Navigating New Horizons: Mapping the Global Technical Potential and Exploring the Material Demand of Offshore Floating Urban Dwellings

A GIS-based Approach Integrating Technical and Motivational Perspectives to Provide Insights into the Global Technical Potential and Associated Material Demand of Modular Floating Structures and Circular Floating Breakwaters as a Proposed Alternative for Sustainable Coastal Communities

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Preface

As I write this preface, I find myself nearing the end six years studying in Delft and Leiden. It all began with my studies in Technical Policy and Management at TU Delft, which I pursued for a year before switching to Biology at the University of Leiden. Throughout these years, I was stimulated by learning about technical systems and modelling in my initial year in Technical Policy and Management and an immense passion for nature, spanning from biodiversity and ecosystems to the intricacies of the immune system, which I cultivated during my time studying Biology. Eventually, I embarked on a Master's program in Industrial Ecology, a joint degree between TU Delft and Leiden focused on the technical, social and environmental perspectives of sustainability. During this Masters, I've had the chance to dive further into both the technical and environmental perspectives, all centered around a highly relevant and crucial of our time: sustainability. This Masters program particularly sparkled my interest in working with Geographical Information System. When I heard about this topic, it immediately caught my interest; the opportunity to unite GIS and my Industrial Ecology perspective with the exploration of an innovative and bold concept within one of the World's largest natural ecosystems — the ocean. All in all, writing this thesis has been an very insightful, exciting and a highly educational journey.

First and foremost, I want to thank my supervisors Dr. Tomer Fishman and Dr. Gil Wang who guided me throughout the whole process. From the first meeting to the last, their passion and expertise for this subject motivated and inspired me. Thank you for the engaging and informative conversations, the willingness to answer and discuss questions, giving the opportunity to present my work in front of experts and for making me comfortable during the whole process. Your insights from both the ocean engineering and Industrial Ecology perspectives have offered a comprehensive understanding of the environmental challenges and sustainable solutions in the marine domain.

Lastly, I would like to extend my gratitude for my family, boyfriend, friends and roommates who that supported me these months. Your support was incredibly valuable for me during this period. Thanks for the many interesting discussions and questions, the company in the University Library, coffee breaks and gently nudging me to, if needed, step away from my work.

After these words there is only one thing left to do, introducing my thesis to you, the reader: *Navigating New Horizons*. In this thesis I conducted an in-depth exploration of the topic of floating cities by zooming in on the technology, while simultaneously maintaining broad perspective on the larger context in which the innovative concept of floating cities exist, allowing for a comprehensive global exploration.

I hope that you are inspired by the insights, methods and perspectives presented in this thesis and that it motivates you to continue the discussion about our future cities.

Here's to exploring new horizons!

Lieke Bikker
Leiden, 05-11-2023

Abstract

Modular Floating Structures (MFS) have emerged as an innovative alternative for sustainable offshore urban development, providing a response to the multifaceted challenges posed by coastal urban expansion: significant urban growth and coastal migration, increasing sea-level rise exposure and land scarcity. This thesis presents a geographically oriented exploration of the global technical and motivation potential of MFS – in maximum achievable suitable area, offshore population and material demand -, integrating technical, environmental, and demographic factors through a comprehensive GIS analysis. The methodology of this analysis involves the following key steps:

1) Establishing the Service Limit State (SLS) technical potential map by considering the natural constraints bathymetry, average wave energy, average wind speed, and hurricane risk; 2) establishing the Ultimate Limit State (ULS) technical potential map based on the SLS map and the extreme value constraints 100-year return significant wave height and 100-year return wind velocity; 3) establishing the ocean planning technical potential based on the ULS map and integrating the ocean planning constraints marine protected areas and shipping routes; 4) establishing the motivation potential maps, which are based on the outcomes of steps 1, 2, and 3 and the proximity to a coastal city as a key motivation factor; 5) evaluating additional motivation layers to reveal where potential driving forces are for floating urban development within local contexts. The maps lead to first estimates of maximum suitable area and offshore population, guiding calculations for required materials in floating breakwaters, proposed as reused end-of-life (EOL) ships, and MFS substructures.

This thesis uncovers several insights. The use of Geographical Information Systems (GIS) in this field enables the exploration of the technical potential of offshore urban development, offering first estimations for total area, offshore population, and material use (specifically EOL ships and steel). On a global scale, about 84000 km2 are suitable for MFS implementation, potentially accommodating up to 1.6 billion people. These results demonstrate the potential to contribute significantly to climate-adaptive housing capacity. If the entire technical potential were to be realized the global demand for EOL ships would be approximately 261000, a demand significantly exceeding the current in-use global merchant fleet by nearly threefold. The global steel demand for the construction of the MFS substructures would be 26 billion tons, a vast amount that exceeds the annual global steel demand by about 20 times. These vast numbers may significantly impact the ship-breaking industry and global steel flows.

These insights provide valuable perspectives on MFS implementation, holding the potential to significantly contribute to climate-adaptive housing capacity, however raising critical questions about sustainable material consumption and production. This research unfolds new possibilities in the field of sustainable offshore urban development and serves as a launchpad for further large scale exploration and analysis in this dynamic area of research. Future research could further assess the sustainability of offshore urban development, building upon the findings of this thesis. Potential areas of investigation include for example comparing material requirements for MFS substructures to those of land-based building substructures or conducting micro, meso or macro-scale scenario-based Material Flow Analysis (MFA) to evaluate the influence on the global steel flow and ship-breaking industry, using the technical potential estimates presented in this thesis on local and global scale as a foundational reference.

KEYWORDS: Sustainability, Offshore Urban Development, Modular Floating Structures (MFS), Geographical Information Systems (GIS), Global Technical Potential, Material Demand, Climate-Adaptive Housing, End-of-Life Ships.

Abbreviations

Table 1: The abbreviations used in this thesis

Abbreviation	Definition
ECU	Ecological Coastal Units
EOL	End-of-life
GIS	Geographical Information Systems
GSLR	Global Sea Level Rise
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LECZ	Low Elevation Coastal Zones
MFA	Material Flow Analysis
MFS	Modular Floating Structures
Mt	Million tons
OECD	Organisation for Economic Co-operation and Development
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SLR	Sea Level Rise
SLS	Service Limit State
ULS	Ultimate Limit State
UN	United Nations
VLFS	Very Large Floating Structures

Table 2: The symbols used in this thesis

Abbreviation	Definition
#	Number of
H_s	Significant wave height
H_s^{100}	100-year return significant wave height
U_{10}	Wind speed
U_{10}^{100}	100-year return wind speed

Contents

Preface **2**

Abstract **3**

Abbreviations **4**

1 Introduction **9**
- 1.1 Problem definition and context . . . 9
- 1.2 Modular Floating Structures . . . 11
  - 1.2.1 MFS and Circular Economy . . . 11
- 1.3 Knowledge gap – global challenges call for global solutions . . . 11
- 1.4 Research questions . . . 12
- 1.5 Industrial Ecology and societal relevance . . . 13
- 1.6 Report structure . . . 14

2 Literature Review **15**
- 2.1 Outlining the context - challenges faced by coastal cities . . . 15
- 2.2 Projecting the future – coastal population at risk . . . 16
  - 2.2.1 From global trends to local variations . . . 18
  - 2.2.2 Sustainable Development Goals . . . 19
- 2.3 Strategies for coastal urban expansion . . . 20
  - 2.3.1 Strategies for climate adaptive urban development . . . 20
  - 2.3.2 Strategies for urban growth in the light of land scarcity . . . 21
- 2.4 Floating urban development . . . 22
  - 2.4.1 Floating structures – state of the art . . . 22
- 2.5 Strategies for coastal urban expansion . . . 22
  - 2.5.1 Modular Floating Structures . . . 23
  - 2.5.2 Proof of technology to proof of scale – exploration of relevant factors for global MFS potential 26
- 2.6 Summary and synthesis of findings . . . 26

3 Methodology **28**
- 3.1 Geographical Information Systems . . . 28
- 3.2 Design of the GIS model . . . 28
  - 3.2.1 Geographical and temporal scope . . . 29
  - 3.2.2 Stage 1: Literature review and expert consultations . . . 29
  - 3.2.3 Stage 2: Data collection, validation and preprocessing . . . 29
  - 3.2.4 Stage 3: Model development . . . 34
  - 3.2.5 Stage 4: Model verification and validation . . . 40
- 3.3 From maps to numbers: area, offshore population and material use . . . 40
- 3.4 Model application with selected case studies . . . 40

4 Results **42**
- 4.1 Technical potential of MFS motivated by the proximity of a coastal city . . . 42
  - 4.1.1 Estimates of global material use . . . 44
- 4.2 Model sensitivity . . . 44

4.3 Application of model - zooming in 46
4.3.1 Global region analysis 46
4.3.2 Leading cities in the technical potential for MFS 46
4.3.3 City case studies 47

5 Discussion and conclusion **51**
5.1 Interpretation of results 52
5.1.1 Results in the SDG context 53
5.1.2 Local exploration of global results 54
5.1.3 Comparing alternatives for coastal urban expansion 55
5.1.4 Convergence of insights - answering the research question 55
5.2 Limitations and discussion of GIS model 56
5.2.1 Data availability and simplifications 56
5.2.2 Future scenario's 57
5.2.3 Adaptability of the GIS model 57
5.3 Reflection on on research approach 57
5.4 Conclusion 57
5.4.1 Future research directions 58

Bibliography **59**

Appendix A: Complete Overview Factors for MFS Implementation **66**

Appendix B: Comprehensive Methodology GIS Model **72**

Appendix C: Comprehensive Additional Methodology **90**

List of Figures

1.1 Floating city concepts, by Oceanix (2023) (left) and Blue21 (2023a) (right). 10
1.2 Visual overview of report structure, guided by the Geographic Approach (Artz & Baumann, 2009). . . 14

2.1 Sustainable Development Goal (SDG) 11, SDG 12, SDG 14. Adapted from KIT (2023) 19
2.2 Floating structures for urban purposes. Projects Harnaschpolder, Delft (left), adapted from Blue21 (2023b) and Schoonschip, Amsterdam (right), adapted from Stedenbouw (2019) 22
2.3 Spatial arrangement of MFS "twin-hull" modules, as presented in G. Wang, Drimer, and Goldfeld (2020) 24
2.4 Proposed design of floating breakwater, as presented in G. Wang et al. (2023) 25

3.1 Workflow diagram technical potential map Service Limit State (SLS) 35
3.2 Workflow diagram technical potential map Service Limit State (ULS) 36
3.3 Workflow diagram technical potential map ocean planning 36
3.4 Snip from Python code GIS model to set the boundaries for output 37
3.5 Schematic overview Weighted Overlay Analysis approach 37
3.6 Workflow diagram technical potential motivated by the proximity of a coastal city. Note: Coastal city is defined as >300,000 inhabitants, <15 km from shoreline 39
3.7 Workflow overview of the motivation perspective 39

4.1 Technical potential map of Service Limit State, motivated by the proximity of a coastal city 43
4.2 Technical potential map based on the Service Limit State and Ultimate Limit State, motivated by the proximity of a coastal city 43
4.3 Final technical potential map based on the Service Limit State, Ultimate Limit State and ocean planning motivated by the proximity of a coastal city 44
4.4 Technical potential maps of A) Lagos, Nigeria; B) Singapore; C) Rio de Janeiro, Brazil and D) Mumbai, India 48

5.1 Overview main GIS model results of the global technical potential 51
5.2 Overview of all Sustainable Development Goals 54
B.3 Complete step-by-step overview of the preprocessing methodology 74
B.4 Geographical scope preprocessing step-by-step. Sub figure of Figure B.2. 75
B.5 Service Limit State (SLS) preprocessing step-by-step. Sub figure of Figure B.2. 76
B.6 Service Limit State - continued - preprocessing step-by-step. Sub figure of Figure B.2. 77
B.7 Ultimate Limit State preprocessing step-by-step. Sub figure of Figure B.2. 78
B.8 Ocean planning and motivation preprocessing step-by-step. Sub figure of Figure B.2. 79
B.9 Complete step-by-step overview of the technical potential and motivation methodology. Note: SLS = Service Limit State, ULS = Ultimate Limit State 85
B.10 Service Limit State model step-by-step methodology. Sub figure of Figure B.8. 86
B.11 Ultimate Limit State, ocean planning and motivation model step-by-step methodology. Sub figure of Figure B.8 87
C.12 Comprehensive step-by-step methodology km^2 conversion. Note: * input can be any map of which conversion is desired 90
C.13 Ratio floating breakwaters per MFS platform. 93

List of Tables

1 The abbreviations used in this thesis 4
2 The symbols used in this thesis 4

2.1 Overview of studies estimating future exposed populations to SLR 17
2.2 Overview of relevant factors for the implementation of floating structures 27

3.1 Overview of factors and their defined boundaries used to determine the global technical potential of MFS, based on relevance and data availability 32
3.2 Overview of factors and their defined boundaries used to evaluate the motivation for MFS, based on relevance and data availability 33

4.1 Global technical potential results, motivated by the proximity of coastal cities 45
4.2 Bathymetry sensitivity analysis compared to baseline boundaries of the final technical potential map, motivated by the proximity of a coastal city 45
4.3 Leading cities in technical potential for MFS - a first overview 46
4.4 Leading cities in technical potential of MFS, considering the motivation of urban population growth - a first overview 47
4.5 Global regions study: results of the final technical potential, motivated by the proximity of coastal cities 49
4.6 City case study: results of the final technical potential, motivated by the proximity of coastal cities . . 50

A.1 Factors relating to the technical and motivation potential, based on literature and expert consultations 66
A.2 Data availability and description of relevant factors for technical potential and motivation potential . 69
B.3 Metadata preprocessing model 72
B.4 Detailed description of Iterator commands presented in Figure B.4 80
B.5 Detailed description of tools and settings presented in Figure B.3, B.4, B.5, B.6, B.7 80
B.6 Metadata technical potential and motivation model 84
B.7 Detailed description of tools and settings presented in Figure B.9, B.10 87
C.8 Detailed description of tools and settings presented in Figure C.11. 91
C.9 Global region selection for GIS analysis. 92

1

Introduction

In a time when the significance of sustainability is widely acknowledged and crystallized into specific goals and aspirations, the concept of floating cities emerges as an bold, innovative alternative for sustainable urban development. The year 2015 marked a milestone when the United Nations (UN) adopted 17 Sustainable Development Goals (SDGs) after years of intergovernmental negotiations and extensive stakeholder consultations (United Nations, 2023). These 17 goals depict a globally agreed development pathway integrating human development aspirations with a stable and resilient planet for 2030. For each goal, several targets were defined, further supported by annually refined indicators. While the goals and targets are carefully established, the question of how to achieve them remains open to interpretation; the targets are qualitative in nature and there is no manual available how to reach these 17 goals. Consequently, there is room for the exploration of various alternative pathways and ideas. It is therefore crucial to assess the potential of these alternative to help reaching the SDGs.

Floating city projects propose floating, adaptive, sustainable communities on water, holding the potential to address a wide range of challenges that are interconnected with all 17 SDGs. In particular, these projects address SDG 11, "Sustainable Cities and Communities," by presenting a climate-adaptive alternative for urban expansion. Moreover, the concept of floating cities is closely tied to SDG 14, "Life below water", emphasizing the critical importance of maintaining healthy oceans, seas, marine environments, and their ecosystems. Additionally, SDG 12 "Responsible consumption and construction" stresses the need of ensuring sustainable consumption and production patterns; closely related to material use for urban development.

Thus, an interesting question raises: could floating cities combat contemporary urban issues, addressing the SDGs; in particular SDG 11 (making cities and settlements inclusive, safe, resilient and sustainable) while not undermining the targets of SDG 14 (conservation and sustainable use of the ocean) and SDG 12 (ensuring sustainable consumption and production patterns)? This thesis takes a dive into this topic by determining the global potential of floating cities and translating this to first estimations of additional housing capacity and material use on a global scale.

1.1 Problem definition and context

The global population is currently undergoing significant growth, with reaching a global population of eight billion in 2022, and an estimated increase of almost two billion people by 2050 (United Nations, 2022a, 2022c). And not only is the population projected to grow, but it's also predicted to become more urban. This population increase and urban migration areas pose significant challenges, particularly concerning depletion of resources and sustainable urban growth. Moreover, the competition for the essential resources like energy, water food and available land will grow (Godfray et al., 2010). As cities are expected to expand by 2.5 to 3 times their current size by 2050, maintaining sustainable urban development without straining land is a complex task (Angel et al., 2005; J. E. Cohen, 2010; M. Cohen, 2017). As such, research and debate about future sustainable development and expansion of our World's mega cities is hot topic and concern a wide variety of stakeholders. From policy makers and urban planners to the prospective citizens and environmental concerns; collectively highlighting the importance and societal relevance of this topic. This challenge is especially pronounced for coastal cities, which account for approximately two-third of World's mega cities (Pelling & Blackburn, 2013). While an increasing number of people are attracted to coastal cities, their spatial growth is constrained by the presence of water on one front. Additionally, the pressing issue of global warming and its related sea level rise further exacerbates the challenge of urban expansion at land for coastal cities.

Considering the combination of the rapid population growth and migration to the coastal cities, the decreasing availability of land, coupled with the physical constraint of one side of the city being bordered by water and the high vulnerability to sea level rise emphasize the urgent need for action in coastal urban areas. Recently, with global warming leading to an even more accelerated sea level rise, the concept of sustainable floating cities became popular (F. Y. Lin et al., 2022). While this might seem utopian, cities on water are not novel. Throughout history humanity has been residing on water, reflecting a symbiosis. Water-based communities such as the floating fisherman villages in Ha-Long Bay, Vietnam, and the Uros people in Bolivia living on reed islands are notable examples ("Water-based communities", 2022). In Europe, the example of Venice stands out: founded on top of a marshland as a response to spatial constraints prompted by invaders and conquerors on the adjacent mainland. However, nowadays Venice is considered more of a sinking city than a floating city - but that's a topic of its own.

Globally, two noteworthy approaches have been explored to address the issue of urban expansion in coastal areas: coastal land reclamation and the implementation of Very Large Floating Structures (VLFS). Conventional land reclamation involves creating new land for agriculture, industry or urban purposes by filling in oceans, seas or rivers. Two of the most straightforward methods include submerged area infilling - layering rocks, clay and soil to achieve the desired height - or draining wetlands (Stauber et al., 2016). Land reclamation projects can be found in various parts of the World. Some notable examples are the Flevopolder in the Netherlands, the artificial Palm Islands in Dubai and, interestingly, 22% of Singapore's land is reclaimed from sea. However, conventional land reclamation proves to be unsustainable due to technical and environmental issues. Technical challenges include limitations imposed by seabed depth and the quality and softness of the seabed soil (G. Wang et al., 2019). Moreover, from an environmental perspective, the use of infill materials is becoming increasingly problematic, as these resources are becoming scarcer. The recent decision of Indonesia - a major supplier for Singapore's sand for land reclamation projects - to lift a sand export ban has sparked a conversation about the (un)sustainability of sand mining (UNEP-WCMC & IUCN, 2023). In reponse to the challenges of conventional land reclamation, VLFS have been promoted. VLFS are large man-made offshore structures designed to float and typically serve one purpose (e.g. airport, storage facility). The concept of VLFS is relatively new and has experienced rapid development the last decade. The MegaFloat in Japan is a well recognized example, serving as a prototype for a floating airport runway (C. M. Wang & Tay, 2011). However, VLFS faces challenges in costs, complexity, and inflexibility (G. Wang et al., 2019).

To address these shortcomings, a different approach to VLFS has emerged: the concept of modular floating cities, allowing dynamic urban expansion (Figure 1.1). While many architects have explored this conceptually, practical implementation is lacking (Oceanix, 2023; Waterstudio.NL, 2023). Recent efforts by G. Wang, Drimer, and Goldfeld (2020) aim to bridge this gap by providing engineering solutions and design methodologies for Modular Floating Structures (MFS), offering a pathway for sustainable offshore urban development.

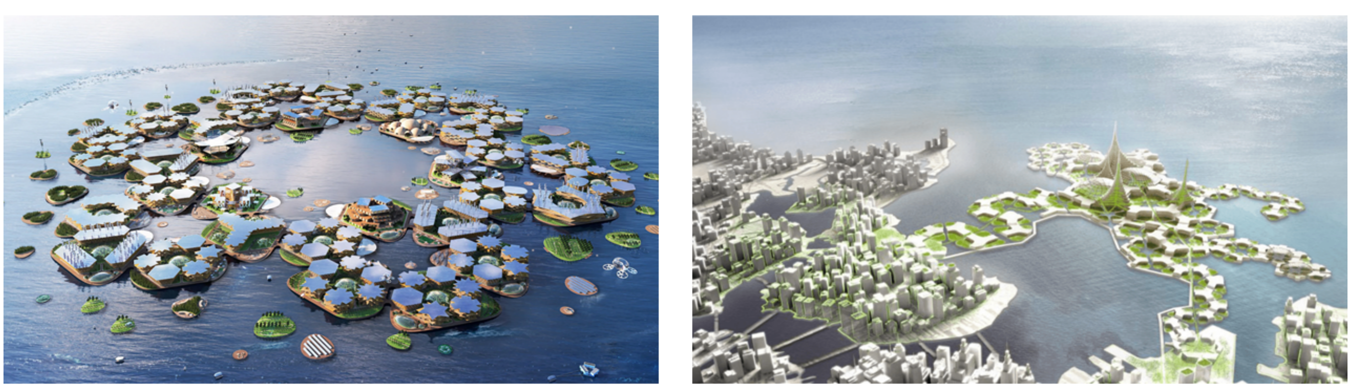

Figure 1.1: Floating city concepts, by Oceanix (2023) (left) and Blue21 (2023a) (right).

