, Port of Rotterdam pollution, sustainability goals Port of Rotterdam, heavily modified water bodies.*

The grey literature emphasized for this research consists of research reports, statistics, informal communication websites, and governmental and policy documents. The governmental and policy documents used were connected to the *Rijksoverheid (central government), Ministry of Agriculture, Nature and Food Quality, Ministry of Foreign Affairs, and Ministry of General Affairs.* The policy documents used for this thesis are related to *seaweed cultivation and aquaculture in the EU/Netherlands* and were extracted from official European Union/Rijksoverheid web pages.

5. RESULTS

The results chapter provides the results answering the sub-research questions. The first question starts with providing a holistic overview of the sustainability strategy in the Port of Rotterdam, followed by multiple paragraphs zooming in on the most important (HAVENVISIE, 2019) sustainability efforts. Additionally, it provides information on the most prominent SDGs in the port and how it is aiming to achieve them. The second question gives insight into how seaweed ecosystem services can be of benefit to the Port of Rotterdam. This section explores the potential functions of seaweed cultivation within an industrial area. Seaweed possesses numerous beneficial qualities, but this section narrows it down to functions within an industrial ecosystem such as the port.

5.1 What are the most important sustainability goals of the Port of Rotterdam and how does it plan on contributing to the SDGs

5.1.1 Biodiversity Initiatives

The Port of Rotterdam is committed to biodiversity through its "Natuurvisie" initiative. Their vision states the importance of considering nature in their development projects, aiming to balance human activity with the environment and compensate for the output of industrial activities. Ecological management includes letting nature thrive on unused lands, using specific mowing techniques to boost biodiversity, combating invasive species, and closely monitoring plant and animal life (Port of Rotterdam, 2022). The port's location supports the migration of species, with "ecological stepping stones" and open waterways aiding fish migrations. They incorporate nature into infrastructure design, encouraging green roofs and evaluating clients' efforts in nature conservation (Expert 6, personal communication, 2024). In the western port areas, key zones focus on nature, forming a green backbone, while the eastern areas still offer ecological benefits. The port protects local natural ecosystems and these actions are part of their broader strategy to create a sustainable and resilient port environment. (Port of Rotterdam, n.d.-g).

5.1.2 Circularity

One key initiative of the port is its aim to become a 'waste-to-value' hub where advanced sorting, large-scale chemical and mechanical recycling, and remanufacturing take place. Additionally, the port aims to support sustainable food production. The port's initiatives are aligned with long-term sustainability goals, including significant CO2 reductions through new circular technologies by 2050. These efforts highlight Rotterdam's commitment to becoming a leader in circularity and sustainability within the industrial sector (HAVENVISIE, 2019)

5.1.3 Climate Change and Energy Transition

According to Expert 7 (personal communication 2024), the biggest challenge the Port of Rotterdam is facing is the energy transition. They are also working on a raw material transition, but this is to a lesser extent. "That energy transition is the biggest challenge, so it's really about efficiency and infrastructure changes from the current energy system, building a new energy system, but also after that new raw materials" (Expert 7, personal communication, 2024).

The Port of Rotterdam Authority has a plan to make the port a key player in the energy transition and ensure its future success. This plan involves three steps to meet climate goals and fit within the overarching four pillars decided by the Port of Rotterdam. First, the industry will implement efficiency measures, using residual heat to warm homes, commercial buildings, and greenhouses, and capturing and storing CO_2 beneath the North Sea. To make this happen, new infrastructure is required to ensure the ability to carry the capacity of the efficiency measures. Second, a new energy system will be established, with electricity and hydrogen playing key roles in making the port sustainable. This will necessitate affordable electricity from renewable sources like solar and wind. Additionally, hydrogen emissions will be stored in depleted gas fields. To become CO_2 neutral it is expected that hydrogen needs to be imported into the port, this requires a solid infrastructure. Third, a new system for raw materials and fuels will be developed, replacing fossil resources with biomass, recycled materials, and green hydrogen. The fourth step is a sustainable port. These four pillars are the foundation of transforming towards a sustainable port

(ESPO & Ecoports Foundation, 2022). Currently, there are over 60 projects in the Port of Rotterdam to reach the four pillars.

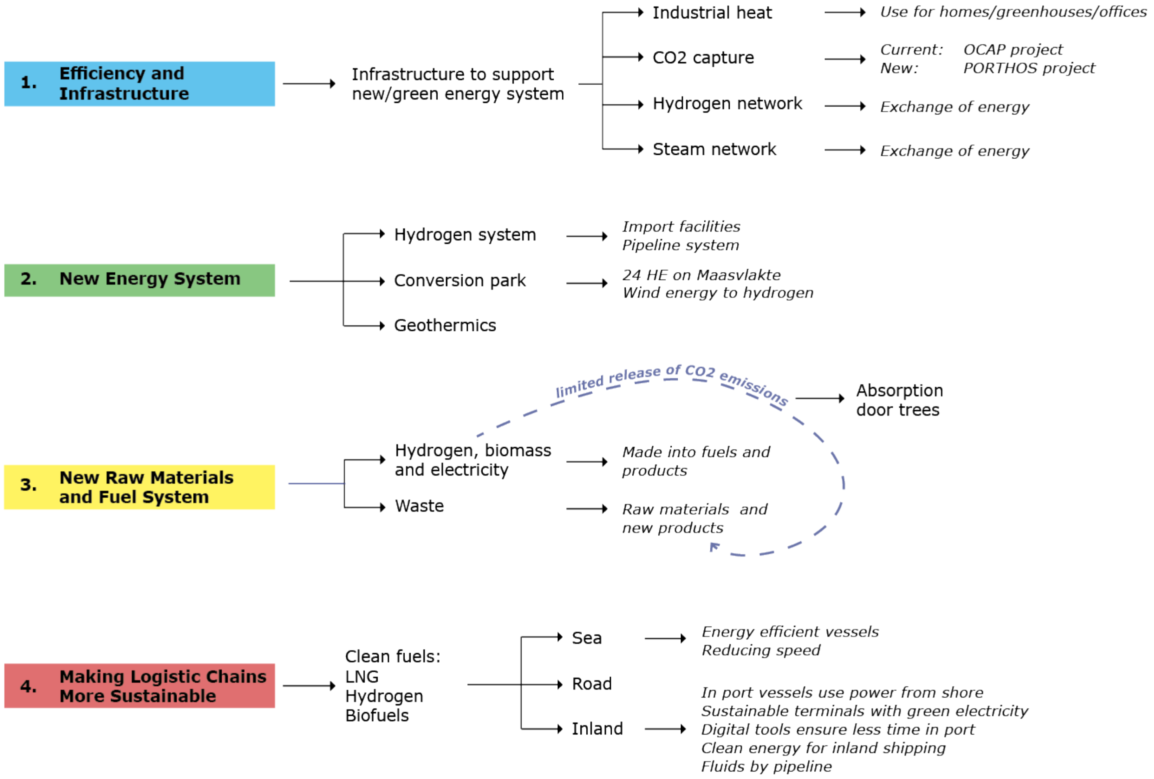

Figure 12: Four pillars towards a sustainable port, Port of Rotterdam (ESPO & Ecoports Foundation, 2022; HAVENVISIE, 2019; Port of Rotterdam, n.d.-a/b/c/e)

5.1.4 CO_2 storage

As the port of Rotterdam needs to become CO_2-neutral as soon as possible, it is working on large-scale CO_2 storage (Expert 7, personal communication, 2024). This sustainability initiative is called PORTHOS where a system is designed to transport and store CO_2 from industries within the port in depleted gas fields beneath the North Sea. Various companies capture the CO_2, which is then delivered to a collective pipeline running through the Rotterdam port area. After that, the CO_2 is pressurized in a compressor station. The CO_2 then travels through an underwater pipeline to a platform in the North Sea about 20 kilometers off the coast. From the platform, the CO_2 is pumped into depleted gas fields located in a sealed reservoir of porous sandstone, three to four km beneath the North Sea. The goal of PORTHOS is to store approximately 37 million tons of CO_2, equivalent to around *2.5 million tons of CO_2 per year for 15 years* (Porthos, 2024).

The PORTHOS project is a continuation of the OCAP project (Appendix 9.1 for infrastructure map), this project currently collects CO_2 from Shell Pernis and supplies it to greenhouses in Westland via an existing pipeline system. This carbon capture and use system in Rotterdam helps reduce emissions by providing pure CO_2 to greenhouses. Since 2005, OCAP has delivered about 400 kton CO_2 per year to 580 growers over 1900 hectares, reducing emissions by approximately 200 kton CO_2 per year by avoiding the need for greenhouses to burn natural gas. With this effort, the port mitigates its marine pollution.