1.2 Modular Floating Structures

MFS are designed to offer a sustainable alternative for offshore urban development. These structures, comprised of a sub (barge) and super structure (buildings) are rigid modules that together form consolidated platforms for urban development, measuring about 500 x 400 m. These modules can serve various urban functions, such as generating renewable energy, providing storage, or accommodating commercial and residential spaces. This design promotes lean, dynamic urban development and is hypothesized to provide a sustainable alternative to address the challenges of urban coastal expansion. Furthermore, G. Wang, Drimer, and Goldfeld (2020) demonstrated that the use of floating breakwaters as a sea wall increases the performance limits and comfort criteria of the MFS design. These floating breakwaters are made from retired end-of-life (EOL) ships, not only contributing to the feasibility of the MFS design but also potentially contributing to the circular economy within the ship-breaking industry.

1.2.1 MFS and Circular Economy

The global merchant fleet includes about 90,000 ships, with 1-2% reaching the end of their lifespan annually (Solakivi et al., 2021). Many of these ships undergo ship-breaking, mainly in Bangladesh, India, and Pakistan, where hazardous working conditions and marine pollution are prevalent. In the ship-breaking industry, currently only around 0.4% of the retired merchant fleet is reused, compared to about 95% being recycled. Prioritizing reuse more could enhance sustainability in the ship-breaking industry, addressing both social (working) and environmental (pollution) concerns (Senavirathna et al., 2022). As proposed by G. Wang, Drimer, and Goldfeld (2020), reusing end-of-life ships as floating breakwaters has the potential to contribute to the circular economy of ships and mitigate the ship-breaking industry's challenges.

1.3 Knowledge gap – global challenges call for global solutions

Additional research is necessary to gain deeper insights in the potential and the subsequent environmental implications of modular floating cities worldwide. The author's observation of a recent significant increase in publications in the Scopus database, with a focus on floating structures for urban expansion, underscores the novelty and relevance of this field. As underlined in a review by Umar (2020)), modular floating cities can be a promising alternative for sustainable coastal urbanization, and, as it is still at its initial stage, has the potential for further interdisciplinary research. The available body of literature, which will be elaborated on in the Literature Review (Chapter 2) presents modular floating cities as a promising alternative for sustainable urban coastal expansion. However, the early stage development is also evident from the available sources.

A number of articles and research papers evaluate the promising concept of sustainable floating cities, discussing the use of energy, water and food as well as habitat regeneration (Mandakini P. Bhatt, 2020; Umar, 2020; H. Yang et al., 2022). However, up to this day these reviews are only conceptual as we have no existing floating city similar to the aforementioned ideas of Waterstudio.NL, Oceanix and G. Wang, Drimer, and Goldfeld (2020). Other sources reflect on local existing case studies of small-scale floating structures, such as individual floating houses (Y. H. Lin et al., 2019).

As mentioned before, G. Wang, Drimer, and Goldfeld (2020) aim to bridge the gap between these conceptual sustainable floating city ideas and the practical implementation. They have designed MFS and extensively studied the engineering and design aspects, meeting naval and residential standards. To stretch the limits of implementing MFS, floating breakwaters – comprised of reused ships - were also designed and tested (G. Wang et al., 2023). The research of G. Wang, Drimer, and Goldfeld (2020) reveals a viable, practical design for floating urban development for sustainable coastal communities. This provides a foundational basis for further comprehensive research into the potential of this alternative for coastal urban expansion, delving deeper into the authors' hypothesis that MFS provide a "sustainable solution for addressing issues related to coastal urbanization and sea level rise."

Concluding, there is 'proof of technology' for floating urban development. Therefore, an interesting next step would be to move to 'proof of scale', to address the global scale of the coastal challenges we are facing. Where and to what degree could floating urban development potentially be implemented? How much people could potentially live at sea and how does this relate to numbers exposed in coastal areas? How much materials would be associated with this? To the best of my knowledge, there is currently no research about the global potential of any design of modular floating cities. Therefore, this thesis will focus on identifying the potential locations where MFS could be implemented on a global scale. Investigating this for MFS could prove valuable in understanding the viability of modular floating cities as an alternative for coastal urban expansion. This entails on the one hand exploring the technical potential of implementation of MFS and on the other hand understanding the underlying motivations for urban expansion to the water, e.g. driven by exposure to rising sea levels and/or limitations in land availability and a growing population. This way, we gain an understanding of to what extent this alternative could contribute to the global issues faced by coastal cities and open the door to a more in-depth evaluation of local outcomes.

At present, studies that involve both exploring suitable locations and floating structures are limited and focus mostly on development of floating wind farms (Castro-Santos et al., 2020; Díaz & Guedes Soares, 2020; Díaz et al., 2019; Melissas & Asprogerakas, 2022) or aquaculture (Perez et al., 2005; von Thenen et al., 2020). These floating structures require different spatial conditions than floating modules for urban development. However, these studies prove that Geographical Information Systems (GIS) is a suitable tool to explore potential for offshore structures and the findings can be used as inspiration for this study (Peters et al., 2020). As far as the author of this thesis knows, there are no academical studies that examine modular floating cities using GIS. Therefore, introducing GIS in this study could be of great value to this field of research.

As such, the aim of this thesis is to map and explore the worldwide potential, hereafter referred to as the global potential, of MFS implementation, both from a technical perspective (the 'where') as well as from the motivation perspective (the 'why'), using GIS as a tool. The technical perspective is addressed by mapping the global "technical potential": in this thesis defined as the maximum achievable area suitable for MFS (in km^2) and the maximum offshore population (in number of (#) people), based on topographical (physical features), environmental (natural (eco)systems) and ocean planning (zoning) constraints. This is subsequently translated into the required amount of materials for achieving this potential, encompassing both the floating breakwaters (in (#)ships) and the substructures (amount of steel) integrating the technical and motivation perspective. The motivation perspective is addressed by mapping and considering topographical, environmental, land-use (zoning) and demographic factors that could motivate or drive advancing to sea. Combining these perspectives, results in a global potential; the maximum achievable area, offshore population and associated material use (in number of ships and steel). This aim defines the main research question and a set of sub questions, presented below.

1.4 Research questions

Based on the outlined context, the research gap and the aim of this thesis described previously, the main research question that this thesis aims to answer is:

What is the global potential of Modular Floating Structures and circular floating breakwaters as an alternative for sustainable urban expansion at sea and what could be the implications for the global steel flows based on this potential?

To answer this main question, five sub questions were defined:

Sub question 1: *What are key factors that constrain or enable the implementation of MFS?*

Involves studying the design features and limits of MFS as an offshore dwelling alternative and identifying relevant limiting factors for floating structures for urban development in a literature review and expert consultations.

Sub question 2: *What are key factors that motivate the need for floating urban development?*

Involves identifying underlying motivation factors for urban expansion at sea in a literature review and expert consultations.

Sub question 3: *What are suitable locations for MFS implementation considering a) the technical potential and b) the motivation within the global territorial, internal and archipelagic waters?*

Involves designing an ArcGIS model using the factors of sub question one (technical potential) and two (motivation) as input and mapping the global technical potential (suitable - yes / not suitable - no), evaluated by the motivation as output.

Sub question 4: *What is the global potential, in maximum achievable additional space (km^2) and offshore population (#people) at sea?*

Involves suitable area (km^2) calculations based on the technical and motivation maps (sub question 2 a, b), translating this to an estimated offshore population and relating this to the global scale of coastal challenges.

Sub question 5: *What is the impact of the demand for floating breakwaters and MFS sub structure construction on the global steel flow based on the global potential?*

Involves a back-of-the-envelope calculation based the results of sub question 3 and 4, combined with literature about global steel scrap demand, supply and the ship-breaking industry and linking this to the circular economy of ships and global steel flows.

The geographical scope of these research questions is the World's territorial, internal and archipelagic waters.

1.5 Industrial Ecology and societal relevance

The earlier mentioned increasing number of publications on modular floating structures highlights the relevance and importance of this research field. As underlined by the United Nations (2022b), G. Wang, Drimer, and Goldfeld (2020) and other studies (Mandakini P. Bhatt, 2020; Umar, 2020; H. Yang et al., 2022) modular floating cities have the potential to enable sustainable urban growth. They are not only presented as a climate adaptive alternative, but also have the potential to mitigate climate change by e.g. reducing CO_2 emissions. The sustainable development of cities, or urban systems, are a well-discussed topic in the field of Industrial Ecology (Kennedy, 2016). In more detail, the field of Industrial Ecology tries to understand and mitigate the urban metabolism: which is enabling a cities' operation, growth and reproduction (Ulgiati & Zucaro, 2019).

While modular floating cities undoubtedly present a climate-adaptive alternative for coastal urban expansion, it poses many interesting questions in regard to environmental, social and economic sustainability. For instance, would the creation of extra land – requiring materials in a period marked by depletion of raw materials – be a promising alternative to building on existing land? What are other alternatives for climate-adaptive coastal urban expansion? If we compare these alternatives, which alternative has overall the lowest impact on the environment? Which alternatives could be combined? What are the technical, social and environmental trade-offs of all these alternatives? How would the marine environment and life be affected if we collectively start living on the water? How can a modular floating city be organized to optimize energy efficiency, water storage, and the use of renewable sources? Should it be interconnected with the city on the adjacent mainland or designed to be self-sufficient? If MFS would be implemented with floating breakwaters as a seawall, can the reuse of EOL ships make a dent in the circular economy of ships and steel?

By using an interdisciplinary approach, incorporating technical, environmental and social factors to explore the potential of MFS, a solid foundation is established to delve deeper into these questions. Having a sense of scale for modular floating cities is helpful for addressing these questions effectively. Identifying potential locations for MFS implementation helps tailor answers to match the specific local contexts. Additionally, a sense of scale enhances accuracy in estimating or evaluating environmental and social impacts. Furthermore, gaining insight into areas with strong motivation but limited technical potential for the implementation of MFS can lead to new research avenues. This could potentially guide future adaptation pathways, MFS design research or reshape ocean zoning plans to enable viable locations. The integration of technical, environmental, and social perspectives within the field of floating cities is closely linked to the systems thinking approach typical for the field of Industrial Ecology. This systems thinking approach is fundamental as floating cities are not isolated entities; they are intricately interconnected with various facets of all perspectives, such as global material flows, global economical flows, social structures, or ocean ecosystems. Recognizing and considering these interconnections, a systems perspective is adopted in this thesis.

The global potential explored in this thesis will give a first indication of the total suitable area (km^2) and number of people that, considering the given technical and zoning constraints, could potentially live at sea. This is translated to first estimations of global material use – required floating breakwaters and steel demand for the sub structures. Additionally, motivation for sea expansion is examined by taking into account motivating factors such as the risk of flooding and urban population growth. These results and the introduction of GIS as a tool in this research field will initially be of great relevance for the engineers and other project members of sustainable modular floating city initiatives, in particular the MFS project. The results and insights of this thesis could also be a valuable addition to the existing and rapidly growing bunch of literature about modular floating cities and their potential to address the related SDGs – to eventually get an idea whether this alternative is a fruitful pathway to commit to the worldwide pursued aspirations of the SDGs. This research will also be relevant to the field of Industrial Ecology, giving rise to numerous follow up studies addressing the sustainable development of coastal urban areas.

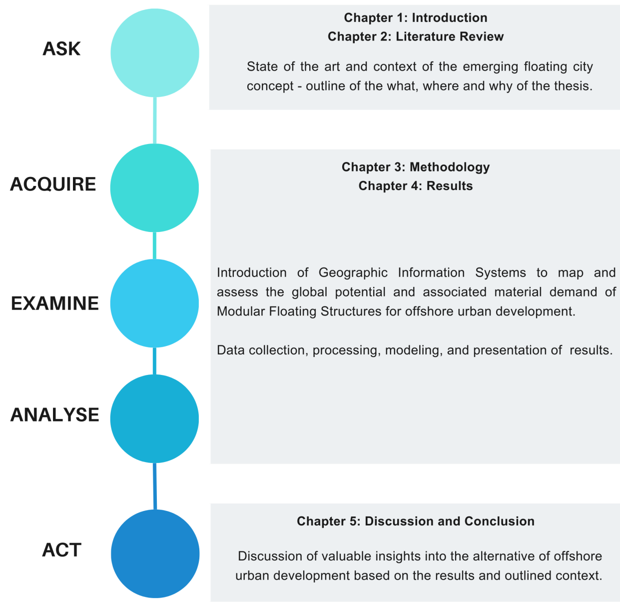

Figure 1.2: Visual overview of report structure, guided by the Geographic Approach (Artz & Baumann, 2009).

1.6 Report structure

The Geographic Approach (Artz & Baumann, 2009) is used as a guideline throughout this thesis. The geographic approach is described as a way of thinking and problem solving that is framed geographically and consists of five steps. For every step, the corresponding chapter(s) is/are indicated. The report structure is visualized in Figure 1.2.

Ask – what is the problem and where is it located;

Chapter 1: Introduction

Chapter 2: Literature review

Acquire – what data is needed for the analysis and where that data can this be found or generated, and;

Examine – inspection of the data, how is the data organised and where does the data come from, and;

Analyse – processing and analysing of data, based on the chosen method of examination or analysis depending on the goal of the study;

Chapter 3: Methodology

Act – how to present and share the results;

Chapter 4: Results

Chapter 5: Discussion, conclusion and recommendations

The following chapter provides an in-depth examination of the ”Ask” step. It includes a comprehensive literature review outlining the relevant context, design of MFS and factors influencing MFS implementation. In Chapter 3, the chosen methodology to answer the sub questions and main research question will be explained in detail, describing the methodology for the ”Acquire”, ”Examine” and ”Analyse” steps. Chapter 4 presents the main results derived from the ”Analyse” step and Chapter 5 will interpret and discuss these results, followed by a conclusion and future research recommendations - concluding the thesis with the ”Act” step.

2

Literature Review

To further outline the context, research gap and approach of this study, this chapter provides a systematic literature review regarding the floating city as alternative for coastal expansion. More in depth information and exploration will be given on a) the challenges faced by coastal cities, b) current adaptation and development strategies to combat these coastal challenges, c) the alternative of floating urban development – in particular Modular Floating Structures (MFS) and d) an exploration of the global potential of MFS.

2.1 Outlining the context - challenges faced by coastal cities

The worlds' coasts are on the frontline of the impacts of natural and climatic hazards. As a direct consequence of their geographical location, they are not only exposed to inland threats such as the natural earthquakes, volcano's, and also climate related increasing temperatures, wildfires, extreme precipitation and droughts, and air pollution but also to ocean-specific hazards such as coastal erosion, saltwater intrusion, and coastal flooding (Day et al., 2021; Neumann et al., 2015; Oppenheimer et al., 2019). The environmental and societal impact of these hazards are exacerbated by climate change and the observed trend of coastal migration. Moreover, intertwined with climate change and coastal migration is the increasing use of valuable land for urban purposes and consequent land scarcity.

Firstly, a positive trend of migration to coastal cities – coastal urbanization - has been observed in the past decades. Today, the worlds' population is about 8.1 billion. Projections anticipate an increase to 9.7 billion in 2050, and 10.7 billion in 2100 (United Nations, 2022c). Additionally, today about 55% of the worlds' population lives in cities – the urban transition. According to the World Urbanization Prospects Report of the United Nations (2022c) this percentage is expected to increase to 68% by 2050 - adding about 2.1 billion people to cities in the coming decades – marking the most substantial urbanization surge in history. This global urbanization trend is particularly pronounced in sub-temperate areas and coastal areas (Day et al., 2021; Seto et al., 2011). The majority of worlds' megacities (defined as cities with over 10 million inhabitants) are within 100 km of coasts and continually attracting a growing number of residents (Sengupta et al., 2018). Throughout history, these areas have always been attractive for human settlement due to the rich supply of natural and resources (like food and minerals), the regulation of local climates with associated ecosystem benefits, logistical reasons (ports offering marine trade and transport) or simply because of recreational, cultural, or spiritual reasons (Bell et al., 2015; Mawren et al., 2022; Yılmaz & Terzi, 2021). This attractiveness fosters coastal migration and forces to expand built-up areas to the surrounding landscape. Consequently, development and utilisation of coastal areas have greatly increased the last decades. For example, Day et al. (2021) reported that in the United States economic activities are predominantly centred in coastal cities, which thus play a substantial role in the productivity and quality of life of the country. However, this also implies that an increasing number of people, vital infrastructure and economic centres are being exposed to the potential impacts of intensifying natural and climate hazards in coastal areas (Kulp & Strauss, 2019; Neumann et al., 2015).

Secondly, climate change exacerbates the environmental impacts of coastal hazards, primarily via an acceleration of Sea Level Rise (SLR). Significantly increased greenhouse gas concentrations are driving global warming and long-term climate change. Consequences are thermal expansion of water bodies and melting ice sheets, both contributing to a notable increase of global sea levels. Historical data shows that in the 20th century global sea levels rose on average by 1.7 mm each year, whereas more recent satellite observations show an average yearly increase of 3 mm since 1993 (Church et al., 2013). Additionally, in their 5th Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) projected a global sea level rise (GSLR) of 26-82 cm by 2100 under four future greenhouse gas concentration scenarios (ranging from low (26) to high (82)). This accelerated rate of GSLR exceeded the previous predictions, as it was significantly higher than the alarming projection put forth in their 4th Assessment Report. However in their most recent Assessment Report they corrected this GSLR range up to 63-101 cm by 2100, catching up with other research (Horton et al., 2020; van de Wal et al., 2022); justifying serious concern. As a direct result of SLR, coastal flooding has become more pronounced and frequent and saltwater intrusion is significantly increased (Kulp & Strauss, 2019; Priyanka & Mahesha, 2015; Rasmussen et al., 2013). Moreover, SLR and the more intense and frequent occurrence of high-impact storms such as hurricanes or cyclones, both also linked to climate change, aggravate coastal erosion (Xu et al., 2021). For example, in the United States coastal cities like Miami Beach, Norfolk and Boston already experience an increase of disruptive floodings associated with climate change; in Africa (Hall et al., 2016; Ray & Foster, 2016; Wdowinski et al., 2016). And also on the other side of the ocean, in Maputo, Mozambique, and in Cape Town, South Africa, there have been increasing occurrences of coastal flooding (Dube et al., 2022). Taken together, these findings underscore the increased vulnerability of coastal areas in the face of climate change.

In literature, the rapid urbanization is also consistently associated with exerting tremendous pressure on natural resources such as raw materials and water and land, while also intensifying the competition for energy and food production (Godfray et al., 2010; Zucaro et al., 2022). The pressure on raw materials and land resources is illustrated below.

According to the UN report 'The Weight of Cities' (IRP, 2018), domestic material consumption (= raw material extraction + physical imports – physical exports of a country) is expected to increase by twofold by 2050, if today's policies remain unchanged. This is also reported in the Organisation for Economic Co-operation and Development (OECD) report 'Global resources Outlook for 2060, as they estimate domestic material consumption to double by 2060 (OECD, 2019). Roughly 75% of the domestic material consumption is being consumed within city boundaries. While these numbers imply an exacerbation of global material scarcity and related pollution, it's also an opportunity for developing climate mitigation and resource efficient cities. Studies on for example resource efficiency and urban mining in cities are gaining considerable interest in the last decade (Arora et al., 2017; X. Yang et al., 2022). Findings in this field of research could help in decoupling the material use of nations from their economic growth.

As megacities in developing and developed countries are expected to increase their size respectively by 3 and 2.5 times before 2030, urbanization also puts pressure on land resources (Angel et al., 2005, 2011). Generally, urban land expansion is growing faster than urban population (Mascarenhas et al., 2019). According to Mao et al. (2020) water and land resources are key determinants for optimal and limit city sizes. This is also implied by Li et al. (2022), as the authors conclude that large city centres have the highest built-up ratio to available land. As a large share of worlds' megacities is situated within 100 km of the coast their spatial growth is inherently bounded by the sea on one side, further limiting the availability of land for expansion and development. The pressing need to accommodate growing coastal populations and vital infrastructure within a confined land area adds a layer of complexity to the challenges these coastal cities face.

2.2 Projecting the future – coastal population at risk

Combing the rapid urbanization and coastal migration with the increase of GSLR, various studies have modelled future exposed populations on a global scale. A comprehensive review by McMichael et al. (2020) presents a comparative table with the key results of all studies between 1999 and 2020 that project exposed populations, including their used datasets, time frame and definitions. To get a good understanding of the size of the global coastal issues presented earlier, several studies reviewed by McMichael et al. (2020) are presented below. The studies were selected on the basis of publication year ($\geq$ 2015) and time frame (includes future projections) (Table 2.1). Studies are categorized on their aim; exposure to specified levels of SLR, exposed people living in flood areas and exposed people living in Low Elevation Coastal Zones (LECZ). The latter can be generally defined as the 'contiguous coastal area below 10 m above sea levels'.

It is challenging to estimate population exposure to SLR, however, all results are in the order of hundreds of millions of people. Key takeaways from these studies are that there is significant data uncertainty in both migration and population projections and sea level rise or socio-economic scenarios. Also, the importance of local variations

Table 2.1: Overview of studies estimating future exposed populations to SLR

Source	Timeframe	Definition Exposure	Results
Population exposure estimates to specified levels of SLR			
Brown et al. (2016)	2000, 2100	Population in coastal flood hazard zone (*below 1000 year return surge zone*), depending on socio-economic pathway and including effect adaptive measures (e.g. dikes).	By 2090, 134 million people are estimated to be flooded annually.
Kummu et al. (2016)	2030, 2050	Population below 5 m elevation above sea level.	By 2030 and 2050, respectively 460 million and 495 million are estimated to live in the zones below 5 m elevation above sea level.
Population living in coastal floodplains or storm surge zones			
Neumann et al. (2015)	2030, 2060	Population exposed to 100 year return coastal flood zones, depending on social economic pathway.	By 2030 and 2060, respectively 282.2 - 285.9 million and 315.5 - 411.3 million people are estimated to be living in the 100 year return coastal flood zones.
Kulp and Strauss (2019)	2050, 2100	Population living on land below the high tide line, or below the local annual flood height.	By 2050 and 2100, respectively 340 million and 630 million live on land below high tide and annual flood height.
Population living in low elevation coastal zones (LECZ)			
Neumann et al. (2015)	2030, 2060	Population living in LECZ, depending on socio-economic pathway.	By 2030 and 2060, respectively 879.1 – 948.9 million and 1052.8 – 1388.2 million people are estimated to live in LECZ.
Jones and O'Neill (2016)	2100	Population living in LECZ, depending on socio-economic pathway.	By 2100, 493 – 1146 million people are estimated to live in LECZ.
Merkens et al. (2016)	2050, 2100	Population living in LECZ, depending on socio-economic pathway.	By 2050 and 2100, 1005-1091 million and 830-1184 million people living in LECZ.

Note: Adapted from McMichael et al. (2020). SLR = Sea Level Rise; LECZ = Low Elevation Coastal Zones.

within global projections is highlighted, which will be addressed in more detail in the next paragraph.

Concluding, urbanization, coastal migration trends and increasing GSLR are putting coastal cities at the forefront of climate change. As such, both environmental and societal impact of coastal hazards are predicted to get worse in the future. Moreover, coastal urbanization is also associated with putting significant pressure on raw material use, land availability and the marine ecosystems, all of which are interconnected with climate change. Coastal cities are looking for sustainable and safe alternatives for more space for living, working, energy generation, food production and recreation while being protected from the increasing natural and climate hazards. While among the most vulnerable places, coastal cities are also recognized to be a key source of climate adaptive and resilient solutions in line with the SDG goals, as they are long-lived centres of innovation and economic activity (Glavovic et al., 2022).

2.2.1 From global trends to local variations

The previous paragraphs show proof for the overall trends of increasing urbanization, coastal migration, coastal exposure to GSLR and consequent pressure on natural resources. However, these trends show disparities and substantial variations across countries and regions (Neumann et al., 2015; Ritchie & Roser, 2018). Urbanization, coastal migration and land-use changes are very complex phenomena, relating to e.g. local population growth, economic development, land rates and policies and to each other and therefore hard to project. This paragraph tends to highlight some local variations that are standing out but will not further elaborate in detail on the underlying dynamics of drivers and barriers of these trends.

In literature continental and regional differences in urban population growth can be distinguished. In contrast to the first urbanization wave, which took place from 1750 onward in high-income countries - especially North America and Europe - the current global urbanization wave is particularly taking place in lower income regions in the Global South: Africa (especially Nigeria) and South East Asia (especially India and China) (Hennig et al., 2015; Schiller & Roscher, 2023; Sylla et al., 2023). Coastal migration is particularly pronounced in China, where the economic development and specific policies drive coastal migration (McGranahan et al., 2007). These regions are also projected to have the highest relative increase in urban land conversion and in raw material use for cities (cement, steel and sand) (IRP, 2018). Additionally, Day et al. (2021) stated that a big contribution of the urban growth the coming decades is within the coastal zone between 30 degrees North and South.

Accordingly, Hennig et al. (2015) state that Asia and Africa experience the highest urbanization rates and reveal that there are several regions in Europe where urban population is not growing or even declining. However, this study also highlights the fact that while the population is not growing, expansion of urban built-up areas is continuing in these European regions. In addition, Peponi and Morgado (2020) noticed two extremes in Europe; 165 million people live in fast growing cities, while 25 million people are living in shrinking cities. In line with this, another study estimated 42% of the European cities losing population (Haase et al., 2016). This underlines the importance of exploring local variations in a global trend. One thing worth highlighting regarding local and global variations in land use – indirect related to the issue of land scarcity – is that the highest relative urban land conversion rate in coastal areas (=% natural landscape or agricultural activities changed to urban built-up area) has been observed in China and South East Asia in the last decades (Neumann et al., 2015; Seto et al., 2011).

The impact of future SLR scenario's is often studied in terms of population exposure or asset exposure to coastal hazards induced by SLR in coastal areas. Literature studying population exposure to SLR converges at the point that the majority of the exposed population lives and will be living in low-income countries, particularly Africa and Asia – related to the excessive projected urban population growth in these areas (McGranahan et al., 2007; Merkens et al., 2016; Neumann et al., 2015). A study by Neumann et al. (2015) projected the population living in LECZ by taking into account the UN population projections, socio-economic development pathways and SLR scenarios. According to this study, Asia has the largest LECZ population (461 million) and is projected to be also the case for 2060, under each of the four pathways – inherent to its large population. In the coming decades, there will be a shift from Eastern Asia (e.g. China, Hong Kong, Japan) to Southeast Asia (e.g. Bangladesh, India, Pakistan, Sri-Lanka, Maldives, Vietnam, Indonesia) and these Southeastern regions will house the majority of LECZ population globally. Africa on the other hand, has lower absolute numbers in LECZ population (54 million in 2000), but will experience the highest rates of growth in all scenarios (up to 174 million by 2060) – especially in Western Africa (e.g. Nigeria, Benin, Cote d'Ivoire and Senegal). Europe does not stand out in absolute LECZ population numbers or projected growth rates. However, Western Europe stands out with the most densely populated LECZ among the European regions, of which half of the population is living in the Netherlands and is expected to keep this European ranking in the coming decades. North America has the second largest LECZ extent; however, the absolute LECZ population is low in comparison to the other continents. This share of coastal population is projected to grow in the coming decades, particularly in the US, to absolute numbers close to the Southeast Asian countries. South America, the Caribbean and Oceania are not standing out in absolute LECZ population or growth rates. Within these continents, Brazil and Argentina are contributing most to the LECZ population now and in the future. These results can be compared to other studies. A study from Hanson et al. (2011), also using UN population projections and socio-economic pathways shows the same trend; While this study considers port cities instead of countries and continents, same trends are visible. In terms of absolute numbers. cities in India (e.g. Kolkata), Bangladesh (Dhaka) China and US are projected to have the highest exposed population in 2070. The list of relative population increase exposed only shows cities in Southeast Asia and Africa – similar to the findings of Neumann et al. (2015). This study also explored projected asset exposure resulting in the inclusion of the Netherlands, US and Japan in the list. Lastly, Day et al. (2021) reviewed literature on coastal cities, climate change and sustainability. Their indication of coastal cities significantly impacted by sea level rise in 2050 reveals the same trend as described above; in terms of absolute population numbers exposed Africa and South East Asia are leading. Important note is that these studies are not taking into account current flooding adaptation measures.

This paragraph makes clear that global trends need local exploration to uncover nuances and identify hotspots where action might be needed the hardest, as also emphasized by Mao et al. (2020). It is evident that while the higher income countries in Northern America and Europe already have significant level of coastal urban development, the coastal cities of low income countries are expected to experience the highest population growth and SLR exposure rates in the coming decades, with Southeast Asia leading in absolute numbers and Africa in relative numbers.

2.2.2 Sustainable Development Goals

The aforementioned attractiveness of coastal areas relates to the critical role of oceans, seas and coastal areas in sustaining the Earth's ecosystems and the increasing development centred in and around cities were acknowledged by the UN in 2015. The UN emphasized the need for "conservation and sustainable use of the oceans and seas and of their resources". Therefore, SDG 14 specifically commits to these aspirations and is included in the 2030 Agenda of Sustainable Development. Specific targets for this goal and are concerning reduce marine pollution and acidification, protect and restore ecosystems, conserve coastal and marine areas and promote sustainable use of marine resources – particularly for developing countries. The projected population growth, rapid urbanization – pronounced in coastal areas – and the increasing GSLR risks are covered in SDG 11. "Sustainable Cities and Communities" was set up by the United Nations to address social and environmental issues that cities face. Their goal: maintaining prosperity and city growth without straining land and resources. The targets are primarily focus on social inclusion, equity and ensuring access to adequate housing, climate adaptivity, disaster risk reduction and supporting least developed countries in this. The challenges such as competition for and depletion of natural resources is covered in SDG 12. "Responsible consumption and production" aims to promote sustainable and efficient resource use as well as encouraging eco-friendly production processes. By targeting areas such as material consumption, SDG 12 strives to minimize negative environmental impacts. See Figure 2.1 for the three described SDGs.

Figure 2.1: Sustainable Development Goal (SDG) 11, SDG 12, SDG 14. Adapted from KIT (2023)

2.3 Strategies for coastal urban expansion

Concluding, coastal areas need future development pathways to deal with the challenges of increasing urban migration, growth, increasing threat of rising sea levels and increasing land scarcity. This requires integrating both climate mitigation and adaptation approaches.

These global coastal challenges call for global solutions. While some advocate coastal adaptation and mitigation strategies, others discuss the alternative of floating urban development. The most relevant and prevalent urban development strategies in respect to land limitations and sea level rise will be outlined in this paragraph to further examine the current context in which the alternative of floating cities is being developed. These urban development and growth strategies do not have to be mutually exclusive, as they can also be integrated in future coastal urban development pathways.

2.3.1 Strategies for climate adaptive urban development

In reaction to GSLR and increased vulnerability of coastal cities the last decade several strategies and alternatives have been discussed in literature. Generally, adaptation strategies to combat the challenge of SLR and its consequent flooding for coastal cities can be classified in protect, accommodate, advance and retreat (Glavovic et al., 2022; Oppenheimer et al., 2019). In the past decades some coastal cities have been integrating some of these strategies, adapting to meters of SLR already. This paragraph will give an overview of these strategies and their relation to floating cities. All statements presented in this paragraph are referenced from the IPCC Cross-Chapter 'Cities and Settlements by the Sea' written by Glavovic et al. (2022), unless specified otherwise.

Protection for coastal cities

Protection of coastal cities is generally divided into hard engineering, soft engineering and nature-based protection. Hard measures include for example breakwaters, sea walls, or dikes and usually have the potential to be complemented with large barriers or 'super-levees'. These adaptation measures are focused on reducing coastal flooding and storing or draining excess water from extreme precipitation events. While effective on short and medium term and widely implemented, it is suggested that technical limits to hard protection may be reached in 2100 for many regions. Soft measures include more sediment-based interventions, such as beach nourishment. This is a widely applied strategy in cities at open coasts. While believed to have a lower impact on coastal ecology and construction costs and materials than hard engineering measures, there are clear limits to this strategy in terms of availability of sand, a scarce resource. Nature-based methods can reduce inland propagation of increased sea levels and can reduce wind-driven waves. For example, mangroves are reported to significantly vertically reduce sea levels behind them; attenuate wind-driven waves and reduce coastal erosion. Seagrass meadows and coral reefs are believed to reduce wave energy; the latter even by 97%, however, this is only effective in limited water depths. In many cases, nature-based solutions are implemented in combination with hard engineering measures.

Accommodation of the built environment

While the previous strategies are primarily focussed on preventing the coastal area from being flooded, this strategy focussing on using exposed land but reducing exposure of coastal infrastructure, residents, ecosystems and activities to floodings. This can be done by avoiding new development in zones prone to major flooding or intense coastal hazards, by elevating houses and infrastructure, integrating flood-proof or amphibious design, increasing water drainage and storage, or implementing early warning systems. This strategy can proof very effective for small changes of SLR but is primarily implemented as an interim solution to buy some time while preparing for strategies to combat more significant SLR and severe coastal hazards.

Advance to sea

The advance strategy entails creating new land seawards, above sea level, reducing risks for the hinterland and the new elevated land. For many decades, coastal land reclamation has been viewed as a viable solution for increasing available land. However, both from a technical (seabed depth and quality) and an environmental (impacts on marine ecosystems, material availability) point of view conventional land reclamation has been discovered to be a wasteful and unsustainable approach (Duan et al., 2016; Peduzzi, 2014). Furthermore, the newly created available land is still vulnerable to future sea level rise. The use of floating structures to increase the available land has been considered to be a more sustainable alternative and is introduced in the last version of the IPCC report as a potential advance strategy which should be researched more. This alternative is the focus of this thesis and worked out in detail in Paragraph 2.4.

Retreat from coastal areas

This is a strategy reducing the exposure by moving people, assets and activities out of high risk coastal areas. This entails migration, involuntary displacement and / or planned relocation away from the coast. The interest in this strategy is becoming increasingly popular; in their systematic literature review, O'Donnell (2022) report a marked increase in academic research into retreat policies. Additionally, in the last decade a few small islands purchased land from other countries to facilitate relocation. While the retreat strategy has the potential to effectively reduce exposure of people to coastal hazards and provide recovery of marine ecosystems, it is still a controversial and difficult strategy to implement, especially in terms of social equity and cultural ties. Literature on planned retreat make an appeal for more research into an environmentally and socially just approach for retreat, particularly in the Global South (Ajibade, 2019). Moreover, the availability and affordability of land away from the coast is brought up as a limitation and should be evaluated further.

In the IPCC Cross-Chapter 'Cities and Settlements by the Sea', Glavovic et al. (2022) underline the importance of combining the presented strategies for an effective adaptation pathway. Also, they underline that for adaptation pathways the local, geographical context is particularly important, as some of the strategies or combinations require certain environments, investments, technical knowledge or materials.

2.3.2 Strategies for urban growth in the light of land scarcity

The issue of finite and depleting land resources and the consequent need for efficient, sustainable land use for urban growth is a well discussed topic in literature. A commonly used term associated with the urban population growth, large uses of land and sustainable urban development is 'urban sprawl'. While in literature there is no agreement on a precise definition of this term, there is a general consensus that urban sprawl is 'characterized by an unplanned and unbalanced growth pattern, driven by many processes and leading to inefficient resource consumption' (Bhatta et al., 2010). This uncontrolled conversion of natural land to urban uses is an ongoing process which has an irreversible impact on losses of farmland, fragmenting habitats, affecting local climates and threatening biodiversity (Bounoua et al., 2018; Seto et al., 2011; Zitti et al., 2015). According to Koziatek and Dragićević (2019) urban sprawl and land-use conversion are 'recognized as one of the contributors to climate and environmental changes'. Not only environmental impacts are associated with urban sprawl; studies show that is also associated with driving inequality and enhancing social segmentation (Habibi & Asadi, 2011). As mentioned before, generally urban land expansion is growing faster than urban population, suggesting that urban growth is becoming more widespread than compact (Mascarenhas et al., 2019). While the negative impacts of valuable land conversion are a global issue, coastal cities in particular face challenges regarding land and urban growth as mentioned before – particularly prevalent in low-income countries in Africa and Asia, having the highest rate of urban population growth and urban land expansion (Mao et al., 2020; Neumann et al., 2015). In reaction to land scarcity, environmental and social impacts of urban sprawl, strategies to control and maintain urban growth without straining land have been widely explored in literature.

The compact city – city densification and vertical growth

A prevalent strategy to tackle the finite valuable land challenge that is discussed in literature published in the last decade is the 'compact city', by means of city densification (Dehghani et al., 2022; Nadeem et al., 2022). Khosravi Kazazi et al. (2022) and Mouratidis (2019) state that compact city and city densification strategies are integrated into contemporary urban planning policies and are predominantly implemented in cities as a reaction to accelerated population growth and land scarcity. Compact cities entail high-rise, high-density, mixed-use development and a well-managed transport system (Nadeem et al., 2022). A bulk of literature shows that the 'compact city' is often promoted as a sustainable strategy for urban growth, both environmentally, economically and socially. Claimed advantages of city densification consider the conservation of valuable land, but also environmental advantages such as optimizing existing services (transport, waste management), minimizing environmental impact, reducing costs and promoting social equity – if well-managed (Fan & Chapman, 2022).

However, it's also criticized on some aspects. Opponents argue that if not defined, designed and managed well, compact cities require more materials and enhance the urban heat island effect (urbanized areas experiencing higher temperatures than outlying areas) and social unevenness (Dehghani et al., 2022; Herburger, 2023; Mahtta et al., 2019). Also, literature shows that the local and geographical context is very important to consider when evaluating the sustainability of a 'compact city' (Fan & Chapman, 2022; Mao et al., 2020). Furthermore, Z. Lin and Gámez

(2018) quote relevant debates, revealing that compact city practices and policies are primarily tied to urban forms in high developed countries. In line with this, Koziatek and Dragićević (2019) report that the interest in the compact city and city densification has primarily been concentrated in high developed countries, such as US, Japan and Australia. In addition, because of significant challenges of limited availability land Europe has also been pushing compact city policies for many decades.

This paragraph presented compact cities as a relevant, sometimes already implemented strategy for coastal cities to cope with excessive coastal population growth with limited land availability. Material use, environmental impact and social impacts are still open for debate and largely depend vertical growth design and on local contexts. There is however proof of potential in the light of land scarcity. For instance, Amer et al. (2017) present an approach for urban densification (roof stacking) and conclude that densification of European cities has a great potential; for example, about 30% of the population increase could be accommodated by roof stacking on existing buildings in Brussels. It is a relevant strategy to consider in the context of the potential for floating urban development; both are presented as strategies for land scarcity in coastal areas.

2.4 Floating urban development

One alternative to overcome these major coastal challenges advancing to sea. The concept of floating urban development has emerged in the last decade, however, the implementation is still limited to small scale projects. This paragraph introduces and evaluates the state of art of urban development at sea, in particular the concept of MFS introduced by G. Wang et al. (2019). Lastly, the transition from feasible small scale projects to larger scale will be discussed – the focus of this thesis.

2.4.1 Floating structures – state of the art

With humanity residing on water for centuries, the concept of floating cities has gained renewed interest in the last decades, driven by the coastal challenges mentioned earlier. General floating structures are currently primarily used for energy production (wind farms, solar cells), agriculture and oil and gas extraction. The number of small scale projects using floating structures for urban purposes is growing. Some notable examples can be found in the Netherlands; including the Schoonschip and Waterbuurt in Amsterdam and Rietgors, Delft Harnaschpolder (Blue21, 2023b; Stedenbouw, 2019). See Figure 2.2) for an illustration of these projects.


Figure 2.2: Floating structures for urban purposes. Projects Harnaschpolder, Delft (left), adapted from Blue21 (2023b) and Schoonschip, Amsterdam (right), adapted from Stedenbouw (2019)

2.5 Strategies for coastal urban expansion

Several studies investigated the concept of Very Large Floating Structures which could overcome the technical and some environmental disadvantages of conventional coastal land reclamation (Lamas-Pardo et al., 2015). VLFS are manmade, naval structures, usually larger than conventional marine structures such as ships or barges. Despite being a well-studied concept, the actual implementation of VLFS is limited. This is mainly due to technical complexity, environmental impacts (such as the marine local light climate), high costs and policy regulation. Furthermore, VLFS are usually designed to have a single purpose, which limits flexible, lean urban development (Lamas-Pardo et al., 2015; G. Wang et al., 2019). It is evident that the exploration of other solutions is needed to facilitate integrative offshore urban development in coastal regions. One solution that is presented is the concept of a modular floating city, solving many of the deficiency's mentioned above (G. Wang et al., 2019). By using small modules as building units, dynamic urban expansion possible. Modular floating urban development has been explored conceptually by various authors as stated in (G. Wang, Drimer, & Goldfeld, 2020). Notable examples of individual floating city projects include the Oxagon City in Saudi Arabia, Oceanix Busan in South Korea - partner of UN Habitat - and Maledives Floating City, of which the latter is currently in development (NEOM, 2023; Oceanix, 2023; Waterstudio.NL, 2023). See Figure 1.1 for an illustration of Oceanix Busan and Maledives Floating City.