5.1.5 Achieving SDGs

Besides the four pillars, the Port of Rotterdam aims to achieve the SDGs following the climate agreement deal in Paris. On behalf of ESPO, and to align with the global SDGs, the Port of Rotterdam published its Port Environmental Review System (PERS) report that covers its environmental management program (ESPO & Ecoports Foundation, 2022). This document includes the port's ways to reduce CO_2 emissions, transition to sustainable energy sources, and implement best practices in environmental management. The Rotterdam Port's sustainability goals and the strategies to achieve them are outlined in the Havenvisie document and the Port Environmental Review System (PERS). Its mission is not to only strengthen in terms of scale but also quality, especially sustainable development. The Port of Rotterdam aspires to lead the energy transition by reducing the industry's carbon footprint and advancing renewable energy, biobased production, and circular economy initiatives. Additionally, it seeks to maintain the port area's significant contribution to prosperity and employment in the Netherlands (ESPO & Ecoports Foundation, 2022)(HAVENVISIE, 2019). As the port authority states to contribute to all the SDGs, the port has the strongest connection with the below SDGs (Figure 13) in its future sustainability plans (ESPO & Ecoports Foundation, 2022).

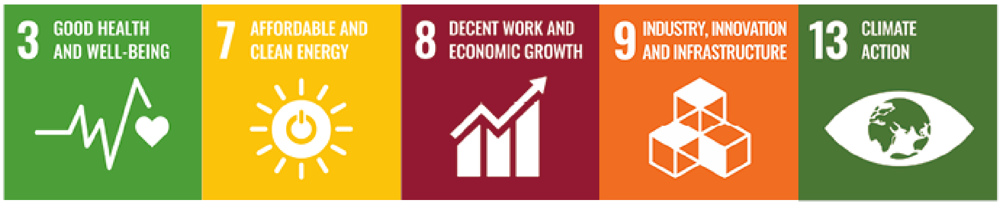

Figure 13: The SDGs the Port of Rotterdam claims to be most important for its future sustainability plans (ESPO & Ecoports Foundation, 2022)(HAVENVISIE, 2019), own visualization

The following table elaborates on the way the Port contributes to achieving the SDGs mentioned above:

Table 4: Contribution of Port of Rotterdam to the SDGs (Port of Rotterdam, n.d.-c)(ESPO & Ecoports Foundation, 2022)(HAVENVISIE, 2019)

SDG	**Contribution**	**Elaboration**
3. Good Health and Well-Being	Ensuring nautical safety Collaboration with authorities on other safety domains Improve air quality Reducing odour and noise	Reducing carbon in port operations Reducing air emissions - Monitoring and reducing concentrations of nitrogen dioxide (NO_2) and particulates in the air Strengthen the high-quality network and accessibility
7. Affordable and Clean Energy	Smart energy infrastructure Growth in renewable energy Clean shipping	Large-scale hydrogen networks across the port complex - 20 Million metric tons of hydrogen are needed to become climate-neutral - Pipeline systems across the country to supply hydrogen need - Hydrogen network Energy infrastructure for residual heat, steam, and CO_2 - Geothermics - Increasing existing industry

		- Using residual heat from industries for district heating Solar and wind energy - Wind turbines - Offshore wind parks - Shore-based power location - Energy storage
8. Decent Work and Economic Growth	Investing in industrial sites and port infrastructure Facilitate social dialogue about the labor market	Provide employment for 180.000 people Social transition by connecting the labor market with education Enhance education
9. Industry, Innovation and Infrastructure	Attract and facilitate start-ups Innovative networks Improving systems and making data available	Digital port and supply chain - Extensive digital platform - Tracking algorithms of vessels and cargo - Use of drones - Implementing AI Attract around €2 billion in investments per year over the next five years Make the logistic system more sustainable
13. Climate Action	Facilitating energy transition CO_2-reduction targets Facilitate sustainable energy production Cooperate with sustainable business networks	Carbon storage - New PORTHOS project - Current OCAP project Biofuels and liquid natural gas (LNG) - Increase LNG facilities Mineralization and greenhouses New material and fuel system - Fossil resources are replaced through biomass, recycled materials, and hydrogen Reducing carbon in port operations

5.2 What are the possible functions of seaweed cultivation in the Port of Rotterdam?

The two seaweed species that are suggested for seaweed cultivation in the Port of Rotterdam are Laminaria Saccharin and Ulva (Expert 1/2/4, personal communication, 2024). A combination of both species can be an interesting solution as the species are seasonal (Expert 3, personal communication, 2024) and the port will benefit from ecosystem services throughout the year. Laminaria Saccharin *(Sugar Kelp)* is a native species in the Netherlands, however, Expert 1 (personal communication, 2024) noted that the "natural population is disappearing enormously" and therefore implementing Laminaria Saccharin "could be a very nice cultivation initiative, certainly in combination with the SDGs". Laminaria Saccharin generally grows best in an environmental condition with salinity above 20 and is seasonally bound to autumn and winter (Expert 2 & 4, personal communication, 2024). Ulva Lactuca *(Sea Lettuce)* is a popular cultivation species with economic potential (Brandenburg, 2016) that has a higher salinity tolerance than sugar kelp. When the salinity is below 24 or fluctuates a lot, Ulva can be a good choice for seaweed cultivation. However, according to Genialg, (2021), the salinity must be much higher. It is the most primitive seaweed species and is grown on water surfaces (Expert 1, personal communication, 2024).

The use of seaweed cultivation in the Port of Rotterdam can be placed within an ecosystem services framework. The possible uses of seaweed cultivation in the Port are highlighted in the table below and elaborated on in the next paragraphs, following the ecosystem services as structure.

Table 5: The ecosystem services provided by seaweed aquaculture according to literature are summarized, together with other literature on seaweed ecosystem services. These services are compared to the newly gained knowledge of seaweed cultivation in the context of the Port of Rotterdam (Clark et al., 2021; Cotas et al., 2023; SeaMark, 2023; Expert 1/2/3/4, personal communication, 2024).

Seaweed ecosystem services in the Port of Rotterdam	
Provisioning	Regulating
Raw materials *Biomass:* Fertilizer, biofuel, biogas, medicine, and biomedical products	*Bioremediation of waste:* Removing pollutants from waters through storing, burial, and recycling *Soil formation:* Increase environment quality for aquatic plants *Gas and climate regulation:* Carbon sequestration, carbon storage, pH regulation, coastal protection *Nutrient and water cycling:* Water purification, seawater balance, improving water quality *Eutrophication mitigation* *Production of oxygen by photosynthesis*
Supporting	Cultural

Habitat provision: Habitat provided by marine organisms and farm structures	*Cognitive development:* Science, education, research, pilot-scale experiments *Sense of place and livelihood:* Employment opportunities, alternative income

Based on the interviews (Figure 14), seaweed cultivation for bioremediation is the most preferred use, while the least favorite is using seaweed as food. The commercial use of seaweed depends on how the biomass is utilized after cultivation. For instance, if the biomass is used for building materials, the quality does not need to be as high as when it's used for biofertilizer, bio-soil, or bioplastics, where the removal of heavy metals is crucial since the Port of Rotterdam is a polluted area (Expert 1, personal communication, 2024). Concluding, chemical pollution needs to be considered when working with seaweed as biomass after cultivation (Expert 2 & 3, personal communication, 2024).

Interviews with experts (1 to 4) on seaweed and seaweed cultivation (Appendix X), together with literature on topics discussed in the methodology, concluded that seaweed cultivation as a nature-based solution in the Port of Rotterdam can best be used for environmental outcomes, such as bioremediation, CO_2 storage, biodiversity benefits, and biomass (Clark et al., 2021; Ould & Caldwell, 2022; Duarte et al., 2021). The Port of Rotterdam is interested in further exploring NbS for environmental purposes due to its limited knowledge (Expert 7/8/9, personal communication, 2024). The port aims to become net positive and not online CO_2 neutral, therefore it wants to invest in natural solutions (Expert 7, personal communication, 2024). These functions are elaborated in the paragraphs below, following the ecosystem services.