However, although presented as a promising solution, the concept of modular floating cities is not studied sufficiently to create a realistic and viable alternative for offshore urban development on a larger scale. According to G. Wang, Drimer, and Goldfeld (2020) in the last years significant steps forward have been made in the field of fossil and renewable energy industry offshore technologies. These actual offshore technologies are however too robust and industrial for urban purposes. To narrow the gap between utopian architectural proposals and actual recent offshore projects G. Wang, Drimer, and Goldfeld (2020) provided suitable engineering solutions and design methodologies for MFS.

2.5.1 Modular Floating Structures

MFS are presented as an alternative for offshore urban dwelling. G. Wang et al. (2019) present the concept of MFS as a 'unique, new and sustainable solution for addressing issues related to coastal urbanization and sea level rise'. Moreover, the authors describe the potential of MFS to decrease pressure on natural land to urban areas conversion – related to reducing greenhouse gas emissions - while complying to demand of real estate – relating to urban population growth - and making use of existing infrastructure. This paragraph will explore the key design features and feasibility of MFS with circular floating breakwaters, from an environmental, occupant comfort and extreme values perspective.

Design: feasibility and occupant comfort analysis

The concept of MFS can be described as individual floating modules ("twin-hull Module9000"), consisting of a substructure (barge) and superstructure (buildings) that are combined to form a multi-body configuration and a unified, large-scale platform. The size of the unified platforms will approximately be 500 x 400 m and can be spatially arranged with other platforms (see Figure 2.3). In the context of 'proof of technology' for MFS a series of studies by Wang and colleagues has addressed various aspects of their feasibility. G. Wang et al. (2019) initiated the research by outlining the necessary design guidelines, emphasizing the interdisciplinary nature of MFS involving naval architecture and civil engineering. Comfort, particularly the ability to perform "well" of MFS in various sea states (seakeeping quality), was found to be pivotal in public acceptance. The research confirmed the feasibility of MFS from a structural perspective, with a focus on safety and comfort, leaving spatial planning and environmental impact for future investigation.

Subsequent studies explored occupant comfort – relating to the overall well-being of individuals in a particular working or living environment - of a single "twin-hull Module9000" in different environmental conditions (G. Wang, Rosenfeld, et al., 2020). The results indicated that a single MFS module reaches performance limits at a certain sea state, and the study emphasized the importance of wave heading on occupant comfort. Another study further analysed open water performance of MFS, now consolidated in a multi-body configuration, with the aim to increase the allowable sea states while safe guarding habitability and residential comfort (see 'part of the hydrodynamic model' Figure 2.3). This study evaluated its efficiency in operational weather – referred to as Service Limit State (SLS) - and extreme storms – referred to as Ultimate Limit State (ULS) (G. Wang, Drimer, & Goldfeld, 2020). It also explored the concept of converting ships into floating breakwaters to reduce wave amplitudes, also promoting a circular economy approach. The environmental input for this study is a calm sea zone in Singapore (with wave periods of 5-7 s and significant wave heights of 1-1.8 m), and an open sea zone in the Eastern Mediterranean Sea (with wave periods of 10.9 - 15.89 s significant wave heights of 4 – 8.5 m). The results show that in calm waters, with wave heights up to 3.0 m, the MFS multi-body configuration performs satisfactorily in terms of occupant comfort without the use of floating breakwaters. With the use of floating breakwaters, the performance was adequately beyond the significant wave height of 3.0 m (up to 8.5 m), validating the potential of a multi-body MFS configuration with floating breakwaters, both in sheltered and open water conditions. These studies collectively shed light on the complexities, and performance of the MFS design and highlighted the need for further exploration in areas such

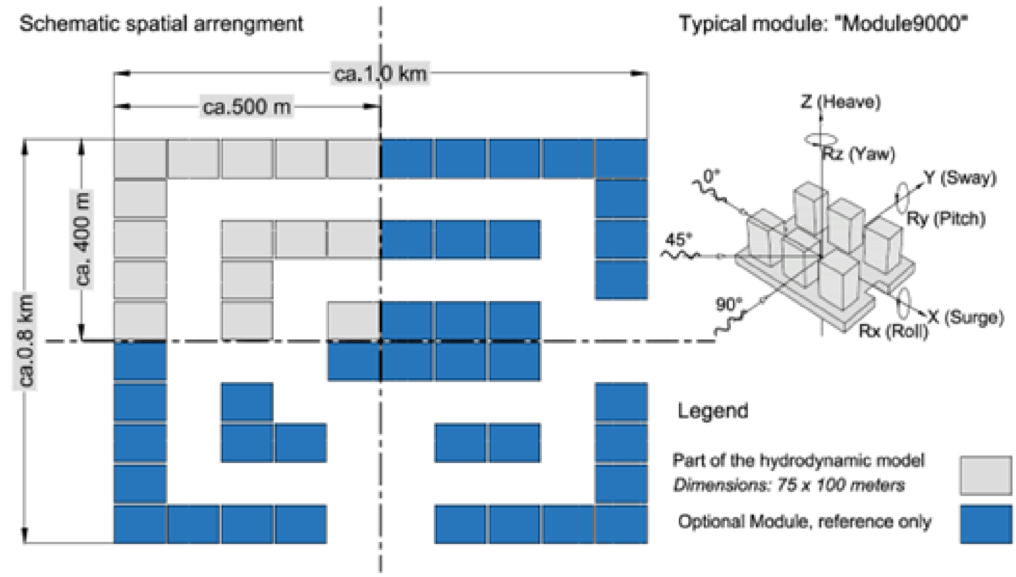

Figure 2.3: Spatial arrangement of MFS "twin-hull" modules, as presented in G. Wang, Drimer, and Goldfeld (2020)

as cost-benefit analysis, spatial planning, and environmental impact. The most recent study further focused on the potential for wave attenuation of the floating breakwaters (G. Wang et al., 2023).

Circular floating breakwaters: stretching the limits

(G. Wang, Drimer, & Goldfeld, 2020) introduce the concept of using EOL ships as floating breakwaters to stretch the limits of the offshore MFS platforms. A promising concept with could potentially save costs, manufacturing time and waste and influence the environmental and social impact of the ship-breaking industry. The proposed design of a floating breakwater is presented in Figure 2.4. To gain a better understanding of this concept, it is necessary to explore the current ship-breaking industry.

The global merchant fleet has around 90 000 ships. 1-2% come to their end of life each year (Solakivi et al., 2021). These end-of-life ships are in most cases being recycled to scrap – so called ship-breaking. The steel scrap recovered from dismantled end-of-life (EOL) ships are primarily used in the construction sector and sometimes in simple household or office equipment (Senavirathna et al., 2022; Shaiful Fitri Abdul Rahman et al., 2018). The ship-breaking process is currently primarily carried out in three countries: Bangladesh, India and Pakistan (Hossain et al., 2016; Shaiful Fitri Abdul Rahman et al., 2018). These ships yards offer the best prices for ship owners, while also known for the bad conditions of ship-breaking. Main drivers that moved the ship-breaking industry to the unregulated 'bad' shipyards in the global south are evident and should be considered carefully. Firstly, these developing countries are big consumers of steel, and have no or little virgin ore; as such, the use of secondary steel scrap from the ship-breaking industry accounts for a large share of domestic steel production in these countries. For example, over 60% of local steel production in Bangladesh is sourced from the ship-breaking industry (L. Lin et al., 2022; Senavirathna et al., 2022). Secondly, the ship-breaking industry offers lots of job opportunities; about 50 000 people are estimated to work in the shipbreaking industry in Bangladesh, where jobs are generally scarce. Therefore, these countries are willingly to import EOL ships for their local economy and job market and making these ship-breaking yards economically attractive for shipowners. The working conditions in those countries are very dangerous, often done by children and the used recycling process is a significant source of marine pollution (Wan et al., 2021). This is uncontrolled and often not in accordance with the current shipbreaking conventions and regulations and is seen as a serious problem by multiple review studies including Barua et al. (2018) and Hossain et al. (2016). Several studies propose solutions. These solutions are often focused on making 'green' recycling yards economically more attractive by minimizing costs for 'green' recycling, improving management and organization on-site and investing in scrap technology (Jain et al., 2017; Zhou et al., 2021).

However, as stressed by L. Lin et al. (2022) it should be considered that by shifting or decreasing workload in the ship-breaking industry jobs are potentially taken away and this can have negative social and economic impacts, particularly in countries like Bangladesh, India and Pakistan. In addition, if EOL ship import would decrease in countries like Bangladesh, short-term shortage in the steel supply might occur in these countries. Additionally,

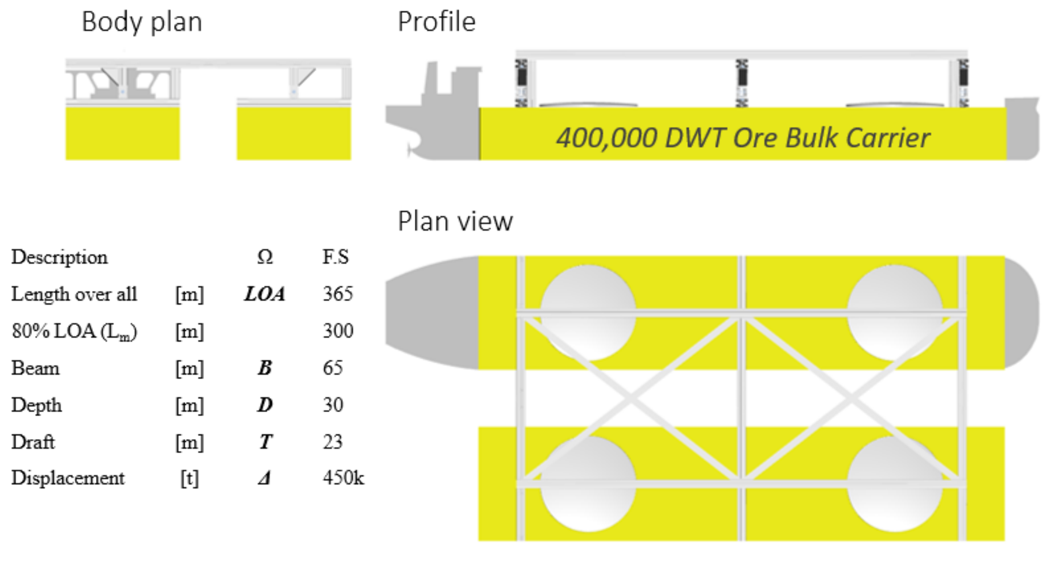

Figure 2.4: Proposed design of floating breakwater, as presented in G. Wang et al. (2023)

several articles point out a dramatic increase in EOL ships up to 2050. The large number of ships now in use will result in a significant, potentially 5 times increase (55 – 68 Million tons (Mt)/yr compared to the current 10 Mt/yr) of EOL ships compared to the current gross tonnage (L. Lin et al., 2022). These numbers are roughly in line with the more recent study of Kong et al. (2022), however, the predictions of gross tonnage in 2050 are slightly lower (up to 50 Mt). Relating this to a study by Pauliuk et al. (2013) addressing future global steel flow predictions reveals that this is about 5-6% of the global old scrap supply (in Mt/yr) in 2050. Both articles stress that the current ship-breaking capacity is insufficient to handle this fast growing number of EOL ships. This would be even more pressured by greener and stricter ship-breaking regulations proposed above.

In addition to this, the global steel demand and scrap supply flows reveal that from 2030 onwards, old scrap (secondary steel) supply is expected to exceed yearly construction demand, the common reservoir for old scrap. The impact of extended lifespans of ships by more sustainable and durable designs will impact the inflow of new ships for the coming decades. Extending the lifespan of a ship by downcycling a EOL ship to a floating breakwater will extend the use of the ship, however, not in its original function. Steel recycle rates after the reuse as circular floating breakwaters are not to be found in literature yet, and the effect of this potential alternative on the steel flows within the ship industry and on the global steel flows is still unknown. Also, as pointed out by Senavirathna et al. (2022), the process of reuse of marine structures is often overshadowed by the recycling process. Only about 0,4% of the merchant fleet are being reused, opposite to 95% recycling. Following Senavirathna et al. (2022) reuse should be prioritized more in the ship-breaking industry to become more sustainable, both for the social (safer) and environmental (less polluting) aspect of the ship-breaking.

Literature about the potential of using EOL ships as circular breakwaters is scarce. In addition to the tests ran by G. Wang et al. (2023) to prove and evaluate the potential of end-of-life ships as floating breakwaters, one other author assessed the effectiveness of this novel concept. Lázaro et al. (2013) however assessed one individual ship, whereas G. Wang et al. (2023) evaluated a constructed seawall, using multiple ships in two configurations. Based on the test, both studies demonstrate a great potential of using ships as circular floating breakwater, significantly attenuating incident wave heights.

Thus, by introducing the possibility to reuse end-of-life ships as floating breakwaters might contribute to the circular economy and mitigate in the poor working conditions of the ship-breaking industry.

2.5.2 Proof of technology to proof of scale – exploration of relevant factors for global MFS potential

Paragraph 2.4.1 gave an overview of the state of the art of floating urban development and highlighted the MFS design of G. Wang et al. (2019). 'Proof of technology' is researched and widely discussed in literature; however, 'proof of scale' is not. While literature about the floating urban development potential is scarce, there is literature available on more 'simple' floating structures such as floating wind farms or aquaculture and their technical potential. Studies research or review factors on the basis of which suitable locations are selected. A synthesis of the factors found in the selected literature can be found in Table 2.2. The information in this table will be used to substantiate the answer to sub question 1 of this thesis.

2.6 Summary and synthesis of findings

In summary, this literature review has highlighted the key challenges currently faced by coastal cities, including the pressures of growing populations and their proximity to a significant rise in sea levels. These challenges are intricately connected to the increasing vulnerability of coastal cities to the consequences of sea-level rise and the limited availability of land in these urban areas. Notably, the global challenges vary on local scale.

Strategies to address these coastal challenges, which have already been put into practice, encompass urban densification, conventional land reclamation, and climate-adaptive measures aimed at safeguarding coastal cities from the impacts of SLR. Within this more in the current regime embedded solutions, the innovative alternative of expanding towards the sea offers a promising avenue for urban development. Offshore development is predominantly employed for industrial purposes at present; offshore development for urban purposes requires more advanced designs, stricter guidelines and thorough impact assessments. Moreover, as this concept is promoted to provide a solution to the aforementioned global challenges, it requires deep exploration of the large-scale potential and implications on a global scale - which has not received as much research attention yet. As an attempt to tackle this research gap, connections to the field of offshore industrial development, such as wind parks and aquaculture were drawn. This gave insights how to establish 'proof of scale' and potential, using GIS.

As such, this literature review connected the motivating factors for urban expansion at sea with the current state-of-the-art and knowledge about the design, technology and feasibility of floating development, in particular MFS. Lastly, this was complemented with literature about technical potential assessments in the field of offshore industry development. This gathered knowledge will be used in the following chapters to establish a method to explore the proof-of-scale, from a technical and motivation perspective, and implications on a global scale for offshore urban development.

Table 2.2: Overview of relevant factors for the implementation of floating structures

Factor	Short Description	Sources
Bathymetry	Bathymetry (water depth) could constrain the deployment of MFS, as there could be a minimal and maximal depth for floating structures.	*VLFS*: Sankalp and De Leeneer (2020) and Somansundar and Panneer Selvam (2019) *Offshore wind*: Castro-Santos et al. (2020), Díaz and Guedes Soares (2020), Díaz et al. (2019), Melissas and Asprogerakas (2022), Nie and Li (2018), Schallenberg-Rodríguez and García Montesdeoca (2018), Umoh and Lemon (2020), and Zhang and Wang (2022) *Other floating structures*: Perez et al. (2005) and von Thenen et al. (2020)
Wave statistics	Wave statistics include significant wave height, wave period, wave frequency, wave amplitude, wave energy, wave direction. These statistics describe the wave climate in areas. Certain sea states limit the implementation of floating structures.	*MFS*: G. Wang, Drimer, and Goldfeld (2020) and G. Wang, Rosenfeld, et al. (2020) *VLFS*: Ding et al. (2017, 2021), Ohmatsu (2007), and Sankalp and De Leeneer (2020) *Offshore wind*: Díaz and Guedes Soares (2020) and Melissas and Asprogerakas (2022) *Other floating structures*: Perez et al. (2005)
(Coastal) seabed slope	A steep slope could contribute to certain unfavorable ocean states (waves).	*Offshore wind*: Díaz and Guedes Soares (2020)
Marine protected areas	Certain sea states limit the implementation of floating structures.	*Offshore wind*: Díaz and Guedes Soares (2020), Díaz et al. (2019), Nie and Li (2018), and Schallenberg-Rodríguez and García Montesdeoca (2018) *Other floating structures*:Perez et al. (2005) and von Thenen et al. (2020)
Military areas	Certain parts of the ocean and seas are dedicated to military purposes. In these areas implementation of floating structures is limited because of environmental reasons.	*Offshore wind*: Díaz and Guedes Soares (2020), Díaz et al. (2019), Schallenberg-Rodríguez and García Montesdeoca (2018), and Umoh and Lemon (2020)
Ports and shipyards	Ports and shipyards can limit implementation of floating structures because of zoning reasons.	*Offshore wind*: Castro-Santos et al. (2020)
Shipping routes	Certain parts of the ocean and seas are dedicated to military purposes. In these areas implementation of floating structures not possible for safety reasons.	*Offshore wind*: Castro-Santos et al. (2020), Díaz and Guedes Soares (2020), Díaz et al. (2019), Melissas and Asprogerakas (2022), Nie and Li (2018), Schallenberg-Rodríguez and García Montesdeoca (2018), and Umoh and Lemon (2020) *Other floating structures*: von Thenen et al. (2020)
Underwater cables and pipelines	Certain parts of the ocean and seas are dedicated to military purposes. In these areas implementation of floating structures not possible for safety reasons.	*Offshore wind*: Díaz and Guedes Soares (2020), Díaz et al. (2019), Melissas and Asprogerakas (2022), and Nie and Li (2018) *Other floating structures*: Perez et al. (2005) and von Thenen et al. (2020)
Existing infrastructure	Existing infrastructure includes wind parks, mineral extraction sites, oil/gas platforms, fish banks/stationary fishing nets. In these areas implementation of floating structures is limited for practical reasons.	*Offshore wind*: Castro-Santos et al. (2020), Díaz and Guedes Soares (2020), Díaz et al. (2019), Melissas and Asprogerakas (2022), Schallenberg-Rodríguez and García Montesdeoca (2018), and Umoh and Lemon (2020) *Other floating structures*: Perez et al. (2005) and von Thenen et al. (2020)

3

Methodology

In this chapter, an overview of used methods is presented. The methodology is based on Geographical Information Systems (GIS), with input aligning with existing literature and/or collected through iterative expert consultations. The methodology is based on answering the sub questions posed in the Introduction:

Sub question 1: *What are key factors that constrain or enable the implementation of MFS?*

Sub question 2: *What are key factors that motivate the need for floating urban development?*

Sub question 3: *What are suitable locations for MFS implementation considering a) the technical potential and b) the motivation within the global territorial, internal and archipelagic waters?*

Sub question 4: *What is the global potential, in maximum achievable additional space (km^2) and offshore population (#people) at sea?*

Sub question 5: *What is the impact of the demand for floating breakwaters and MFS sub structure construction on the global steel flow based on the global potential?*

3.1 Geographical Information Systems

GIS is a powerful system used in various fields of research to capture, store, analyse, and visualize spatial data (Esri, 2023). It allows for understanding and interpreting geographic information by integrating maps, data, and analytical techniques. A map can consist of one or multiple layers, each representing certain data with a spatial reference. The software that is used in this thesis is ArcGIS Pro version 3.1, produced by Esri.

Studies mentioned in Paragraph 2.4.3 prove that GIS is a suitable tool to explore the technical potential for offshore structures and their methods can be used as inspiration for this study (Peters et al., 2020).

3.2 Design of the GIS model

To answer the research questions introduced in Chapter 1, I conducted a Literature Review and designed a GIS model. The input for the GIS model are data layers of identified relevant factors for establishing the technical potential. The GIS model combines them and generates technical potential maps as an output. This output is then combined with layers representing motivational factors to get a comprehensive overview of the global potential of MFS. On the basis of these output maps, calculations were performed, estimating the maximal achievable area where MFS could potentially be implemented, the offshore population and required materials – also in regard to the motivational potential. This section elaborates in detail on the GIS model design steps. An overview of the methodology can be found in Figure 3.1,, Figure 3.2, Figure 3.3, Figure 3.4 and Figure 3.5. The steps and decisions taken are also briefly described below. For a step by step description of all the analysis performed in GIS, see the

Figures B.2-B.10 and Tables B.3-B.7 in Appendix B. The ArcGIS Project and Python code for data preprocessing and the GIS model are attached in the ZIP folder of this thesis.

3.2.1 Geographical and temporal scope

The aim of this thesis is to establish a model that explores the global potential of MFS. Therefore, the geographical extent is worldwide. More specifically, the total area of all territorial waters (12 nautical miles), internal waters and archipelagic waters, covering roughly about 6% of Earth's oceans and seas, is chosen as the geographical scope for this thesis (NOAA, 2023b). Territorial, internal and archipelagic waters refer to the internal and coastal waters adjacent to a nation's land territory. According to the Oxford Online Dictionary, these waters are considered an extension of a country's land territory, and subject to its jurisdiction and control (Oxford University Press, 2023). Beyond the territorial waters, implementation of MFS is assumed not relevant as this is not under full sovereignty, thus limited control, of the adjacent coastal state. The temporal scope of the technical potential is fixed (static), grounded in current data of topographical, environmental, and ocean planning constraints. In contrast, some motivation maps include data layers of future projections, considering socio-economic and representative concentration pathways, which will be elaborated more on in Paragraph 3.2.4.

3.2.2 Stage 1: Literature review and expert consultations

In order to answer sub question 1 I conducted a literature review into the technical potential of offshore floating structures (see Paragraph 2.4). This resulted in the identification of relevant topographical, environmental and ocean planning factors. For sub question 2, environmental and demographic factors related to offshore urban development motivation were synthesized from literature (see Paragraph 2.1 and Paragraph 2.2). Both an expert in the field of Industrial Ecology and urban materials and an expert in the field of Ocean Engineering and MFS participated in expert consultations. During these expert consultations we discussed all synthesized factors and we collected and reviewed additional factors for both the technical potential and the motivation. A comprehensive overview of all reviewed factors can be found in Table A.1, Appendix A. This table includes an indication of whether each factor was presumed to be relevant to the thesis's goal and scope or not.

Assumed relevant factors for exploring the global technical potential of MFS include a topographical constraint - *bathymetry (water depth)*; *environmental constraints - wave statistics (significant wave height, wave period, wave length, wave energy, wave direction), wind velocity* and *hurricanes and cyclones*; and ocean planning constraints - *marine protected areas*, *shipping routes*, *military areas* and *existing infrastructure*. Assumed relevant factors for exploring the motivation for MFS include demographic factors – *urban growth rates*; topographic factors – *slopes, proximity to coastal city*; environmental factors – *exposure to SLR, exposure to natural land hazards, such as earthquakes*; and land-use factors – *land protected areas*.

3.2.3 Stage 2: Data collection, validation and preprocessing

This list of relevant factors was limited by the availability of reliable data on a global scale – bringing down the list to a final selection to be included in the GIS model (see Table A.2, Appendix A). Each factor in the final selection was then categorized as an 'exclusion' or 'evaluation' factor. Exclusion factors are input for the model and exclude certain areas from the map, based on their acceptable boundary conditions. Evaluation factors are not used to exclude certain areas but rather to give some extra context to the suitable areas. The set boundaries for the exclusion factors are based on literature and the numerical and physical studies of MFS conducted by G. Wang, Drimer, and Goldfeld (2020), G. Wang, Rosenfeld, et al. (2020), and G. Wang et al. (2019), determining the design limits for both residential use under average, or annual storm conditions (SLS) and for stability and safety during rare, or 100-year return storm conditions (ULS). Additionally, the set boundaries were discussed in the expert consultations. Economic and political considerations for setting the boundaries were not taken into account in this thesis. Table 3.1 and Table 3.2 show the final overview of factors (exclusion or evaluation) relevant for the implementation of offshore MFS, selected on the basis of relevance to this thesis and data availability on a global scale.

Data verification and validation

Data validation refers to the process of (visually) checking the quality, accuracy and uncertainty of the used data sources before importing and processing the data. For inclusion of this thesis, the collected data for this thesis was obtained from recent academic sources to ensure the quality. Most ideally raw datasets are used, and limit modifications to the raw data within the GIS model. Accuracy of the obtained data can be impacted by the level of resolution at which the spatial data is made available. When data is provided with a coarser resolution, the divergence between the dataset value and the true value may be more pronounced, resulting in decreased accuracy – as is the case for the raw data extreme wave and wind values. Regarding data uncertainty the use or inclusion of future projected data is important to consider. When dealing with the future projections of urban growth and SLR, there are inherent uncertainties because these projections are based on assumptions and models; the underlying assumptions of the used data projections are elaborated on in the short factor descriptions below.

Data verification refers to the process of checking whether the used data accurately represents the actual data you are interested in, by for example cross referencing it. Acquiring detailed global-scale wave climate data for coastal waters proved to be a challenging task. Available data was restricted to long-term averages of wave energy provided for each kilometer of coastal shoreline – not providing variance within these averages. To ensure the accuracy of this data in representing average wave climates, I conducted a cross-reference with the data sources utilized in G. Wang, Drimer, and Goldfeld (2020), which presented calm sea conditions (Singapore) and open sea conditions (Eastern Mediterranean). The used average wave energy data showed this difference between calm and open sea conditions by defining these coasts into "very low" (Singapore) and "low" (Eastern Mediterranean), effectively capturing the fundamental difference between these two distinct wave climates. Also, I found the classification "moderately high wave energy" in the North of Portugal to correlate with a study describing local wave climates of the Portuguese coast (Silva et al., 2012). Additionally, I reviewed the raw data of the extreme analysis values in Takbash et al. (2019), obtained from Prof. I. Young. I used data of the wave characteristics described in the work of G. Wang, Drimer, and Goldfeld (2020) to validate the obtained extreme values, as these extreme values were mathematically derived from raw data as documented in Takbash et al. (2019). The 100 year significant wave height of Singapore Bay and the Eastern Mediterranean Sea were respectively 3.9 - 4.4 m and 8.3 m in the obtained data; this corresponded to the wave statistics published in G. Wang, Drimer, and Goldfeld (2020).

Lastly, exact shipping routes data couldn't be obtained on a global scale, as such, I decided to use data of shipping density as a proxy for this factor. The shipping density data was analogous to the general intensity of shipping activity, revealing intensively used routes comparable to the global marine shipping network as presented in 'Port Economics, Management and Policy' (Notteboom et al., 2022).

Data preprocessing

After data validation and verification, the next step was to import the obtained spatial data in ArcGIS Pro as individual layers. The datasets were obtained in different formats, resolution and geographical coordinate systems. The different formats include shapefiles, raster data and tables. Following the definitions of Esri (2021), shapefiles are simple formats storing storing the location, shape and attributes of a geographic features. These geographic features can be represented as points, lines or polygons (area). A raster is a matrix of equally sized cells, arranged in rows and columns, where each cell contains a value representing specific information, for example the bathymetry. The spatial resolution is associated with raster data and refers to the size of the cells in a raster. Data in table formats should store the geographical location of a feature to convert the table to spatial data. Lastly, the geographical coordinate system of the data defines where the data is located based on two numbers, the coordinates. The most common method of displaying locations on the sphere globe of Earth is by using the two coordinates 'latitude' and 'longitude'. Both resolution and the coordinate system are important to consider, as these can determine how accurately and consistently spatial data can be measured, displayed and analysed. When using multiple data layers in a GIS model or analysis, coordinate systems and resolutions should ideally be the same. As such, before analysing these layers together, preprocessing of the individual layers was needed for coordinate alignment, cell resolution and geographical coverage extent. Below, the rationale for selecting the most suitable geographical coordinate system and resolution for this thesis is explained. A comprehensive overview of the datasets that I obtained, including a short description and the original format, resolution and geographical coordinate system can be found in Table A2, Appendix A.

The chosen geographical coordinate system used as a basis throughout the GIS analysis in this thesis was WGS84, with degrees as the unit of measurement. This choice is rooted in the fact that this is a widely recognized coordinate system, thus the coordinate system used for the majority of the obtained datasets, and to maintain consistency throughout the GIS analysis.

The resolution of raster layers used in the GIS analyses refers to the size of individual grid cells within a raster layer. I carefully selected an appropriate cell resolution that aligns to a certain extent with the original raster data, accommodates the global scale extent, while maintaining a desired level of detail for the coastal shoreline: 0.0125 x 0.0125 degree. This choice is based on the dimensions of the MFS modules shown in Figure 2.3. The resolution of 0.0125 x 0.0125 degree (latitude x longitude) varies roughly between 1.3 x 1.3 km at 0 degrees latitude – the equator - to 1.3 x 0.5 km at 67 degrees latitude North/South – the (an)artic circle; fitting at least one block of MFS modules. In this thesis, the geographical scope encompasses territorial, internal, and archipelagic waters. A shapefile representing these waters was collected online and used as the spatial extent for the data layers. (Table A2, Appendix A).

Because of computational limitations I divided the bathymetry and wave energy layer into 128 tiles (each of 20 x 20 degrees), preprocessed them individually and finally reassembled them back together using the *'Mosaic to new raster'* tool. For the preprocessing of the extreme values, I requested the underlying raw data of Figure 4 in Takbash et al. (2019). As the raw data was a Matlab script, I first converted the Matlab data (table) into a georeferenced .tif file, which I was able to load into GIS. This georeferenced .tif was the input for the preprocessing model in GIS. The Matlab script written to produce the georeferencend .tif is included in the ZIP folder of this thesis.

Table 3.1: Overview of factors and their defined boundaries used to determine the global technical potential of MFS, based on relevance and data availability

Factor	Short description		Boundaries (exclude or evaluate)	Data source
Bathymetry	Water depth could constrain the deployment of MFS, as there could be a minimal and maximal depth for floating structures. MFS deployment in deep water waves.		Exclude -35 m >depth >-2500 m	GEBCO Compilation Group (2023)
Wave statistics	Wave statistics include significant wave height, wave period, wave length, wave energy, wave direction. Used to describe the wave climate. Certain wave characteristics limit the deployment of MFS - occupant comfort criteria must be met. Also used to determine the use of floating breakwaters (calm vs open water). Significant wave height (H_s) – crest to trough- (average of highest 1/3 of waves). 100-year return Hs ($H_s^1$00) – a H_s that is on average exceeded only once every 100 year. Wave energy – depends on wave height, wave period, water depth. Excludes rogue / freak waves.	Average wave energy at coast (SLS)	Exclude high wave energy, very high wave energy Calm water: quiescent, very low wave energy Open water: low wave energy, moderate wave energy	U.S. Geological Survey (USGS) in partnership with Esri (Sayre et al., 2021)
		100-year return H_s (H_s^{100}) (ULS)	Exclude H_s^{100} >8.5 m Calm water (no breakwater): H_s^{100} <4.5 m Open water (breakwater): 4.5 m $<H_s^{100}$ <8.5 m	Takbash et al. (2019)
Wind velocity	MFS might not meet occupant criteria with certain wind velocities. Wind speed (U_{10}) – wind speed 10 meters above Earth's surface. 100-year return U_{10} (U_{10}^{100}) – a U_{10}that is on average exceeded only once every 100 year.	Average wind speed (U_{10})	Exclude U_{10} >9 m/s	GWA (2023)
		100-year return U_{10} (U_{10}^{100})	Exclude U_{10}^{100} >30 m/s	Takbash et al. (2019)
Hurricanes and cyclones	During cyclones a maximum significant wave height and wind speed are reached that are to some extent under sampled in the altimeter data that H_s^{100} and U_{10}^{100} is based on.		Evaluate areas with high hurricane risk.	K. R. Knapp et al. (2010) and K. Knapp et al. (2018)
Marine protected areas	MFS cannot be deployed in marine protected areas / restricted areas, unless scientific evidence proves potential for mutualism.		All excluded	UNEP-WCMC and IUCN (2023)
Shipping routes	MFS cannot be deployed crossing commonly used shipping routes.		All excluded	The World Bank (2023)

Note: MFS = Modular Floating Structures; SLS = Service Limit State; ULS = Ultimate Limit State.

Table 3.2: Overview of factors and their defined boundaries used to evaluate the motivation for MFS, based on relevance and data availability

Factor	**Short description**	**Boundaries (exclude or evaluate)**	**Data source**
Proximity to a coastal city	The proximity of a coastal city (>300,000 inhabitants; <15 km from coast) is necessary for MFS implementation, as the offshore structures might require the use of existing infrastructures and are assumed to be an extension of an existing coastal city.	Exclude areas outside a radius of 35 km of city centre.	United Nations Department of Economic and Social Affairs (2018)
City growth	The proximity of an existing, growing city is motivating for MFS expansion.	Evaluate cities with high urbanization rate.	United Nations Department of Economic and Social Affairs (2018)
Exposure to SLR	Cities most exposed to sea level rise in the future could benefit from urban expansion at sea.	Evaluate coastal cities with future coastal flood risk.	World Resources Institute (2020)
Land protected areas	Spatial factor that restricts city expansion to hinterland.	Evaluate cities restricted by land protected areas.	UNEP-WCMC and IUCN (2023)
Slope	Spatial factor that restricts or enables urban expansion to hinterland.	Evaluate cities restricted by steep slopes.	Esri et al. (2023)
Natural hazards at land - Earthquakes	Areas with a high earthquake risk, e.g. close to active faults could have a motivation for urban expansion to sea.	Evaluate coastal cities with high earthquake risk.	Pisut (2020)

Note: SLR = Sea Level Rise; MFS = Modular Floating Structures.

3.2.4 Stage 3: Model development

In order to answer sub question 3, I developed a GIS model. The model construction took place in two phases, starting with a small-scale model covering the territorial and internal waters of Eastern Mediterranean Sea and then scaling up to the global level. Building the model initially on a smaller scale made the model construction process more efficient and allowed for model verification through a small case study. The GIS model performs a weighted overlay analysis. For the goal and global scope of this thesis all input layers were assumed to have an equal weight in this analysis. The GIS model generates technical potential maps of:

1. the Service Limit State (SLS). As described in the Literature Review, the SLS refers to the performance of MFS in normal, operational conditions. In this thesis, the SLS map considers factors that are assumed 'everyday'. This includes the factors *bathymetry*, *average wave energy*, *average wind speed* and *hurricane risk*;

2. the Ultimate Limit State (ULS). As described in the Literature Review, the ULS refers to extreme scenarios, such as the 100-year return storm. In this thesis, the ULS map considers factors that are assumed extreme. For this thesis, I have chosen to define the ULS conditions as a to complement the SLS conditions; the ULS conditions represent an additional layer of exclusion and wave climate differentiation, and thus complement the SLS map. The ULS map includes the *100-year return significant wave height* and *100-year return wind speed*; and

3. the ocean planning, complementing the SLS and ULS map, including the factors *marine protected areas* and *shipping routes*.

Assembled together, these layers form the technical potential map, mapping all potential suitable areas for MFS implementation within the territorial, internal and archipelagic waters.

Technical potential - SLS, ULS and ocean planning

All technical potential factors listed in Table 3.1 were used as input for the GIS model after preprocessing, generating the technical potential maps as an output. The general overview of the model generating the technical potential maps is described below and visible in Figure 3.1 (SLS), Figure 3.2 (ULS), Figure 3.3 (ocean planning). The input factors of the GIS model are briefly introduced below.

Bathymetry

The bathymetry (water depth) layer supposes a natural spatial constraint on the technical potential. This constraint is closely tied to the design of the MFS and floating breakwaters outlined in Chapter 2, as well as on the local sea characteristics such as wave energy and composition of the seabed. Minimal disruption of the seabed and its ecosystem should be the starting point for offshore MFS implementation in deep water, to intervene as little as possible in the natural wave action and coastal erosion processes. In this thesis this is simplified by establishing a, rather conservative, rigid boundary for the global GIS analysis, neglecting the fact that local sea characteristics vary among different coastlines which could influence the allowable boundaries. The upper limit of -35 m and a lower limit of -2500 m were set based on the technical feasibility of mooring systems and the dimensions of the MFS and floating breakwater design. As optimal underwater keel clearance for minimal disruption of the natural seabed and coastal wave interaction could not be determined, a conservative underwater keel clearance of at least 5 m was used to safeguard these aspects.

Wave statistics

The average wave energy and 100-year return significant wave height (H_s^{100}) layers present a natural spatial constraint on the technical potential, respectively for the SLS and the ULS. The average wave energy of every 1 km coastal segment was classified in 'quiescent', 'very low', 'low', 'moderate', 'moderately high' 'high', 'very high', based on a set of variables (among which wave height and seabed slope profile) describing the ecological setting of the coastal segments (ECU) ((Sayre et al., 2021). Based on data validation results, coastal areas with an average wave energy of 'high' and 'very high' were excluded from the analysis as they are assumed to not comply with SLS criteria. Based on the numerical results of G. Wang, Drimer, and Goldfeld (2020), a H_s^{100} greater than 8.5 m limits the deployment of MFS. Also, in this thesis H_s^{100} determines the necessity of floating breakwaters; I assumed this to be necessary in open water (H_s^{100} >4 m).

Wind velocity

The average wind velocity (U_{10}) can be expressed through the mean values of 10 m above Earth surface. From a technical side, areas with an average wind velocity above 9 m/s are excluded from the GIS analysis. Wind speeds above this limit are classified as strong, near gale winds, assumed not to comply with SLS criteria (NOAA, 2023a). 100-year return wind speeds (U_{10}^{100}) are not allowed from the ULS perspective above 30 m/s, based on the numerical study of G. Wang et al. (2019).

Hurricanes and cyclones

The hurricane and cyclone risk layer, based on historical data of hurricane tracks, is treated in this thesis as an evaluation criterium rather than an exclusion criterium. This factor can be used to evaluate where MFS deployment might require additional design considerations specifically addressing frequent hurricane or cyclone exposure.

Marine protected areas

The marine protected area layer represents the most comprehensive overview of World's marine protected areas (UNEP-WCMC & IUCN, 2023). These project correspond to added value natural zones. These are conservation areas, in which defence and survivability of biodiversity are the priority. This is a spatial zoning constraint, relating to the ocean zone planning. As long as there is no convincing bunch of literature that MFS would hold a symbiotic relation with the oceans ecosystems, these areas should be considered excluded from an environmental perspective.

Shipping routes

The shipping density layer reveals intensively used routes of the global marine shipping network. No permanent construction is allowable at a major shipping route; in this thesis it is assumed that this for now also applies for offshore MFS implementation. However, re-routing of the shipping lanes could be discussed.