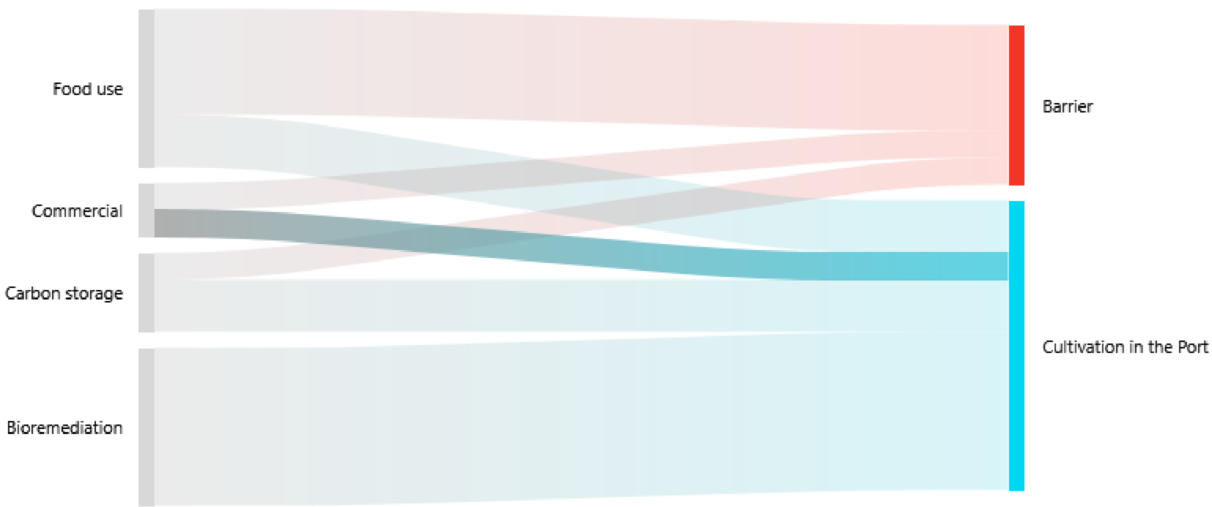

Figure 14: Sankey diagram showing the different possible uses for seaweed cultivation in the Port of Rotterdam, the possible uses of seaweed are on the left. When referred to as a 'barrier', it means that the use of seaweed cannot be achieved without encountering opposing factors (Expert 1/2/3/4, personal communication, 2024).

5.2.1 Provisioning services

The Port of Rotterdam works with biomass and moves towards becoming a circular port (Expert 7, personal communication, 2024; Port of Rotterdam, n.d.-b). Expert 7 states that the port is "actually the largest biomass cluster in any case in Europe" and that they can use seaweed biomass very well "for all kinds of other assets in the Port of Rotterdam" (2024). According to Arcadis NL & Rijksoverheid, (2023), due to the port's characteristics, it plays a key international role in facilitating the transition to sustainable materials. However, focused on cultivating seaweed in the Port of Rotterdam, its biomass cannot be used for human consumption or use due to its polluted waters (Figure X)(Steenhoek, 2024; Aldridge, 2024; Expert. 1, 2, 3, personal communication, 2024). As biomass is often related to renewable energy sources, it can also play an important role in the exploration of biofuel production using seaweed biomass. According to Thakur et al (2022), seaweed-derived biofuels could potentially replace 20% of the transportation sector's fossil fuel demand by 2050. Current trends and research in renewable energy production highlight the growing interest in using seaweed as a biofuel source. However, research on seaweed biomass as biofuel or biogas is limited and needs further exploring, especially technological barriers, optimization efficiency, and large-scale cultivating (Zhao et al., 2022; Thakur et al., 2022).

5.2.2 Regulating services

Bioremediation

Bioremediation involves using marine organisms to absorb pollutants through storage, burial, and recycling. Coastal areas are affected by pollutants from rural, urban, and industrial activities, including ports. Seaweed can absorb nutrients such as nitrogen, phosphorus, and carbon from the water and transform them into proteins and pigments (Clark et al., 2021; SeaMark, 2023). It can also accumulate metals and other contaminants at higher levels than the surrounding seawater. Due to this ability, seaweed is often referred to as an effective "biofilter" (Clark et al., 2021). As seaweed grows quickly, it has more capacity to absorb (Expert 1, personal communication, 2024). In this way, seaweed contributes to the natural climate underwater (Expert 3, personal communication, 2024). Additionally, the cultivation of seaweed might offer a cost-efficient method for managing nutrient pollution compared to some on-land approaches (SeaMark, 2023). However, the potential for bioremediation depends on the cultivation's species, scale, and environmental conditions (Clark et al., 2021.) With offshore seaweed cultivation, bioremediation is mostly seen as a secondary benefit and is an example of the valuable services that seaweed farming can provide to the ecosystem (Clark et al., 2021; Ould & Caldwell, 2022). According to SeaMark (2023), modeled studies estimated the removal of nutrients around *60,000 kg nitrogen/km2/yr* of the Saccharina latissimi species in an area near Scotland.

Carbon sequestration

Seaweed is drawing attention as a potential means to mitigate climate change. Especially due to their high rates of net primary productivity, they can be significant carbon sinks. Their ecological value, economic contribution to coastal areas, and potential for aquaculture make them a key focus for nature-based carbon sequestration (Ould & Caldwell, 2022). *Carbon sequestration* refers to the process of capturing and storing CO_2 in the biomass of plants or soil (U.S. Geological Survey, 2019). As seaweeds grow, they absorb dissolved inorganic carbon from seawater and convert it into organic carbon through photosynthesis. This process lowers the pressure of CO_2 in the seawater, pushing the ocean to absorb more CO_2 from the atmosphere, resulting in the potential to reduce CO_2. However, depending on the end-use, the captured carbon may remain locked away or be released into the atmosphere. How long the carbon is locked away depends on the harvested seaweed's lifecycle and its end-use (Clark et al., 2021; Expert 1, personal communication, 2024). Additionally, proving that seaweed can store CO_2 and lead to carbon sequestration is quite complex due to the influence of different processes. It involves tracking the movement of carbon through different pathways (both particulate and dissolved organic carbon) in constantly changing coastal waters, and also accounting for the interactions between the atmosphere and the ocean (Hurd et al., 2022).

Quantifying carbon sequestration in marine ecosystems is difficult as the fate of the captured carbon differs and is not entirely understood yet (Genialg, 2021). However, it is understood that in order to estimate the amount of sequestered carbon, it is essential to comprehend the following aspects (Genialg, 2021):

1. Level of carbon capture, also referred to as carbon uptake.
2. Quantity of lost biomass indicates torn off and carried away.
3. Percentage of the carried away biomass that becomes part of the short and long carbon cycles, associated with…
4. The timeframe (permanence) of carbon stored in deep-sea or coastal sediment, known as sequestered carbon.

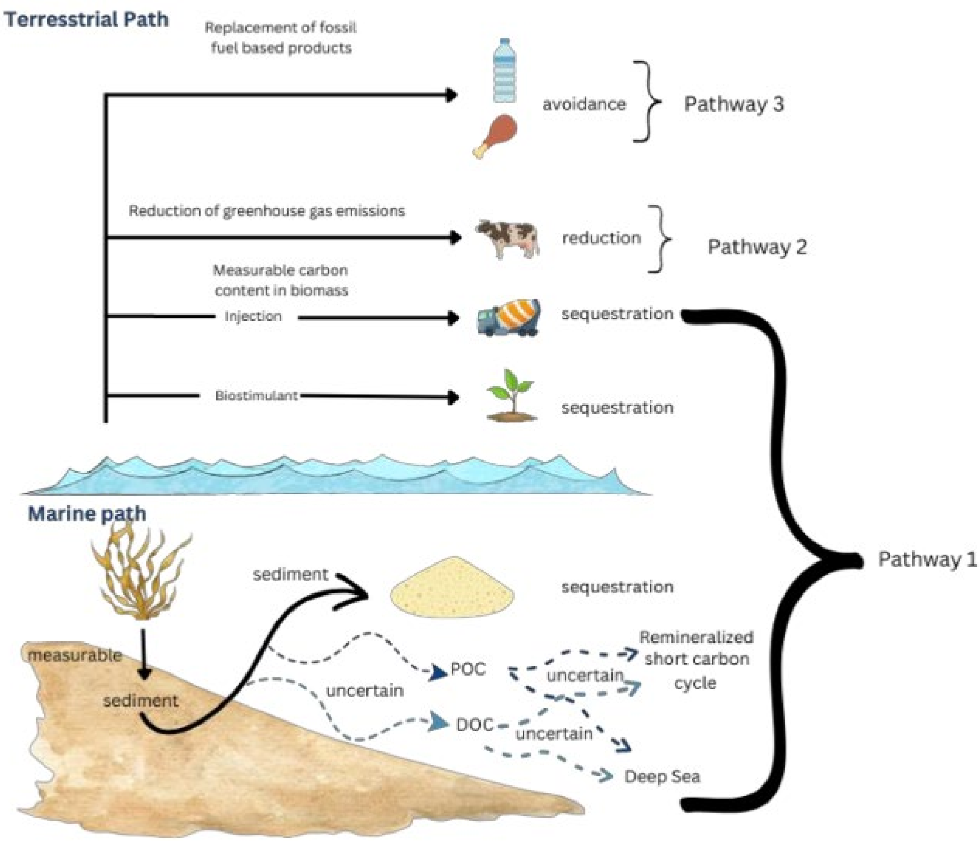

Figure 15: Pathway of carbon, from seaweed to product. The figure shows pathway one, where the carbon cycle is long and the carbon gets sequestered in the sediment and deep sea (this needs further research), and is remineralized or stored away in long-term biomaterials. The second and third paths are short carbon cycles where the carbon will end up in the atmosphere again through bioproducts or food/feed(Genialg, 2021).

5.2.3 Supporting

Seaweed's supporting services include habitat provision. According to Duarte et al. (2021), seaweeds act as ecosystem engineers stimulating biodiversity while simultaneously serving other benefits. Seaweed aquaculture creates complex habitats that support the restoration of degraded coastal areas, increasing the wealth and diversity of macrofauna (Duarte et al., 2021). As seaweeds can absorb nutrients, they support ecosystems to reverse the eutrophication process (NOAA, 2024). Additionally, seaweeds provide habitats for various marine organisms and act as buffers against strong wave actions, protecting shorelines (Cai et al., 2021; United Nations et al., 2024). However, this depends on the cultivation location as ports already protect themselves against environmental disturbances (EcoShape, 2020).

To support local biodiversity, partial harvesting over several years can help maintain the habitat, while full annual harvesting may leave the area without biomass, disrupting the ecosystem. This means harvesting a different part each time. Cultivation methods, such as using vertical or horizontal structures, also play a significant role in creating habitats for marine species (SeaMark, 2023)

5.2.4 Cultural

Cognitive development

When it comes to the development and understanding of ecosystem services, there is a need for significant research and spreading of knowledge. These efforts play a crucial role in raising public awareness, engaging stakeholders, and advancing scientific understanding in the field (SeaMark, 2023).

Employment opportunities

Seaweed cultivation supports employment opportunities within the Port of Rotterdam for the cultivation process and logistics, as new infrastructures are required when introducing NbS (Kraan, 2020; Clark et al., 2021). Additionally, the seaweed industry needs a large number of workers, especially during harvest periods (Expert 1, personal communication, 2024). Adema (2024) and Expert 1 (personal communication, 2024) propose that the fishery business could integrate aquaculture practices alongside its fishing operations as the fishery sector is experiencing a decline in job opportunities.

5.3 What are the constraining and enabling factors for seaweed cultivation in the Port of Rotterdam?

This section provides a table including all the data on enabling and constraining factors of seaweed cultivation in the Port of Rotterdam. The table provides the next step for the enabling factors before they can be realized, followed by a table including the potential involvement of the Port of Rotterdam.

Table 6: Enabling and constraining factors for seaweed cultivation in the context of the Port of Rotterdam, the data is provided by literature and interviews with experts.

Enabling		**What is the next step?**	**Potential involvement Port of Rotterdam**
Funding	European Commission is focused on funding aquaculture and seaweed initiatives, seaweed farming qualifies as a carbon farming practice (Kraan, 2020; SeaMark 2023)	Support research and development to improve the methods for measuring the services provided by seaweed ecosystems. These methods are crucial for certification processes (SeaMark, 2023)	Pilot for growing seaweed in different locations of the port and analyzing the chemical composition and carbon uptake (Expert 2, personal communication, 2024)
	There are multiple funding options for seaweed aquaculture, such as Horizon Europe and BlueInvest Europe (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	Research and innovation on sustainable aquaculture is an important condition to qualify for the Horizon Europe funding and the development of sustainable technologies for BlueInvest (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	Research regarding seaweed aquaculture and sustainable cultivation technologies
Carbon credits	Seaweed farming is not yet considered a carbon farming practice. If the port can quantify the amount of carbon sequestered by its seaweed farms, it could earn carbon credits, which can be sold or traded on carbon markets (SeaMark, 2023)	Developing standardized methodologies for quantifying the carbon sequestration potential of seaweed. This includes not only understanding the carbon uptake during the growth phase but also the fate of carbon post-harvest, such as its integration into commercial products (SeaMark, 2023)	Research for standardized methodologies to quantify carbon sequestration
Space	The Port of Rotterdam wants to focus on NbS (Expert 7/8/9, personal communication, 2024)	x	The Slufter is a research area, a 250-ha depot on the Maasvlakte, where contaminated dredged material from harbor basins and shipping channels are stored (Expert 7, personal communication, 2024; Port of Rotterdam*, n.d.-c)*
	Coordinate spatial planning is needed for implementing aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	Abandoned industrial facilities should be converted into aquaculture practices (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	Include seaweed cultivation in the early stages of spatial planning
	There are different ways to cultivate seaweed: onshore, offshore, or integrated with other aquaculture practices (Ould & Caldwell, 2022)	Seaweed cultivation requires good infrastructure (Expert 3, personal communication, 2024)	Investing in infrastructure for seaweed aquaculture
Ecosystem Services	Seaweed ecosystem provides provisioning, regulating, and supporting, cultural services (Table X) (Clark et al., 2021; Cotas et al.,	This requires well-managed seaweed aquaculture, finding a fitting location, and comprehensive evaluation of	Research regarding seaweed aquaculture and ecosystem services

	2023; SeaMark, 2023; Expert 1/2/3/4, personal communication, 2024)	the ecosystem services (Theuerkauf et al., 2021)	
	Seaweed cultivation gives direct and indirect benefits to multiple SDGs (Duarte et al., 2021)	The prerequisite is a collaboration between businesses, governments, and academia (Duarte et al., 2021)	Bring the different stakeholders together within an innovation cluster as a part of the innovation ecosystem
	Direct connection to waterbodies and marine ecosystems (Clark et al., 2021; Cotas et al., 2023; SeaMark, 2023; Expert 1/2/3/4, personal communication, 2024)	The ports' sustainability vision should include SDG 14 in its sustainability vision	Research regarding seaweed aquaculture and ecosystem services
	Ecosystem services could offer port officials new viewpoints on how the development of the surrounding natural and socio-economic systems affects them directly (Jansen, 2020)	Understanding the benefits of seaweed cultivation in the natural/marine ecosystem (Theuerkauf et al., 2021)	Research regarding seaweed aquaculture and ecosystem services
Net positive	NbS can support the port's aim to become net-positive (Expert 7, personal communication, 2024)	Further exploration of NbS is needed because of the limited knowledge of the port (Expert 7/8/9 personal communication, 2024)	Exploring possibilities of using seaweed for carbon uptake in sustainability pillar 3: 'New Raw Materials and Fuel system' (Figure X)
Economic opportunities	Creating green jobs for the cultivation process and logistics (Kraan, 2020; Clark et al., 2021)	x	More attractive employment opportunities
	Production of biomass for raw materials and potentially biofuel and biogas (Kraan, 2020)	Further research is needed on the potential of biofuel and biogas (Zhao et al., 2022; Thakur et al., 2022).	Research regarding biogas or biofuel from seaweed biomass
	The United Nations proposed that businesses and governments that use an ecosystem approach are more successful in adapting to new information and shifting demands (Jansen, 2020)	x	Implement an ecosystem approach
Research and innovation	The interrelated objectives in the EU Commission's strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 highlight the importance of innovation clusters for research for sustainable aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021	x	Increase the innovation ecosystem by focussing on seaweed aquaculture projects that reduce emissions and share resources
	Investigating the potential application of seaweed for animal feed can increase the market for Dutch algae and seaweed products (Brandenburg, 2016; Ministry of Agriculture, Fisheries, Food Security and Nature, 2020)	x	Pilot for growing seaweed in different locations of the port and analyzing the chemical composition, which helps define the purpose of biomass (Expert 2, personal communication, 2024)
Biomass	Can be used for biogas or biofuel (Kraan, 2020; Clark et al., 2021; Cotas et al., 2023; SeaMark, 2023)	This needs to be further researched (Zhao et al., 2022; Thakur et al., 2022)	Research regarding biogas or biofuel from seaweed biomass