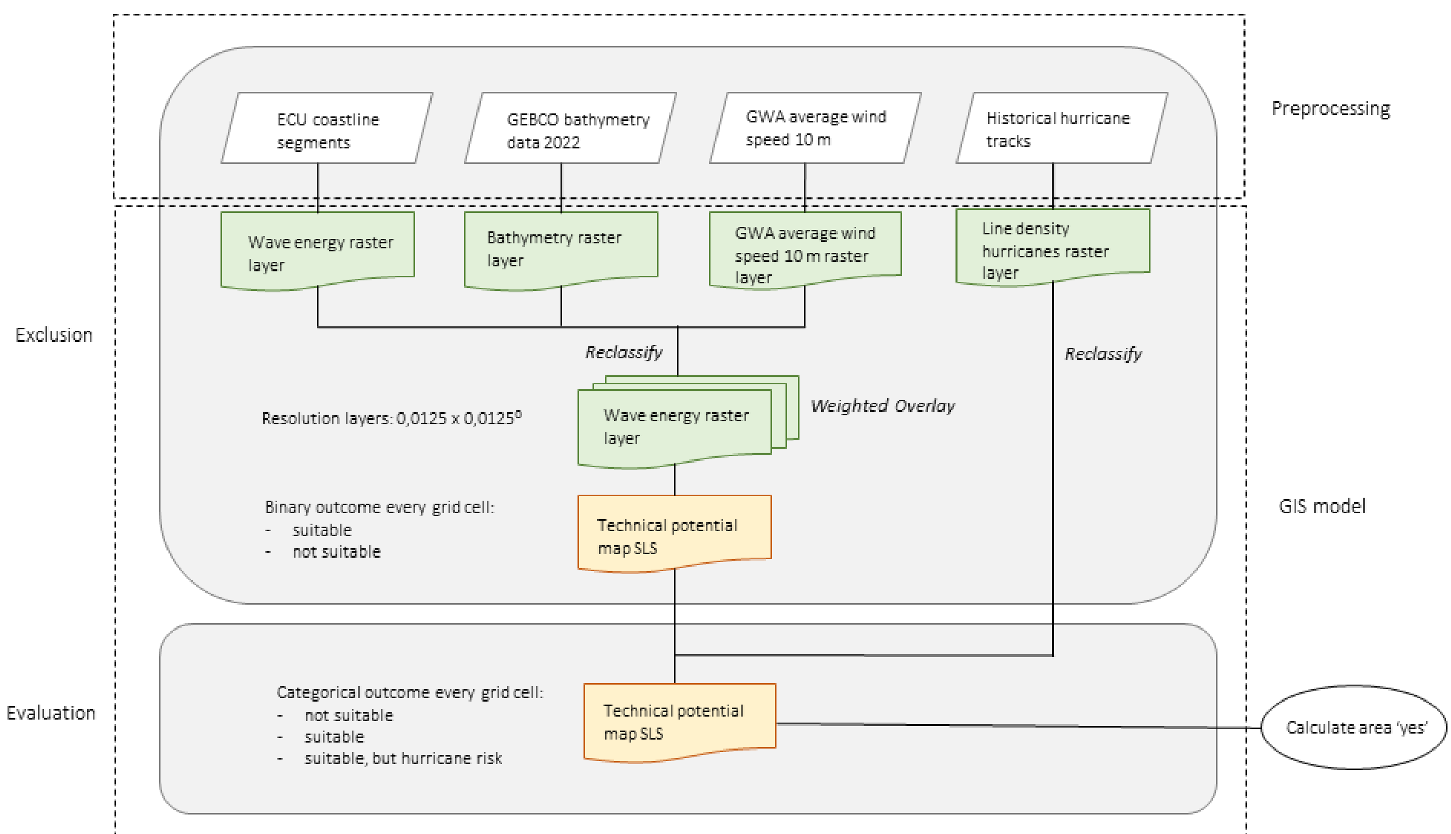

Figure 3.1: Workflow diagram technical potential map Service Limit State (SLS)

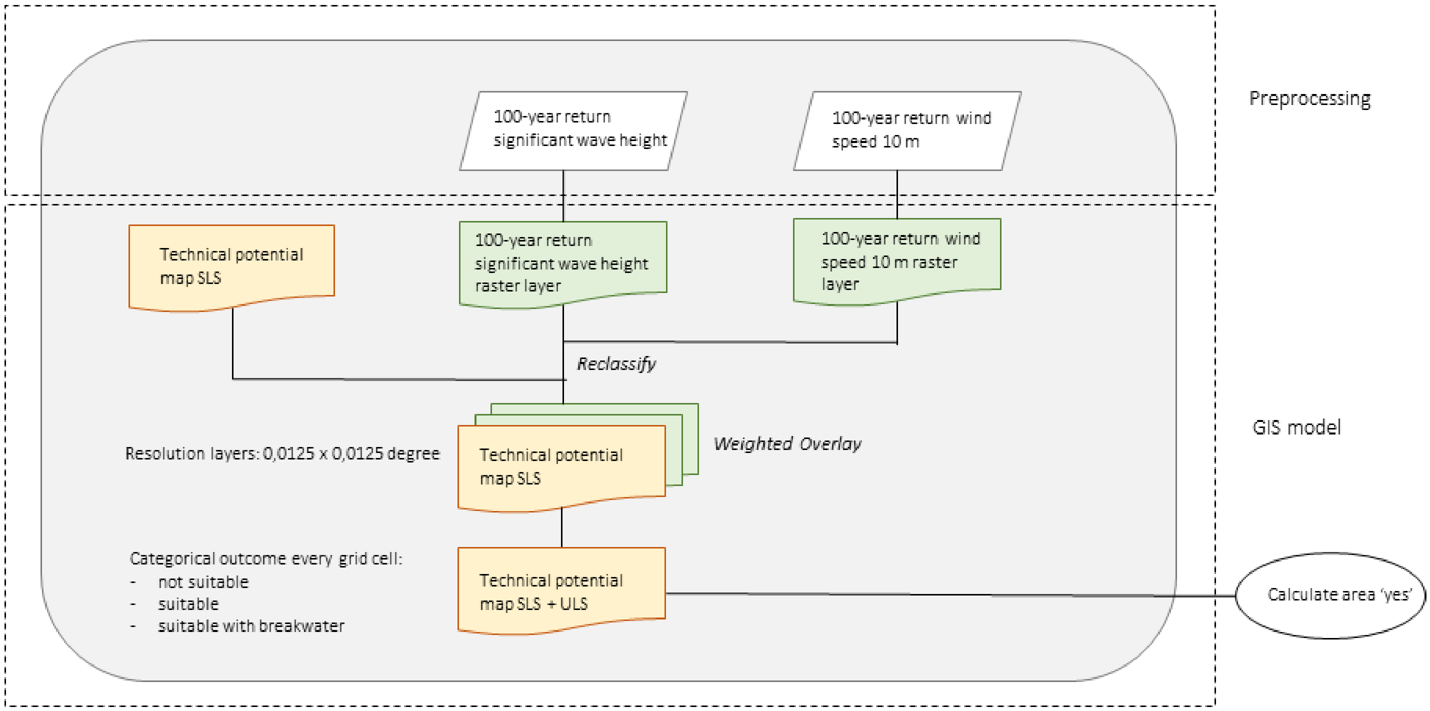

Figure 3.2: Workflow diagram technical potential map Service Limit State (ULS)

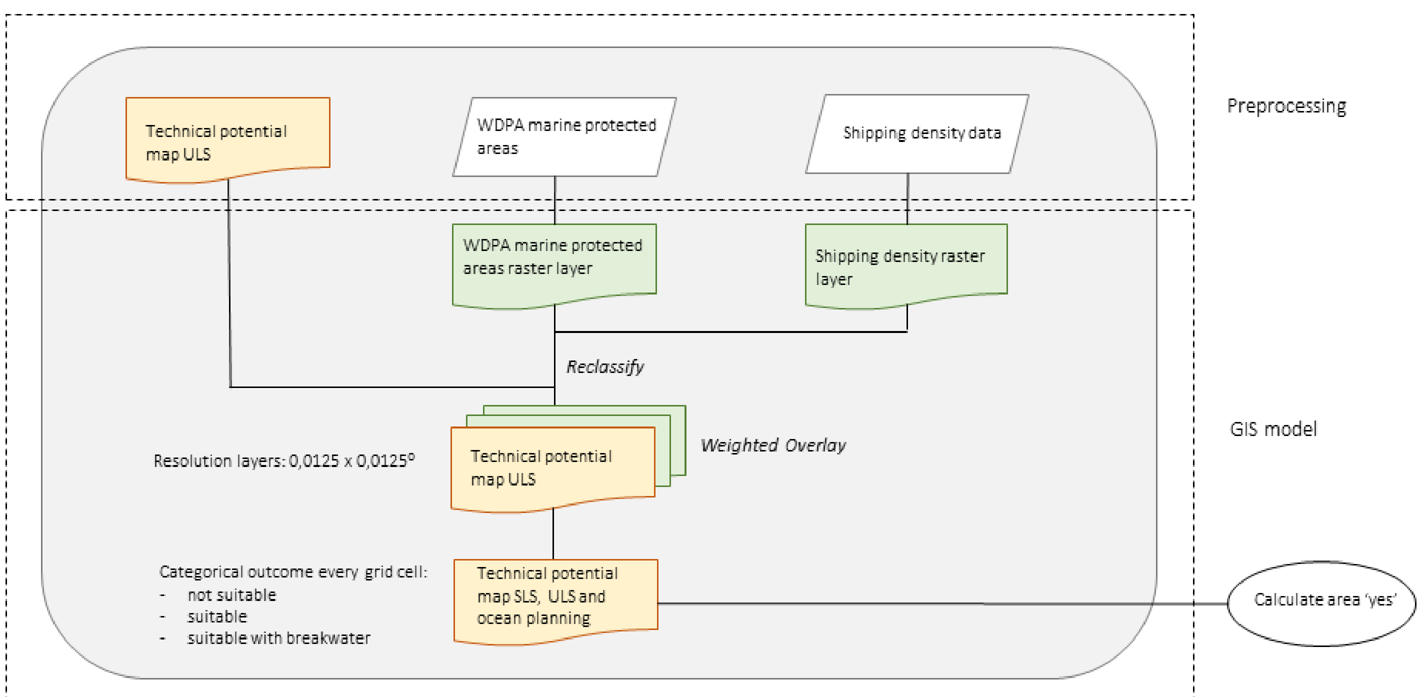

Figure 3.3: Workflow diagram technical potential map ocean planning

Step 1: *Reclassify*

After preprocessing, I first reclassified all input layers into ‘0’ and ‘1’, respectively ‘not suitable for MFS implementation’ and ‘suitable for MFS implementation’. In case of the SLS, I assigned a classification of ‘2’ if the cell was suitable but had a high hurricane risk – however, this layer is just used for evaluation; in the next maps I treated this classification as ‘1’; suitable. In case of the ULS and ocean planning, ‘1’ specifically referred to suitable cells in calm water conditions, not requiring a breakwater and I classified the cell as ‘2’ if the cell was suitable but classified as open water based on the extreme values; so, only suitable when using floating breakwaters. For easy adaptation of the code beyond the scope of this thesis, the specific boundaries for classification can be set in the code line ## Set boundaries (Figure 3.4).

Step 2: *Weighted Overlay analysis*

The next step in the model was to overlay the reclassified layers on one another, with each cell in the resulting map containing values of ’0’, ’1’, or ’2’ based on the input layers. If the output cell had at least one input of ‘0’, it was designated as ’0’ in the resulting technical potential map - the OR operator in logic. If the cell had no ‘0’s, but at least one ‘2’ as input, this cell was assigned to ‘2’; see Figure 3.5.

```
## Set boundaries for bathymetry, wind speed,

# Bathymetry (m)
bd_wd_min = "-2500"
bd_wd_max = "-35"

# Wind speed (m/s)
bd_ws = "9" #m/s
```

Figure 3.4: Snip from Python code GIS model to set the boundaries for output

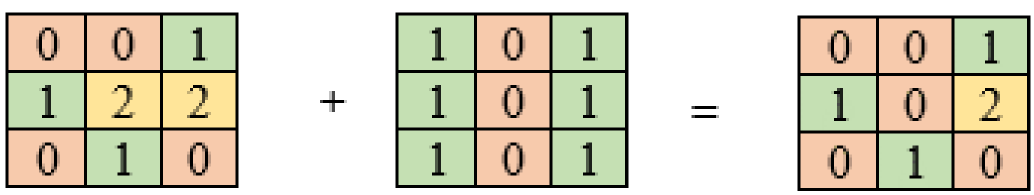

Figure 3.5: Schematic overview Weighted Overlay Analysis approach

Motivation perspective

Lastly, I finalized the GIS model by incorporating the motivation factor ’proximity to coastal cities’ to exclude areas not within proximity of a coastal city. Consequently, the GIS model excluded all cells located more than 35 km away from a coastal city centre. In addition, I incorporated the remaining identified factors for MFS implementation into the ArcGIS project for visual assessment of the GIS model output maps and the potential motivation for MFS. As such, the final GIS model output could be interpreted using the other drivers motivating for MFS. The general overview of the model generating the motivation maps and layers are visualized in Figure 3.6 and Figure 3.7.

Proximity to a coastal city

The data layer representing coastal cities (>300,000 inhabitants in 2018) was used to exclude areas assumed too far from the city centre to be of interest for the scope of this thesis; as offshore dwelling is proposed as an alternative to expand existing cities at sea. Coastal cities were defined based on the proximity of their city centre to the coast (<15 km). An list of the resulting coastal cities can be requested. This motivation factor was included in the model to exclude areas from the technical potential maps, as seen in Figure 3.6. The choice of a fixed 35 km radius from the city centre was made under the assumption that implementing MFS beyond this distance would lack practicality; offshore MFS are intended as an extension of existing cities.

City growth

One of the main drivers for urban expansion is urban growth; contributing to land scarcity and higher exposure to SLR. As underlined in the Literature Review, the multifaceted factors influencing urban growth, including economic development, policy dynamics, are inherently complex. In this thesis, future predicted urban population growth on city level is included providing insights into potential hotspots and/or areas of lower significance in the light of urban population growth. The projected urban population growth rates in this study are based on the population forecasts provided by the United Nations, as documented in United Nations Department of Economic and Social Affairs (2018). These growth rates serve as an motivation assessment layer, enhancing the generated maps in the GIS model with additional motivation context.

Exposure to SLR

Another primary driver for urban expansion at sea, as highlighted in the Literature Review, is the risk of coastal flooding, attributed to rising sea levels. This is why I included future SLR exposure as a driving factor for MFS. The data I used to represent this factor shows the inundation depth, referring to the depth of water that covers a particular area during a flood or inundation event. As this is a future projections, several scenarios represent different data. I chose to use a data layer representing the inundation depth in 2050, for a 100-year return storm, under a high future emission scenario, commonly referred to as Representative Concentration Pathway (RCP) 8.5. The RCP scenarios are used in climate science to project future greenhouse gas emissions and their impact on global climate. Specifically, RCP 8.5 represents a high greenhouse gas emissions scenario in which the concentration of greenhouse gases, such as carbon dioxide (CO^2) in the Earth's atmosphere, continues to rise throughout the 21st century and beyond. Serving as a motivation evaluation layer, these inundation depths augment the GIS model's generated maps with supplementary motivation context.

Land protected areas

Given the significance of marine protected areas in constraining available space for offshore infrastructure, I also recognized the importance of land protected areas when considering urban expansion into the hinterland. I employed the database provided by UNEP-WCMC and IUCN (2023) to depict the world's terrestrial protected areas. These land protected areas are employed as a motivation assessment layer to enhance the GIS model's generated maps with potential motivation context.

Slope

The decision to prioritize urban expansion to sea over hinterland development could be grounded in the nature of surrounding slopes; as such, I chose this factor as a potential driver for urban expansion at sea. The steepness of the terrain not only affects the practicality of construction and infrastructure development but could also intertwine with cultural values and traditions. Research has highlighted the crucial relevance of this factor, as it imposes substantial limitations on inland urban growth (Duan et al., 2016). Hence, this layer enriches the GIS model's generated maps by providing information about the steepness of slopes surrounding coastal cities.

Natural hazards at land - Earthquakes

Lastly, natural hazards at land were considered motivating for urban expansion to sea. I decided to include the risk of earthquakes as an illustrative example, but this factor could be expanded to include other natural land hazards like wildfires or volcanoes.

Step 3: *Extract by mask*

To delineate areas close to coastal cities, I used the input layer representing the area within 35 km from the included city centres as a mask. Consequently, only the cells falling within this mask were considered in the global potential maps, which encompassed the technical potential maps driven by the proximity to coastal cities.

Incorporating the other motivation factors into the GIS model turned out to be challenging due to their inherent complexity in relation to coastal city growth and land scarcity. These are therefore not included in the GIS model, but do offer additional spatial contextual information which is very relevant in interpreting and evaluating the results in more depth; they can be used complementary to the output of the GIS model to further explore the motivation for MFS, as illustrated in Chapter 4, Results. The constructed model allows for the generation of the technical potential maps (SLS, ULS and ocean planning), considering the motivation factor representing the proximity of a coastal city. Additionally, it provides the capability to navigate through input layers, allowing the exploration of specific layer contributions to the technical potential maps.

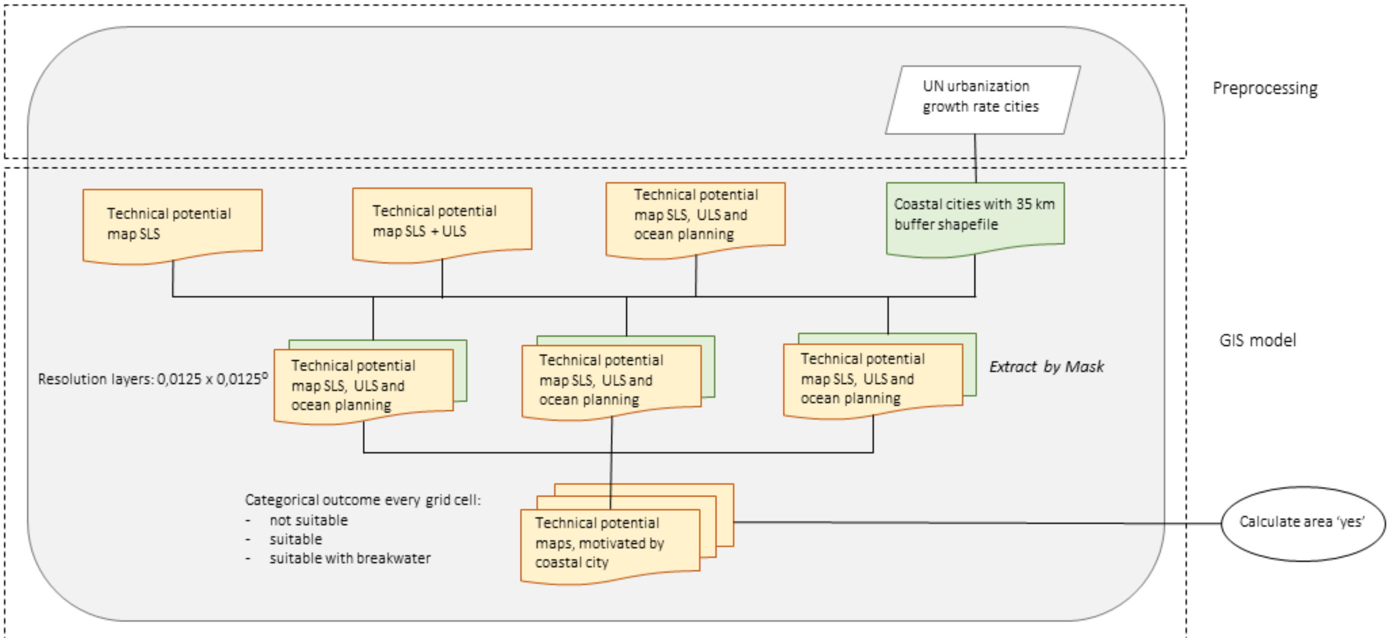

Figure 3.6: Workflow diagram technical potential motivated by the proximity of a coastal city. Note: Coastal city is defined as >300,000 inhabitants, <15 km from shoreline

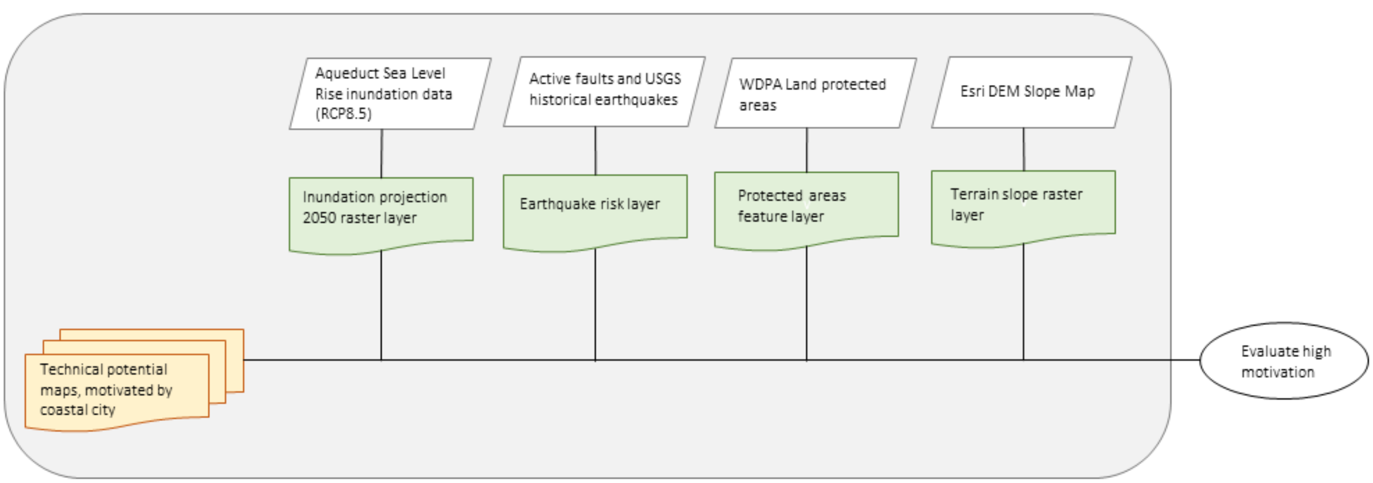

Figure 3.7: Workflow overview of the motivation perspective

3.2.5 Stage 4: Model verification and validation

The verification of the model refers to the process of assessing whether the model is constructed correctly and behaves as it should. I verified the model construction throughout the whole process, by constructing the small scale model layer by layer and checking whether each reclassification and overlay process resulted in the expected layers or maps. The global model generated the same output as the initial small-scale model for the Eastern Mediterranean Sea, and thus could be assumed that the model was correctly upscaled. As an additional verification, I checked that the total count of '0', '1', and '2' cells in each potential map matched with the underlying data layer cell counts.

Model validation refers to the process of ensuring that the correct model is built for the objective of this study. The aim of this thesis is to explore the global potential of offshore MFS implementation in maximum achievable area (km^2), people and material use. The output generated by the model correctly reflects all input layers of the validated data and their restrictive boundaries, and the technical potential maps can be used to identify the technical potential based on SLS, ULS and proximity of a coastal city. For the motivation factors, a visual inspection of the spatial distribution of urban growth rate and inundation depth revealed an outcome aligning to high risk areas emphasized in literature (Paragraph 2.2).

3.3 From maps to numbers: area, offshore population and material use

In order to answer sub question 4 and 5, the output of the GIS model should be translated to total suitable area (km^2), total number of people and total material use. The output of the GIS model are maps representing the suitable locations for MFS implementation per cell of 0.0125 x 0.0125 degree, based on natural and ocean planning constraints and motivated by the proximity of a coastal city centre. I translated this mapped technical potential into a maximum achievable area (km^2), housing (#people) and material use (#floating breakwaters and steel demand for platforms). After careful examination, I used the Behrmann equal area cylindrical projection as the coordinate system to assess the cell sizes on each row along latitudes. This projection is useful for accurate areas and is suitable for the global extent.

The approach for the coordinate conversion to km^2 is described below and the comprehensive version can be found in Figure C.11, Appendix C, complemented by Table C.8, Appendix C. For calculating the total number of people, I made the assumption that per km^2, one MFS block, comprised of 54 modules (see Figure 2.3 could be deployed. Additionally, I assumed that one MFS block could house 19 000 people. I presumed that the material use for the superstructures (buildings) was not significantly different from building on land. The material requirements for the substructures were calculated based on the substructure's weight, as reported in G. Wang et al. (2019), under the assumption that it consists entirely of steel. Lastly, I used a ratio of 10 floating breakwaters per five MFS blocks for the calculation of the demand of retired ships (see Figure C.12, Appendix C for the underlying calculation).

Step 1: Using the '*Raster to point*' tool, convert every cell to a point that conserves the assigned category (0, 1, or 2).

Step 2: Using the '*Spatial join*' tool, join the point shapefile (step 1) to the shapefile containing all latitude rows and corresponding average areas. [] The number of points and their category are reported for each row of latitude.

Step 3: Calculate total area on each latitude row by multiplying the total cells with the assigned average area. Repeat for each category (0, 1 and/or 2).

Step 4: Sum the total areas of each row. Repeat for each category (0, 1, and/or 2).

3.4 Model application with selected case studies

To illustrate what the GIS model could potentially be used for, I conducted a few studies exemplifying how to further analyse the global results, by zooming in on different scales. As stressed in Chapter 2, the local exploration of global trends is important and useful. Particularly noteworthy is the local variation in motivational factors, which significantly influences a region's drive for the implementation of advancing to sea. As such, I provided a first overview of the leading cities in terms of technical potential. Furthermore, I made a selection of case studies (on global region and city level) to explore the local variations of the technical potential, showing the added value of the motivation perspective and how the GIS model, complemented by the motivation factors, could be used in future projects or research. I based the choice for this selection on the Literature Review and an visual inspection of the motivation factors, primarily *urban growth rates* and/or *exposure to SLR*, which are described below.

The global regions that I analysed were Africa, Southeast Asia, Western Asia, East Asia, Europe, Latin America and Oceania (Table C.9, Appendix C). The cities that I selected are Lagos (Nigeria), Mumbai, (India), Singapore (Singapore), and Jakarta, (Indonesia). This selection was motivated on the basis of the Literature Review – cities at risk in the face of SLR – and the motivation layers of the GIS model – *urban growth, exposure to SLR, earthquake risk* and *slopes*. The technical potential maps, motivated by the *proximity of coastal cities*, were delineated to the spatial extent of the case study by the *'Extract by mask'* tool. For the global regions study, I selected all cities within the selected global region, using the *'Select by attributes'* tool. I applied the methodology described in Paragraph 3.3 to each of the resulting case study maps. For the leading cities overview, I converted the technical potential maps to points with the *'Raster to Point'* tool, allowing for counting the number of suitable cells within the 35 km buffer of coastal cities using a *'Spatial Join'*.

4

Results

In this chapter, the results of the GIS analysis are presented. After analysis of the World's territorial, internal and archipelagic waters, three technical potential maps were created, all motivated by the proximity of a coastal city:

1) the SLS technical potential map based on the factors bathymetry, average wave energy, average wind speed and hurricane risk (see Figure 4.1);

2) the ULS technical potential map based on the SLS map and the factors 100-year return significant wave height and 100-year wind speed (see Figure 4.2); and

3) the ocean planning technical potential map based the ULS map and on the factors marine protected areas and shipping routes, hereafter called the final technical potential (see Figure 4.3).

These map shows the areas where MFS platforms could potentially be deployed in dark green, the areas suitable but only with floating breakwaters in yellow, and the areas where MFS cannot be deployed in red. The results of a selection of smaller scale studies based on the global GIS model are presented, to get a better understanding of the added value of the motivation perspective and the spatial distribution of the technical potential of MFS. Also, these studies can be used as inspiration for future studies on continental, regional or city scale.

4.1 Technical potential of MFS motivated by the proximity of a coastal city

The Worlds territorial, internal and archipelagic waters cover an area about 19,000,000 km^2 according to the GIS model. For the motivation factors, 'proximity to coastal cities' was used to exclude areas in absence of a coastal city in the GIS model. 547 cities were classified as coastal cities, based on their number of inhabitants (>300,000) and proximity of city centre to coast (<15 km). The relevant numerical results based on the technical potential maps motivated by the proximity of a coastal city are presented below (Table 4.1). All raw data can be found in the Excel file attached in the ZIP file of this thesis.

About 569,000 km^2 of all territorial, internal and archipelagic waters is relevant to the objective of this thesis, as this the area is within 35 km of a coastal city. This represents about 3% of the total global extent. Based on this and the SLS criteria, the technical potential resulted in a maximum achievable area of 244,054 km^2; representing about 43% of the total area. The technical potential based on SLS and ULS criteria resulted in a maximum achievable area of 166,367 km^2; representing about 29% of the total area. When the ocean planning constraints were added, the technical potential resulted in a maximum achievable area of 84,455 km^2; representing about 15% of the total area.

Considering this global technical potential (combined SLS, ULS and ocean planning), the maximum feasible MFS structures that could be deployed is 84,455 MFS blocks. The offshore population could reach approximately 1,6 billion.

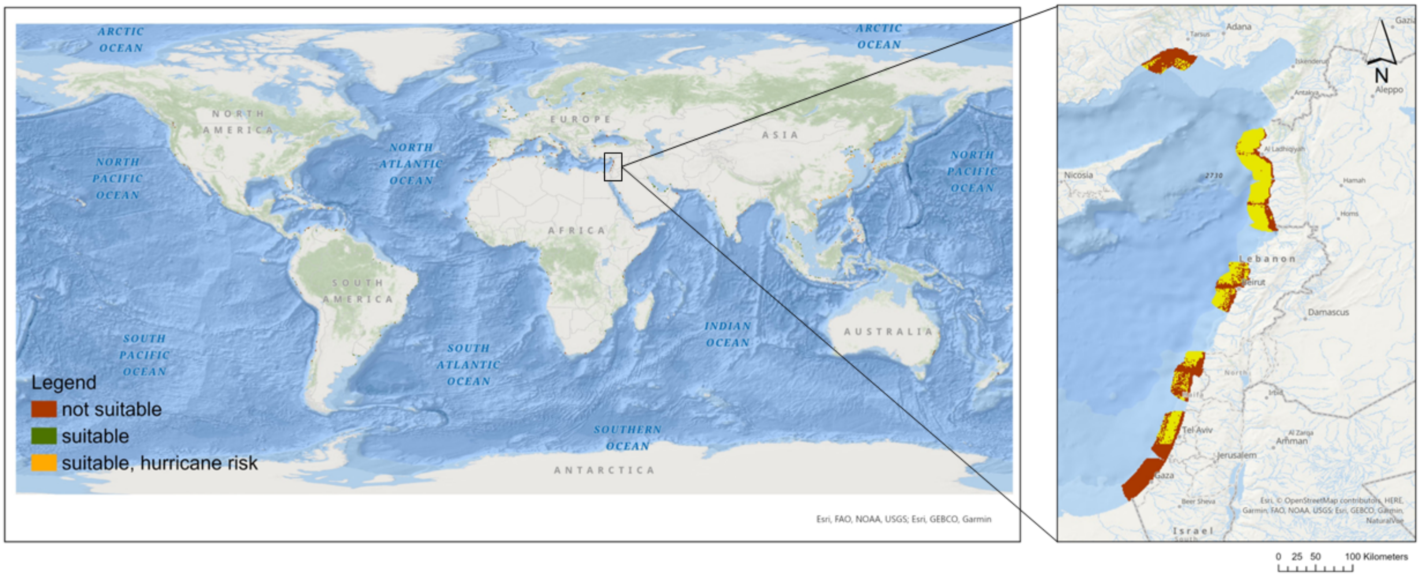

Figure 4.1: Technical potential map of Service Limit State, motivated by the proximity of a coastal city

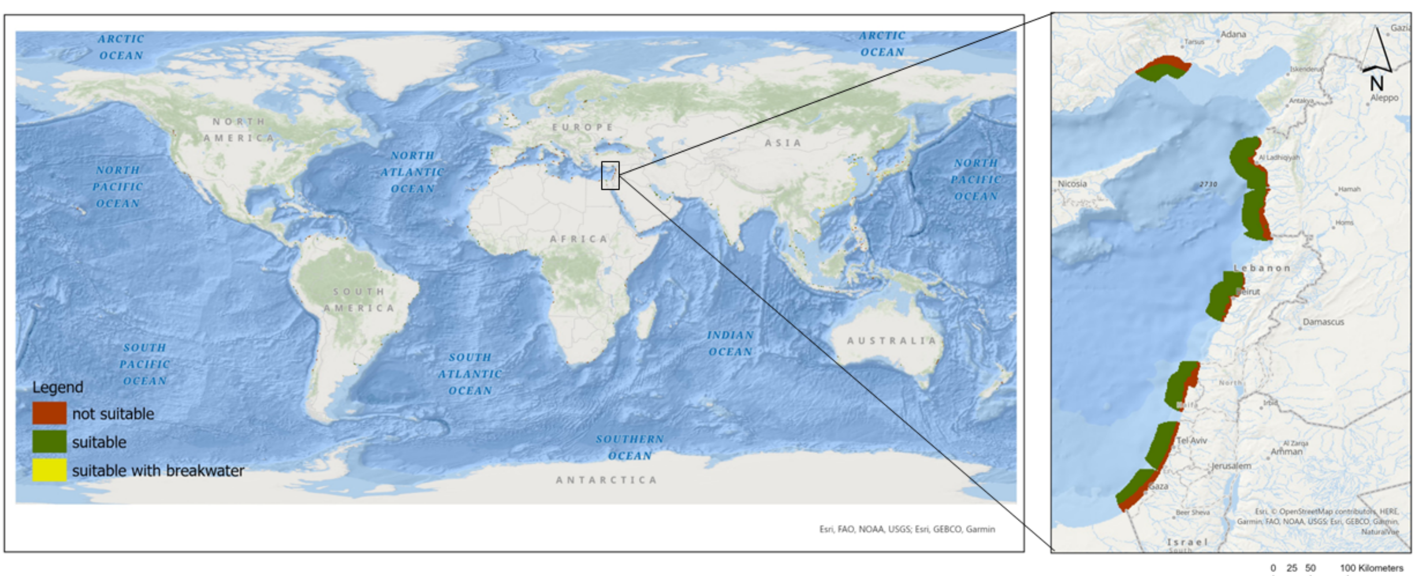

Figure 4.2: Technical potential map based on the Service Limit State and Ultimate Limit State, motivated by the proximity of a coastal city

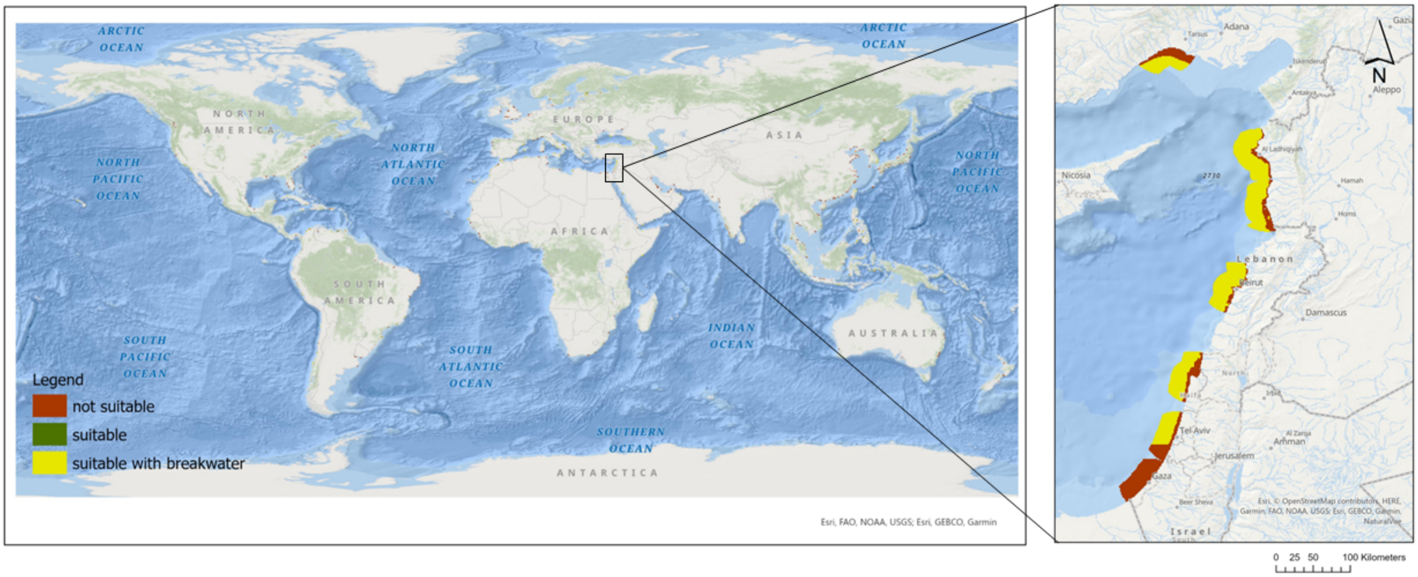

Figure 4.3: Final technical potential map based on the Service Limit State, Ultimate Limit State and ocean planning motivated by the proximity of a coastal city

4.1.1 Estimates of global material use

The global technical potential results reveal that for 77% of the MFS the use of floating breakwaters is necessary. This translates to 261,158 EOL ships. For the sub structures of the MFS modules, a steel demand of 25,539 Mt (Million tons) is estimated.

4.2 Model sensitivity

When examining the individual contributions of factors to the global potential based on SLS, ULS, ocean planning and motivated by the proximity of a coastal city, it is evident that the 'bathymetry' factor has the most significant constraining impact (see Excel file attached to the ZIP folder of this thesis, worksheet 'cell_counts'). Following is the shipping route constraint. It's worth noting that, as outlined in the methodology, the bathymetry boundaries are somewhat rigid and rather conservative for MFS implementation. Consequently, a sensitivity analysis was conducted, based on the input of the 'bathymetry' factor. The results indicate that a 10% decrease in the upper limit (-35 to -31.5 meters) lead to a $\tilde{2}$% increase in the total suitable area.

Nonetheless, when modifying the bathymetry boundaries for an alternative scenario, where MFS and floating breakwater dimensions are not considered and the boundaries align closely with the depths viable for conventional land reclamation, a reduction of 60% of the upper limit (-35 to -14 meters) results in a 38% increase in the suitable area (Table 4.2). Using EOL ships is not considered for this scenario as it is assumed that <30 m is not feasible for floating, based on the floating breakwater dimensions proposed by G. Wang et al. (2023).

Table 4.1: Global technical potential results, motivated by the proximity of coastal cities

Technical potential		**Area (km^2)**	**MFS blocks (#)**	**Offshore population (#people)**	**EOL ships (#)**	**Steel demand (Mt)**
SLS	Suitable	244,0555	244,055	4,637,035,500	-	73,802
SLS + ULS	Suitable, no floating breakwater	31,392	166,367	3,160,971,100	539,898	50,309
	Suitable, with floating breakwater	134,975				
Final (SLS + ULS + ocean planning)	Suitable, no floating breakwater	19,165	84,455	1,604,639,870	261,158	25,539
	Suitable, with floating breakwater	65,290				

Note: MFS = Modular Floating Structures; EOL = end-of-life; Mt = Million tons; SLS = Service Limit State; ULS = Ultimate Limit State

Table 4.2: Bathymetry sensitivity analysis compared to baseline boundaries of the final technical potential map, motivated by the proximity of a coastal city

Bathymetry sensitivity		**Area (km^2)**	**Offshore population (#people)**	**EOL ships (#)**	**Steel demand (Mt)**
Scenario 1: deep water - small variation upper limit (-10%)	Suitable, no floating breakwater	+3.41%	+1.89%	-	+1.89%
	Suitable, with floating breakwater	+1.40%		+1.40%	
Scenario 2: shallow water - significant variation upper limit (-60%)	Suitable, no floating breakwater	+64.47%	+38.32%	-	+38.32%
	Suitable, with floating breakwater	+29,93%		-	

Note: EOL = end-of-life; Mt = Million tons

Table 4.3: Leading cities in technical potential for MFS - a first overview

City	Country	# Suitable cells
Lattakia	Syria	994
Valparaíso	Chile	840
Sochi	Russia	822
Ambon	Indonesia	817
Tartus	Syria	796
Concepción	Chile	750
General Trias	Philippines	749
Tarabulus (Tripoli)	Lybia	669
Banghazi	Lybia	653
Denpansar	Indonesia	644

Note: At the equator the area of one cell equals $\tilde{1}.4$ km^2; at 60 N/S - the (an)artic circle - one cell equals $\tilde{0}.97$ km^2

4.3 Application of model - zooming in

The results of the evaluation layers representing additional motivation factors are used to complement the maps generated by the global GIS model and are used to determine a selection of relevant case studies to further explore the motivational perspective for MFS implementation. In addition to providing a global maps, the global GIS model can be used to analyse the continents, countries or regions more in depth. The results of a selection of analyses for which the GIS model can be used are presented below.

4.3.1 Global region analysis

As underlined in the literature review, the global trends of coastal challenges need local exploration for better understanding of the dynamics. As such, the global results of the technical potential are outlined per continent. The continents are Africa, Southeast Asia, West Asia, East Asia (China and Japan), Latin America and Caribbean, North America, Oceania and Europe. The results of the final technical potential (SLS, ULS, ocean planning), motivated by the proximity of coastal cities are presented in Table 4.5 and key findings are briefly described below. Complete results can be found in the Excel file attached in the ZIP folder of this thesis.

Southeast Asia has the highest technical potential (20,488 km^2 – 389 million people) in absolute numbers, inherent to its size; the territorial, internal and archipelagic waters within 35 km of Southeast Asian's coastal cities comprise about 19% of the global waters. Within Asia, a similar percentage was observed for relative share of suitable areas of the total Southeast area. However, East Asia has a similar share of total waters to South east Asia, but a significant lower technical potential (4,054 km^2 – 77 million people). As can be derived from breaking up the assembled technical potential, the ULS factors decrease the technical potential the most (see raw data in the Excel file attached in the ZIP folder of this thesis, worksheet 'raw_data').

While in total area comprising about 15% of the global area, the continent of Africa comes at a second place for absolute numbers of potential (19,000 km^2 - 361 million people), due to its relatively large share of suitable areas for MFS implementation within the continent (22%). Compared to the high technical potential, a relatively low number of floating breakwaters is needed in Africa. Another interesting finding is that West Asia, in total area only comprising about 7% of the global area, has a significantly high share of suitable areas within the continent and thus a relatively high absolute contribution to the global technical potential (12,340 km^2 – 234 million people).

4.3.2 Leading cities in the technical potential for MFS

A first overview of ranking coastal cities based on their potential defined in this thesis, reveals the top ten presented in Table 4.3. The ranking is solely based on the initial count of suitable cells and not further converted to area, offshore population, floating breakwaters and material demand. However, to provide a bit of context corresponding km^2 to suitable cells are indicated in the table notes. The complete ranking can be found in the the Excel file attached in the ZIP folder of this thesis, worksheet 'cities_top'.

Table 4.4: Leading cities in technical potential of MFS, considering the motivation of urban population growth - a first overview

City	Country	# Suitable cells	Urban population growth rate / yr 2030-2035
Lattakia	Syria	994	2.68
Ambon	Indonesia	817	1.53
Tartus	Syria	796	2.68
General Trias	Philippines	749	2.05
Denpansar	Indonesia	644	1.52
Lobito	Angola	556	3.563
Benguela	Angola	546	3.57
Merca	Somalia	522	3.89
Al-Mukalla	Yemen	495	3.08
Adan (Aden)	Yemen	486	3.07

Note: Only cities with a projected urban growth rate for 2030-2035 >1.5 are considered for this ranking. Urban population growth rates are based on United Nations Department of Economic and Social Affairs (2018)

4.3.3 City case studies

Significant urban growth in Lagos, Nigeria

The motivation results show a significant urban growth the coming decade for Lagos, as the urban growth layer shows an average projected growth rate of 3,5 up to 2035. For the case study focusing on Lagos, Nigeria, an overview of the main results are can be found below (Table 4.6). In Figure 4.4A the technical potential map of Lagos is presented.

Land scarcity in Singapore

The case study of Singapore was primarily chosen based on the evident problems regarding pressing land scarcity in literature, combined with the fact that Singapore has had quite some (ongoing) land reclamation projects, another alternative for coastal expansion. For the case study focusing on Singapore an overview of the main results are can be found below (Table 4.6). In Figure 4.4B the technical potential map of Singapore is presented.