	Can be used in sustainability pillar 3: ‘New Raw Materials and Fuel system’ (Figure X)	Using seaweed’s biomass for products or fuel motivates the port’s aim to become circular (HAVENVISIE, 2019)	Pilot for growing seaweed in different locations of the port and analyzing the chemical composition, which helps define the purpose of biomass
	The Port of Rotterdam wants to be the European hub for biomass (Expert 6 & 7, personal communication, 2024; Port of Rotterdam Authority, 2015)	Using seaweed’s biomass for products or fuel motivates the port’s aim to become circular (HAVENVISIE, 2019)	Research the role of seaweed biomass in their vision of a ‘biomass hub’ and ‘circular economy’
Job opportunities	The seaweed industry needs a large number of workers, especially during harvest periods (Expert 1, personal communication, 2024)	The fishery business could integrate aquaculture practices besides its fishery practices (Adema, 2024; Expert 1, personal communication, 2024)	Get in contact with fishery companies, share knowledge, and explore this field
Species	Brackish water allows multiple species to grow for different uses (Expert 1, personal communication, 2024)	Location for the proposed species Laminaria Saccharin and Ulva Lactuca (Expert 1/2/4, personal communication, 2024).	Pilot research areas for seaweed cultivation to test different species
Stakeholder involvement	Interdisciplinary collaboration is needed for seaweed cultivation and scaling up sustainable practices (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	x	Bring the different stakeholders together within an innovation cluster as a part of the innovation ecosystem
	Different stakeholders must work together to create awareness of seaweed cultivation (ILO et al., 2022)	x	Bring the different stakeholders together within an innovation cluster as a part of the innovation ecosystem
	Collaboration between different stakeholders is a prerequisite for seaweed ecosystem services (Duarte et al., 2021; McManus, 2009)	x	Bring the different stakeholders together within an innovation cluster as a part of the innovation ecosystem
Global position	The Port wants to promote itself and increase its global position (HAVENVISIE, 2019; personal communication 8 & 9, 2024)	Expanding activities while minimizing negative external activities is a challenge in the port (HAVENVISIE, 2019)	Work with seaweed cultivation as an innovative NbS to increase global social value and work alongside technological interventions
Government interest	ESPO reported that climate change, air quality, and water quality are the top five most important priorities for European ports (Espo, 2024)	The Port wants to promote itself and increase its global position (HAVENVISIE, 2019; personal communication 8 & 9, 2024)	Work with seaweed cultivation as an NbS to address multiple challenges at once
	There is an aim to promote new types of aquaculture in this sector (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)	x	Increase social global value by promoting seaweed aquaculture
	The Dutch government needs to follow the EU guidelines and is showing more interest in seaweed cultivation (North Sea Farmers, 2024)	x	Increase national value by promoting seaweed aquaculture

Constraining		**Potential strategies for constraining factors**
Environmental conditions	The port's water quality is not ideal for seaweed growth, with issues like low light penetration, high turbidity, and pollution affecting the growth and utilization of seaweed biomass (Expert 1,2/3/4/5, personal communication, 2024)	x
	The seabed composition of sludge, sand, mud, and pollution poses challenges to restoring ecological balance (Expert 1/2/3/4/5, personal communication, 2024)	x
Funding	The Port of Rotterdam stated that the port will not initiate such initiatives itself as it is not its role (Expert 6/8/9, personal communication, 2024)	Seaweed initiatives could receive support from the port if they align with the vision of biodiversity and sustainability (Expert 6/8/9, personal communication, 2024)
Carbon credits	Measuring carbon uptake in seaweed cultivation is challenging due to several factors, such as the variability in seaweed productivity across different locations and seasons, and the complexities involved in tracking the fate of carbon in marine environments (Genialg, 2021)	However, it is understood that to estimate the amount of sequestered carbon, it is essential to comprehend the four aspects explained on p.42 (Genialg, 2021)
Space	Competition for space and access due to the pot's economic activities could interrupt port activities (Expert 3/4/6, personal communication, 2024)	Bring the relevant stakeholders together as early involvement of relevant stakeholders is needed to distribute the space and water for different activities
	The cultivation area could be a risk to the safety of the ships and waterways within the port, this could be challenging as safety is highly important within the port (Expert 6/8/9, personal communication, 2024)	Include designated areas for suitable aquaculture in its spatial planning process, coordinate spatial planning is needed for implementing aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)
	For large-scale bioremediation and carbon storage purposes, a lot of space is needed, which is challenging to secure amid the dense industrial and logistical activities of the port (Expert 3 & 4, personal communication, 2024)	Include designated areas for suitable aquaculture in its spatial planning process, coordinate spatial planning is needed for implementing aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)
	The lack of space makes it even harder to get permits (Expert 2, personal communication, 2024)	Land-based seaweed cultivation can be an alternative option (Expert 2, personal communication, 2024)
	Nutrient reduction can occur if seaweed farming is too intensive, potentially leading to competition with local ecosystems' salinity (Clark et al., 2021)	The Port of Rotterdam is a nutrient-rich environment (Port of Rotterdam, n.d.-h), depleting nutrients is not likely
	Technology development is needed to achieve large-scale and economically viable cultivation systems for bioremediation	The development of sustainable technologies for sustainable aquaculture is funded by BlueInvest (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)
Biomass	Carbon uptake gets lost depending on the end-use of the biomass/product (Expert 2 & 5, personal communication, 2024).	There needs to be more research to storing long-term carbon in bioproducts, such as building materials e.g. cement (Genialg, 2021)
	The high pollution levels in the port's water limit the potential uses of harvested seaweed, particularly for products that require high-quality biomass, such as biofertilizers and bioplastics (Expert 7 & 12, personal communication, 2024).	Research growing seaweed in different locations of the port and analyzing the chemical composition, which helps define the purpose of biomass (Expert 2, personal communication, 2024)

Policy	During the transition towards sustainability, the Best Available Technique (BBT*) is chosen for its effectiveness and accuracy, even though it may not be the most sustainable. Policy and regulation always require BBT, which can limit innovation	If there is still a need for additional solutions, innovative solutions can be considered (BBT+), the port can explore the possibility of using seaweed for carbon uptake in sustainability pillar 3: 'New Raw Materials and Fuel system' (Figure X)
	The lack of a seaweed cultivation framework (Expert 2 & 5, personal communication, 2024; Kraan, 2020)	Working together with governmental bodies to facilitate research for implementing the EU Commission's strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030
Costs	The hatchery period is more costly and due to environmental aspects a hatchery period is needed (Expert 1, personal communication, 2024)	The maintenance costs of technological engineering solutions might be more costly in the long term than the realization costs of NbS (Seddon, 2022)
	Offshore cultivation has higher costs due to the logistics and infrastructure (Brandenburg, 2016)	x
	The most expensive thing about a port is its space (Expert 11, personal communication, 2024)	Include designated areas for suitable aquaculture in its spatial planning process, coordinate spatial planning is needed for implementing aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021)
	The value of ecosystem services is hard to define (SeaMark, 2023)	Working together with SeaMark, who has started quantifying ecosystem services (2023)
Species	The proposed species, Laminaria Saccharin and Ulva Lactuca, are seasonally bound, limiting the periods during which they can be effectively cultivated	A combination of both species can be an interesting solution as the species are seasonal (Expert 3, personal communication, 2024) and the port will benefit from ecosystem services throughout the year

***BBT (Best Available Technique)**

During the transition towards sustainability, the Best Available Technique (BBT) is chosen for its effectiveness and accuracy, even though it may not be the most sustainable (Expert 10, personal communication, 2024). These are the most effective methods to achieve a high level of environmental protection by preventing or minimizing emissions and other negative environmental impacts from an industrial facility. These techniques should be economically and technically feasible within the industry, considering costs and benefits (*Wet Algemene Bepalingen Omgevingsrecht*, 2022). Policy and regulation always require BBT, which can limit innovation. If there is still a need for additional solutions, innovative solutions can be considered (BBT+). Cultivating seaweed on a large scale will most likely only be supported if it is a BBT solution and not a BBT+ or even BBT++ (Expert 10, personal communication, 2024).

6. DISCUSSION

6.1 Interpretations

After comparing the findings on seaweed cultivation with existing literature, the results show that while seaweed cultivation is well-documented as a sustainable practice in coastal and marine environments, its application in heavily industrialized settings like ports remains underexplored. The Port of Rotterdam's extensive sustainability strategy underscores the need for an industrial ecology where nature holds a prominent place within planning and development processes. However, the challenge comes in ensuring that as the port expands its activities, there is still a focus on ecological preservation and restoration. The port's efforts to create ecological stepping stones and integrate nature into infrastructure design represent positive steps toward achieving this goal. Nevertheless, holistic strategies that fully intertwine nature and industrial development are missing, highlighting the necessity to explore the Building with Nature (BwN) approach.

However, the analysis of seaweed ecosystem services confirms that these services align with many of the Port of Rotterdam's sustainability goals and therefore the first steps towards a BwN approach are already out there. Seaweed's capacity to provide services such as carbon sequestration, habitat provision, and bioremediation fits well within the BwN concept and supports the port's ambitions to reduce carbon emissions and enhance environmental quality.

As discussed, the BwN approach is underexplored in the port, partly due to a lack of knowledge about nature-based solutions (NbS) and space scarcity in the densely populated port area. These limiting factors are likely interrelated; the urgent need for fast environmental mitigation encourages the adoption of Best Available Techniques (BBTs), which are favored over innovative solutions like NbS. A prime example is the PORTHOS project, a large-scale CO2 storage initiative that requires significant infrastructure, taking up valuable space in the port. On the other hand, seaweed aquaculture also demands proper spatial planning and investment in infrastructure, suggesting a competition for space between technological and natural solutions. The research revealed that space scarcity is one of the most significant constraints for the feasibility of seaweed cultivation, aligning with the expectations outlined in the research aim.

Given the spatial constraints, offshore cultivation methods for seaweed could be considered, though harvesting and processing the biomass would still require onshore facilities. Moreover, if the port chooses offshore cultivation, the lack of a clear framework for seaweed cultivation complicates the permitting process. This creates a negative feedback loop where a lack of policies restricts the promise of new cultivation areas, yet more research on aquaculture is needed to establish a robust policy framework, which therefore implies the need for more aquaculture sites.

The findings suggest that NbS should be integrated into the early spatial planning stages of port development. However, due to the urgent need for sustainable solutions, many spatial planning strategies have already been established. The interviews also reveal that BwN is a relatively new concept that still needs further research before it can be effectively incorporated into the port's spatial planning processes. This indicates that the need for technological innovations, particularly BBTs, to address sustainability challenges makes it difficult to prioritize and implement NbS. Within the current sustainability strategy of the Port of Rotterdam, the third pillar shows the first sustainability step which makes use of the ecosystem services of trees to absorb the remaining CO_2. This stage could also serve as an opportunity to introduce seaweed cultivation to achieve a net-positive environmental impact.

The results also highlight that the most promising potential of seaweed cultivation in the Port of Rotterdam lies in its regulating services, given the environmental conditions of the port. However, the absorption of heavy metals by seaweeds could limit the potential end-use of the biomass, raising the possibility that the seaweed might not be harvested at all, a finding that contradicts the initial expectations in this thesis. The analysis of the enabling and constraining factors indicates that 'provisioning' services do not have a place in the Port of Rotterdam (yet). On the other hand, this suggests a more prominent position of SDG14 in the port and ensures the (BwN) paradigm shift to building *with* nature.

As the results in Table 6 on enabling and constraining factors illustrate, there is a profound need for research at multiple levels of seaweed cultivation. This raises the question of whether investing in seaweed cultivation as an NbS might be premature in the context of the Rotterdam Port and that the focus should be on supporting the EU Commission's need for innovation clusters where numerous stakeholders share and obtain new knowledge on NbS and seaweed cultivation practices, which stimulate the permitting and policy process.

Furthermore, the Port of Rotterdam is a leading port and is both an influencer and a victim of climate change. The results might indicate that this makes the port the ideal role model with the potential for a significant ripple effect. Therefore this study suggests that small steps can lead to big impacts, and starting with small pilot areas for seaweed aquaculture research could potentially gain significant international attention and influence and thus strengthen the port's global position.

The final finding on the results is the mentioning of costs for cultivating, but the lack of knowledge on the benefits for the ecosystem services. The difficult quantification, and not fully explored value of ecosystem services, make it hard to define the value of seaweed cultivation in a cost/benefit analysis.

In conclusion, the findings suggest that seaweed cultivation in the Port of Rotterdam should primarily be pursued for research purposes at this stage. Stakeholders should be encouraged to form innovation clusters, which could serve as the starting point for integrating seaweed cultivation into the port's sustainability strategy and achieving broader SDGs. As knowledge and expertise in seaweed cultivation grow, these innovation clusters could help establish the necessary permits and frameworks, potentially identifying a test site, such as Slufter. By sharing knowledge on seaweed cultivation practices, the Port of Rotterdam could also enhance its global position as a leader in sustainable port development.

6.2 Implications of Research

This research contributes to the knowledge gap regarding NbS in industrial and marine ecosystems, by exploring the application in heavily modified water bodies. While NbS are thoroughly explored in coastal and natural settings, their potential in industrial contexts has been underexplored. This study provides a framework for understanding how NbS like seaweed cultivation can be integrated into industrial ecology, thus expanding the applicability of these solutions beyond traditional contexts.

Additionally, the study shows the importance of the BwN approach in achieving a balance between industrial activities, economic growth, and natural preservation. By identifying the gaps in current practices and proposing a shift toward more integrated planning, this research adds to the theoretical understanding of how BwN can be operationalized in complex industrial ecosystems. As the BwN is a relatively new approach, the research underscores the need for early integration of BwN approaches in the spatial planning of complex systems, which is important for policymakers and planners in the Port of Rotterdam and other similar contexts.

The Port of Rotterdam highlighted their limited knowledge of NbS and specifically seaweed cultivation. The study's findings on enabling and constraining factors for seaweed cultivation in industrial ports, such as space scarcity, regulatory gaps, and the competition between technological and natural solutions provide valuable insights for future research in this area and create an understanding of specific challenges associated with implementing NbS in the Port of Rotterdam.

With this new knowledge, the Port of Rotterdam can focus on implementing NbS in new sustainability strategies. This focus can lead to a more resilient infrastructure. Additionally, the port can understand its position in the shift towards BwN approaches and address the global lack of knowledge. This understanding can result in pilot research projects on seaweed cultivation, the behavior of seaweed in polluted waters, and the possibility of using seaweed biomass in the energy transition. Overall, the Port of Rotterdam is in a unique position where it can take a prominent lead in sustainable development of port areas and supporting aquaculture practices.

6.2 Research Limitations

6.2.1 Scope of the Study

The thesis focuses specifically on the Port of Rotterdam, which may limit the findings to other ports or industrial areas, especially outside of the EU where there are different policies and regulations.

6.2.2 Qualitative Data

As this research is built upon qualitative data, there is a limitation to the results. To create a full comprehensive answer to all the research questions, a field study to gather data is more detailed. However, due to the limitation in time and the seasonal characteristics of seaweed, this is not possible. Therefore, this study is meant to provide the first steps towards a possible long-term research of the potential of seaweed cultivation in the Port of Rotterdam and other port areas.

6.2.3. Individual Research

The research area of this thesis is the Port of Rotterdam, however, a collaboration on the thesis topic might have provided more insight on their environmental policies, future visions, and previous projects that have a resemblance to this study. Additionally, the potential of the Slufter was left underexplored.

6.2.4. Limited Time Frame

The research was conducted over a limited period, which has restricted the lack of quantitative data and potentially may also have limited the number of interviews or the scope of the literature review, such as obtaining more information about the Slufter location.

6.2.5. Early Stage of the BwN Concept

The BwN approach is relatively new, and its application in the context of industrial ports is unexplored. This means that the research may be limited by the availability of empirical evidence on the effectiveness of BwN in similar settings.

6.3 Future Research Directions

This thesis provides the basis for further research regarding aquaculture practices by highlighting the existing gap before implementing seaweed cultivation. Future research should focus on several points to further explore and enhance the understanding of seaweed cultivation as an NbS in industrial contexts like the Port of Rotterdam.

1. Investigating the long-term environmental impacts, particularly the effects of regulating services and biodiversity enhancement, is needed to assess the ecological viability of seaweed cultivation in heavily modified water bodies.
2. Developing methods to quantify the ecosystem services provided by seaweed, will enable more precise cost-benefit analyses and support the economic viability of large-scale operations.
3. Research should also explore innovative cultivation techniques and the integration of NbS into port planning, addressing the challenges of space scarcity and the need for comprehensive regulatory frameworks.
4. Explore the possibility of the Slufter for seaweed aquaculture.
5. The formation of innovation clusters and global knowledge exchange will be essential for advancing the adoption of NbS in ports worldwide.

7. CONCLUSION

7.1 General Conclusion

This study aimed to establish the enabling and constraining factors for seaweed cultivation in an industrial context, such as the Port of Rotterdam, and explore how seaweed cultivation would fit within the sustainability vision of the port. To answer the research question, three sub-research questions were answered and a foundation for the results led to several key conclusions. Overall a comprehensive analysis of existing literature and interviews with stakeholders were done to provide the relevant data for the results.

The findings indicate that the sustainability strategies of the port focus on numerous initiatives, whereas most prominent in their shift in the energy transition. The Port of Rotterdam's extensive sustainability strategy provides a solid foundation for integrating nature into its development processes, yet the challenge lies in balancing industrial expansion with ecological preservation. Highlighting the SDGs they feel most connected to, shows that the natural environment is one of the main SDGs the port aims to achieve. However, they also acknowledge the importance of their environment and the aim to become a "bio-port". A more holistic strategy, such as the BwN approach, is necessary to fully intertwine nature and industrial development. However, the lack of specific aquaculture and seaweed cultivation frameworks slows down innovative technologies which motivates the use of BBTs.

The analyses of seaweed ecosystem services showed that seaweed cultivation works well within a marine ecosystem can provide numerous benefits and aligns well with many of the port's sustainability goals. However, together with the data on enabling and constraining factors, numerous challenges are related to large-scale seaweed cultivation and using its biomass. Therefore research and development are crucial, particularly in measuring carbon sequestration and improving sustainable cultivation technologies. This can be established by collaboration between businesses, governments, and academia, focusing on creating innovation clusters for sustainable practices. Therefore seaweed cultivation fits within the sustainability vision of the port as a part of the innovative ecosystem that strengthens its global position and increases its social value.

7.2 Recommendations for the Port of Rotterdam

In this section, I provide recommendations for the Port of Rotterdam regarding seaweed cultivation as a nature-based solution.

7.2.1 Integrate Nature-Based Solutions Early in Spatial Planning

Incorporate NbS like seaweed cultivation into the early stages of spatial planning for new developments. This proactive approach will ensure that NbS is not forgotten next to more immediate technological solutions, such as Best Available Techniques (BBTs). Ensure that the sustainability strategy of the Port of Rotterdam includes NbS alongside technological innovations. This could involve expanding the third pillar to incorporate seaweed cultivation and other NbS that can provide net-positive environmental impacts. Additionally, recognize that while space is limited, innovative planning can balance the needs of both BBTs and NbS.

7.2.2 Initiate Pilot Research Projects for Seaweed Cultivation

The thesis showed the need for more research regarding seaweed aquaculture practices which can serve as research projects to gather data. Prioritize research on the specific environmental conditions of the Port of Rotterdam that affect seaweed cultivation, such as heavy metal absorption and the resulting implications for biomass use. Research should also focus on the potential ecosystem services provided by seaweed, including carbon sequestration, bioremediation, and habitat creation. This can contribute to the quantification of Ecosystem Services which will motivate the value of seaweed cultivation.

7.2.3 Establish Innovation Clusters

Boost the innovation ecosystem by integrating seaweed aquaculture initiatives as research themes within the port. Establish and support innovation clusters focused on NbS, including seaweed cultivation. These clusters should involve collaboration between businesses, governments, and academic institutions to share knowledge, stimulate research, and drive policy development. Additionally, use the position of the port to advocate for the adoption of NbS in industrial and complex ecosystems.

7.2.4 Align with SDG14

Given the potential of seaweed cultivation to contribute to life below water (SDG 14), increase the emphasis on this goal within the port’s sustainability strategy and focus on a more comprehensive sustainability approach that recognizes the importance of a well-balanced marine ecosystem to deliver ecosystem services.

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8.2 Figures and Images

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9. APPENDIX

9.1 Maps Port of Rotterdam

Image 1: General map of the Port of Rotterdam (Rotterdam Transport, n.d.)

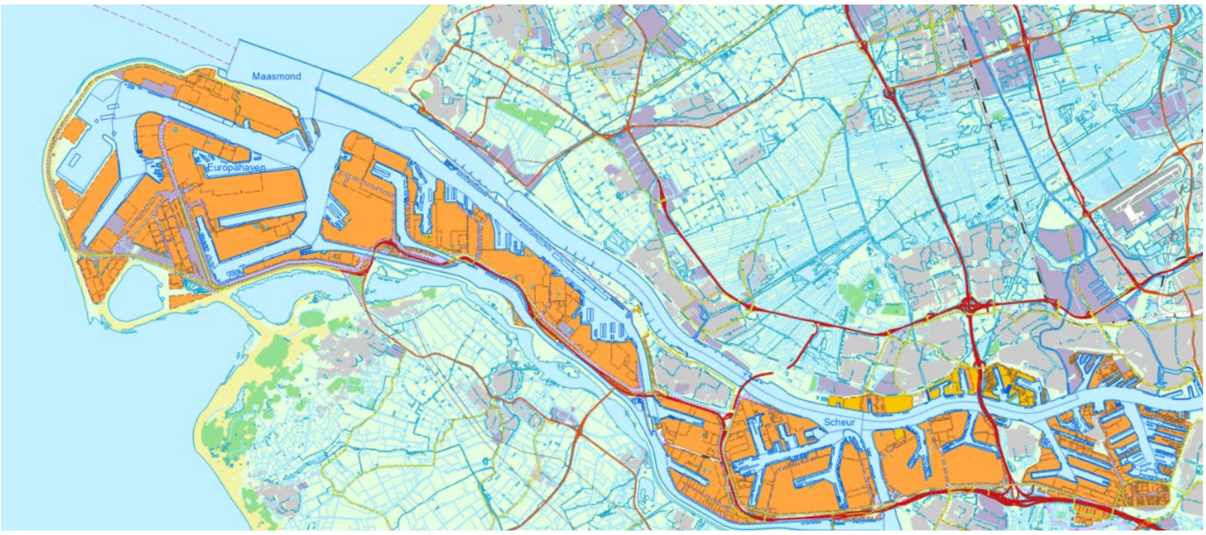

Image 2: Map with industrial purposes/segments per area of the Port of Rotterdam (Rotterdam Transport, n.d.)

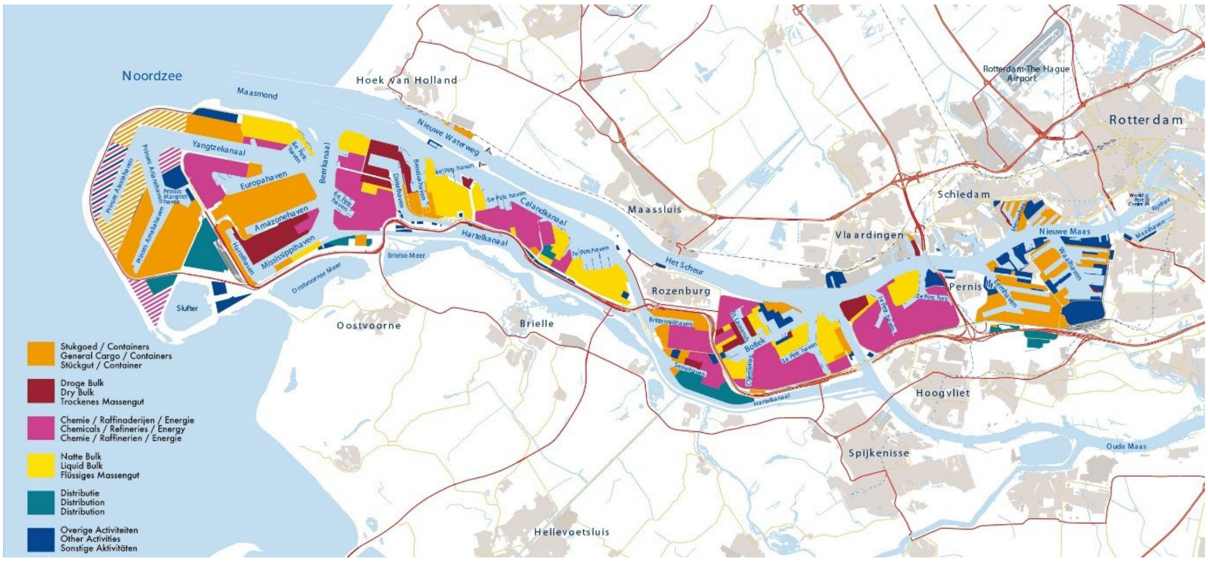

Image 3a: Live snapshot of shipping activities around the Port of Rotterdam

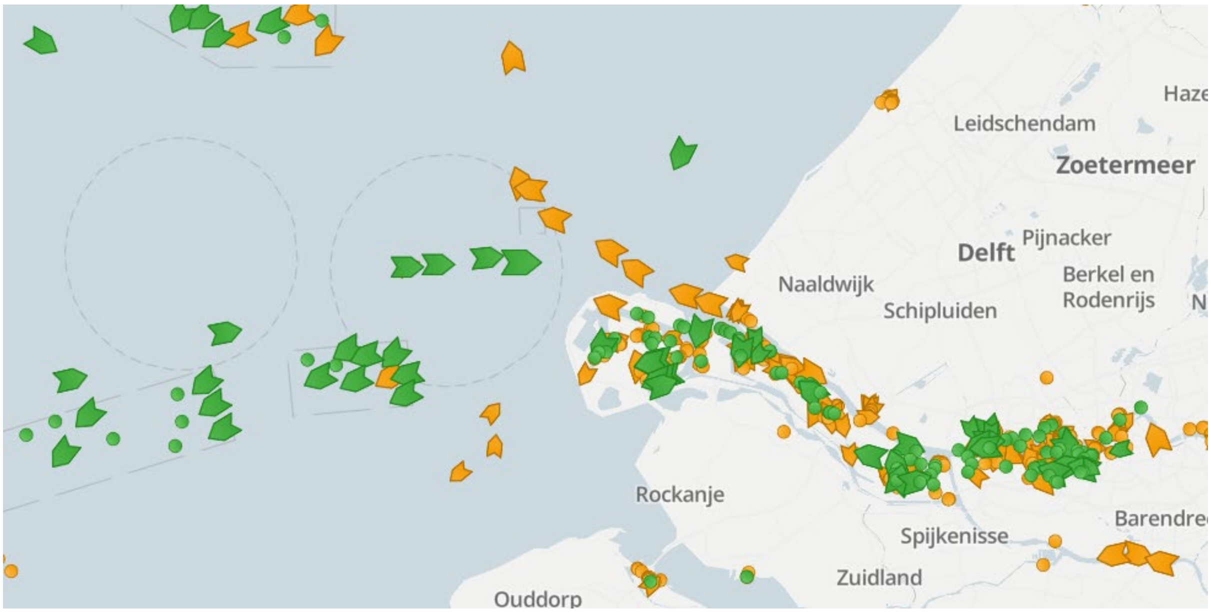

Image 3b: Live snapshot of shipping activities around the Port of Rotterdam (Schepen Volgen, 2023)

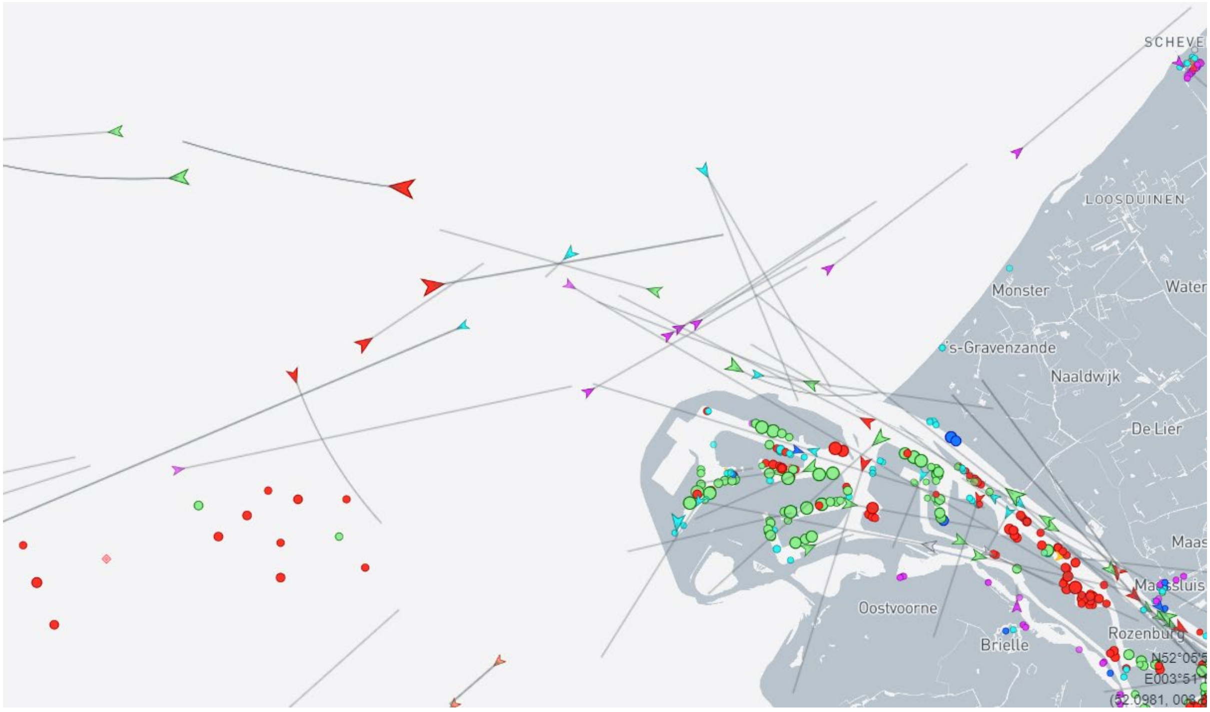

Image 4: Offshore map with fairways and anchorages for the shipping industry at the Port of Rotterdam (Port of Rotterdam, 2024)

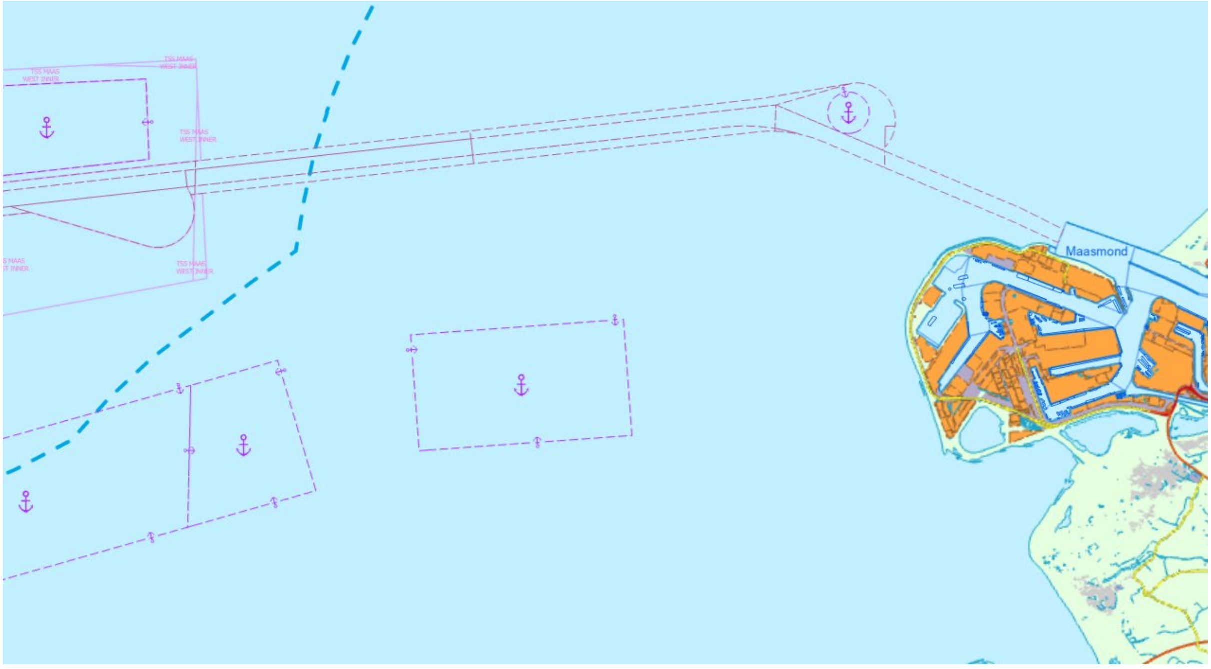

Image 5: Infrastructure OCAP and PORTHOS project Port of Rotterdam (Port of Rotterdam, n.d.)