Geographic and land-use boundaries in Rio de Janeiro, Brazil

The motivation results show potential geographic boundaries for urban expansion in Rio de Janeiro. Both 'slope' and 'land protected areas' show reasons - steep slopes, enclosed by Natura2000 zones - why expansion to the hinterland would not be feasible here. Moreover, the city is projected to grow in the coming decade according to the 'urban growth' factor. For the case study focusing on Rio de Janeiro, Brazil, an overview of the main results are can be found below (Table 4.6). In Figure 4.4C the technical potential map of Rio de Janeiro is presented.

High flood risk in densely populated Mumbai, India

The motivation results show a significant projected growth factor of 2,1. Also, the inundation depth layer reveals that Mumbai will probably be a high-risk area for coastal floodings. This is both in accordance with findings and projections in literature. For the case study focusing on Mumbai, India, an overview of the main results are can be found below (Table 4.6). In Figure 4.4D the technical potential map of Mumbai is presented.

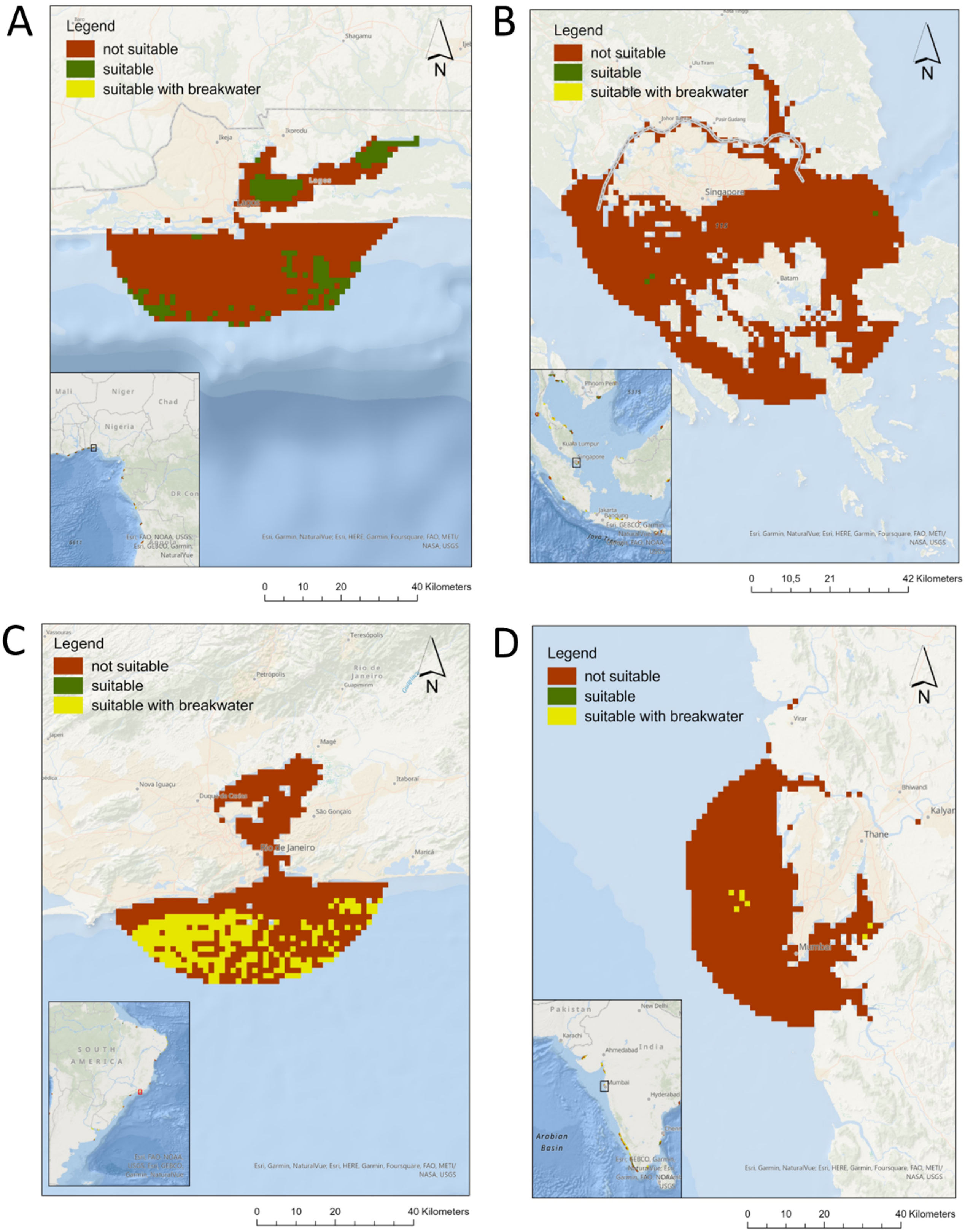

Figure 4.4: Technical potential maps of A) Lagos, Nigeria; B) Singapore; C) Rio de Janeiro, Brazil and D) Mumbai, India

Table 4.5: Global regions study: results of the final technical potential, motivated by the proximity of coastal cities

Global region	**Global region area (km^2)**		**Technical potential (km^2)**		**Offshore population (# people)**	**EOL ships (#)**	**Steel demand (Mt)**
Africa	Total	86,260.38	Total	18,999.77	360,995,630	39,914	2872.77
	% of global area	15%	% of global region area	22%			
Southeast Asia	Total	110,741.60	Total	20,487.89	389,269,815	67,528	3097.77
	% of global area	19%	% of global region area	19%			
West Asia	Total	42,441.90	Total	12,339.62	234,452,780	32,581	1865.75
	% of global area	7%	% of global region area	29%			
East Asia	Total	110,984.90	Total	4,053.74	77,021,060	16,215	612.93
	% of global area	20%	% of global region area	4%			
Oceania	Total	18,668.63	Total	758.38	14,409,13	3,034	114.67
	% of global area	3%	% of global region area	4%			
North America	Total	43,463	Total	2,848.24	54,116,503	11,393	430.65
	% of global area	8%	% of global region area	7%			
Latin America and Caribbean	Total	17,174.89	326,322,967	60,376	2596.84		
	% of global area	14%	% of global region area	21%			
Europe	Total Total	75,196.70	Total	7,991.61	151,840,495	30,915	1208.33
	% of global area	13%	% of global region area	11%			

Note: EOL = end-of-life; Mt = Million tons. See Table C.8, Appendix C for the classification of the global regions

Table 4.6: City case study: results of the final technical potential, motivated by the proximity of coastal cities

Case study	Motivation	Technical potential (km^2)		Offshore population (# people)	EOL ships (#)	Steel demand (Mt)
Lagos	Evaluation of 'urban growth rate' reveals a significant growth rate >3% for the coming decade. This significant urban growth projection is also stressed in literature – pressing coastal challenges.	Suitable	352.35	6,694,669	-	106.55
		Suitable with floating breakwater	0		-	
Singapore	Literature shows that Singapore has evident problems regarding land scarcity and population growth, currently ongoing land reclamation projects.	Suitable	9,19	174,639	-	2.78
		Suitable with floating breakwater	0		-	
Rio de Janeiro	Motivation findings set limits for Rio de Janeiro's urban expansion, with steep 'slopes' and 'land protected areas' constraining hinterland growth, while future 'urban growth' is expected.	Suitable	0	7,453,301	-	118.63
		Suitable with floating breakwater	392.28		1569	
Mumbai	The evaluation of 'urban growth rate' and 'inundation depth projections' designates this area as at high risk for flooding and significant exposure. This significant exposure projection is also stressed in literature.	Suitable	0	673,016	-	10.7
		Suitable with floating breakwater	35.42		142	

Note: EOL = end-of-life; Mt = Million tons.

5

Discussion and conclusion

This chapter starts with presenting the main GIS model results of the global technical potential, motivated by the proximity of a coastal city in Figure 5.1. Subsequently, I revisit the sub questions introduced in the Introduction and link them to the obtained results. By reviewing the sub questions, the obtained results are further examined, interpreted and discussed with literature findings. The main research question is answered once all sub questions are covered. This chapter concludes with an overarching conclusion, a reflection of this research approach and future research recommendations.

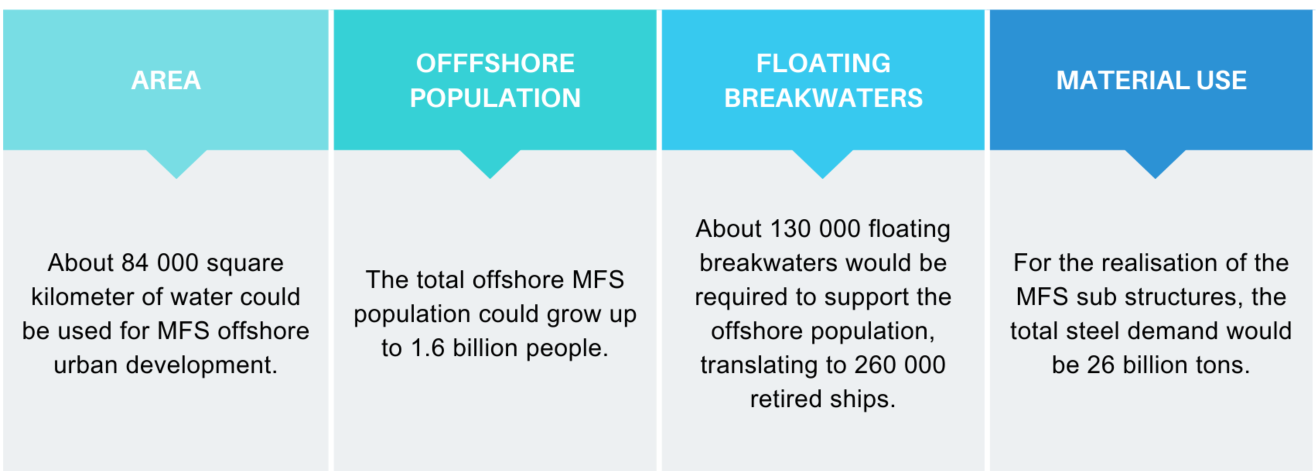

Figure 5.1: Overview main GIS model results of the global technical potential

The first two sub questions posed were:

Sub question 1: *What are key factors that constrain the implementation of MFS?*

Sub question 2: *What are key factors that motivate the need for floating urban development?*

These first two sub questions were aimed at identifying relevant factors for the implementation of MFS, from the techincal perspective. The second sub question was aimed at an exploration of relevant factors that could drive urban expansion at sea. As such, one the one hand the technical feasibility on a global scale was assessed - the 'where' and on the other hand the motivation for urban expansion at sea was assessed - the 'why'. Based on literature and expert consultations assumed relevant factors for exploring the global technical potential of MFS include a topographical constraint - *bathymetry (water depth); environmental constraints - wave statistics (significant wave height,* *wave period, wave length, wave energy, wave direction), wind velocity* and *hurricanes and cyclones*; and ocean planning constraints - *marine protected areas, shipping routes, military areas* and *existing infrastructure*. Assumed relevant factors for exploring the motivation for MFS include demographic factors – *urban growth rates*; topographic factors – *slopes, proximity to coastal city*; environmental factors – *exposure to SLR, exposure to natural land hazards, such as earthquakes*; and land-use factors – *land protected areas*. From this list of relevant factors for the technical potential and motivation for MFS, *existing infrastructure* and *military areas* were excluded due to data unavailability on a global scale.

The outcome of these two sub questions formed the foundation for next sub questions:

Sub question 3: *What are suitable locations for MFS implementation considering a) the technical potential and b) the motivation within the global territorial, internal and archipelagic waters?*

Sub question 4: *What is the global potential, in maximum achievable additional space (km^2) and offshore population (#people) at sea?*

The map presented in Figure 4.3, Chapter 4 depicts the suitable locations for MFS implementation, based on the factors relevant to the technical perspective and delineated by the motivation factor *proximity to a coastal city*. As illustrated in Figure 5.1, the total area (km^2) suitable for MFS implementation would be around 84,000 km^2; the offshore population could grow up to 1.6 billion people.

Sub question 5: *What is the impact of the demand for floating breakwaters and MFS sub structure construction on the global steel flow based on the global potential?*

Based on the ULS map, the GIS model generated a technical potential map that indicated where floating breakwaters would be required for MFS implementation. Based on these areas, reaching the maximum potential presented in sub question 3 and 4 would require about 130,000 floating breakwaters - corresponding to 260,000 EOL ships. Furthermore, to answer this sub question I assumed that the super structure materials are comparable to building on land; therefore, the material demand for MFS implementation is based on the material use for the sub structures. Assuming that the sub structure is entirely made of steel, this demand would reach up to 26 billion tons of steel. The relation to the impact on the global steel flow and on the circular economy will be elaborated on below; as well as a more in depth examination of the results of sub question 3 and 4. This interpretation gives the context to answer the main research question of this thesis, see Paragraph 5.1.4.

5.1 Interpretation of results

This aim of this thesis was not to answer the question whether MFS is a sustainable alternative for coastal urban expansion. Instead, this thesis provides an exploration of the 'proof of scale'; an interesting next step after the 'proof of technology' is established. As such, it gives first global estimates of the scale of impacts of MFS implementation. The results are thus a first step to assess the potential of offshore MFS implementation and the alignment with the SDGs. This paragraph will further discuss the results in the light of the findings in the Literature Review and relating this to the bigger picture - with the goal to comprehensively address the main research question.

5.1.1 Results in the SDG context

The global results for the technical potential, motivated by the proximity of a coastal city centre, are revealing that the maximum achievable area for MFS implementation is about 84,000 km^2; more than twice the surface area of the Netherlands. This total area could accommodate an offshore population up to 1,6 billion individuals. Using the global and urban population projections for 2050, this translates to respectively 17% and 24% of the total and urban population potentially living in floating cities. As outlined in the literature review, projections of people living in Low-Elevation Coastal Zones (LECZ), at high risk of coastal flooding, on a global scale range in the magnitude of hundreds of millions – up to 1,3 billion for 2050 and 2100. If the entire technical potential were to be realized, the concept of offshore dwelling would reach a scale comparable to, even surpass, the entire population at risk globally by 2050. This could be a promising pathway to align with the targets of SDG 11 ("Sustainable Cities and Communities"), ensuring access to adequate housing and disaster risk reduction by establishing a substantial offshore area for urban expansion, which has the potential to have a significant impact in these domains.

Moreover, the global results indicate that approximately 130,000 floating breakwaters would be required if the entire technical potential were to be realized, to ensure the safety and comfort of the offshore dwellings. By repurposing retired end-of-life (EOL) ships as floating breakwaters, there is the potential to contribute to the circular economy within the shipbreaking industry. It is indeed evident that the ship breaking industry is currently unsustainable from both environmental and social perspectives. Also, there are indications in literature that reusing EOL ships will enhance the sustainability of this sector. 261,000 EOL ships would be needed to allow for the realization of the technical potential. To put this into perspective, this is roughly 3 times the current total merchant fleet – with only 1200 reaching EOL each year. However, projections indicate a forthcoming surge in EOL ships, with an estimated increase of 3 to 5 times the current yearly EOL gross tonnage. This poses a challenge because the current capacity is insufficient to handle the recycling of all these ships, particularly if this will be only in future 'green' certified shipyards. The demand for EOL ships at the scale of the global technical potential has the potential to address this overshoot. The substantial quantity of EOL ships that could be reused as breakwaters rather than promptly recycled has the potential to greatly impact the shipbreaking industry. However, this could also greatly impact the local economies of the primary ship breaking nations; Bangladesh, India and Pakistan.

Furthermore, the demand for steel associated with the construction of the MFS sub structures could potentially reach 26 billion tons if the entire technical potential were to be utilized. To put this number into perspective, it's approximately 20 times the world's annual steel demand and, if looking at construction, a magnitude of 100 bigger than the current yearly global steel demand for this sector (Churkina et al., 2020). The essential question to consider is whether material demand at such scale aligns with the challenges we face in an era marked by concerns about material depletion and resource sustainability.

These findings prompt the hypothesis that material use for floating development may be the limiting factor for global scale implementation.

Assessing the impact on SDG 14, "Life below water" was beyond the scope of this thesis, however, this SDG should also be taken into consideration as serious as the other SDG's described above - particularly when considering the significant potential for global offshore population. Indirectly, this SDG is integrated into the model through the exclusion of marine protected areas and the adoption of a conservative approach to water depth. This approach is intended to minimize the impact on the seabed's ecosystem. Nevertheless, also other important factors such as water quality, critical habitats for endangered species, migration routes and nesting sites should be critically considered in the extent of the territorial, internal and archipelagic waters. Currently, floating urbanism projects promote the potential for a mutually beneficial relationship between floating structures and ocean ecosystems. This is for example promised by the introduction of ample surfaces that could support the flourishing of animals and plants, thereby enhancing biodiversity. Nevertheless, conflicting findings exist in studies, with some suggesting negative relationships between floating structures and the marine environment, while others indicate positive interactions (de Lima et al., 2022; Maxwell et al., 2022). The relationship between floating structures and ocean ecosystems and ecology remains an important area requiring further exploration.

Nevertheless, the outcomes and, in a broader sense, the concept of floating cities, are not limited to the scope of these three SDGs (see Figure 5.2 for an overview of all SDGs). I believe that they are inherently intertwined with all 17 SDGs. For instance, the creation of urban land at sea would also directly influence life on land and alters land-use rates. Furthermore, the substantial available space at sea for urban development has the potential to extend into opportunities for renewable energy generation and agriculture; more indirect, yet linking to the generation of affordable and clean energy. Although social and economic factors were beyond the scope of this thesis, the substantial numbers resulting of this thesis do prompt further investigation into their implications for the social and economic SDGs. This is particularly important because this thesis identified the developing countries, notably in Africa, as potential hotspots for floating development; both in the Literature Review and in the Results section. The Literature Review stressed the need for sustainable urban development strategies in these areas, driven by the combination of high projected coastal population growth rates and a high susceptibility to SLR. The results of this thesis showed that Africa, in particular, emerged as possessing a significant technical potential for the expansion of floating urban areas in terms of available sea space and offshore population. Exploring the implications from social and economic perspectives in these regions is an interesting avenue for further investigation.

Figure 5.2: Overview of all Sustainable Development Goals

5.1.2 Local exploration of global results

The global region analysis is an example of how the global GIS model can be used for more in-depth exploration. The results can be compared to the literature review in Paragraph 2.2.1. The analysis results highlighted Southeast Asia's substantial absolute contribution to the global technical potential, motivated by the proximity of coastal cities, including 389 million people, 67 thousand ships, and 3 billion tons of steel. This is attributed to the combination of a high number of cities in relation to the total available area and a relatively significant percentage of suitable area within the continent. Southeast Asia stands out in coastal urban development literature due to its significant projections for future 'LECZ population, which is estimated to reach 350-400 million by 2060. This figure is within the same order of magnitude as the maximum achievable offshore MFS population. However, it's crucial to recognize that meeting this estimate in Southeast Asia would require a vast amount of EOL ships and steel. Only the steel demand represents ten times the global annual steel demand for the construction sector (Conte, 2021).

Literature also emphasized the pressing need for action in Africa, where evident coastal challenges are intensified by the highest projected urban growth among all continents. The GIS model reveals a great potential for Africa in terms of maximum achievable offshore population, potentially reaching up to 360 million people. These results are in the same order of magnitude of the projected LECZ population in 2060. Interestingly, although West Africa's total area within the proximity of a coastal city is not that big, it shows the highest relative suitable area within the continent. Approximately one-third of the total area in close proximity to coastal cities in West Africa is suitable for MFS implementation. Conversely, in East Asia, despite its vast size, only 4% of is coastal areas suitable for MFS deployment. A closer examination of the contribution of SLS, ULS and ocean planning reveals that in East Africa two third of the areas are excluded on the basis of the SLS layer (see Excel sheet attached to the ZIP folder of this thesis, worksheet 'results_global'). Additionally, there is a significant decrease of technical potential (-21%) based on the ULS layer. In contrast, only half of the coastal areas in West Africa are excluded by the SLS and ULS layers, indicating, on average, more favourable sea conditions in this region This is also reflected in the fact that East Asia lacks areas with technical potential for MFS without the presence of a floating breakwater, while West Asia has a substantial proportion of areas where floating breakwaters are not needed - presumed calm waters.

Key takeaways are that the global technical potential of MFS is particularly pronounced in developing countries (Southeast Asia and Africa) with relatively high percentages of suitable areas. Developed East Asia has, despite its considerable size, a significant low potential for MFS implementation, which also holds for Oceania.

5.1.3 Comparing alternatives for coastal urban expansion

As discussed in the literature review, there are various alternatives that address land scarcity and/or SLR, from vertical growth to land reclamation and climate-adaptation to retreat. It is essential to carefully assess and compare each alternative concerning their potential, trade-offs, and environmental impacts, particularly in the context of specific local conditions. Accommodating 1.6 billion people will always involve the use of materials. The critical question is to determine at what scale materials are needed for the different alternatives and how this relates to the potential of for example climate adaptability. For instance, a city with the potential for vertical growth through densification policies can accommodate a certain number of additional residents and this will require a specific material use. However, adopting this policy, a cities' adaptability to climate and the risk of flooding must also be examined carefully. Moreover, the various alternatives do not necessarily exclude each other and combining should also be considered, as for example the report of PBL referenced in Chapter 2 shows. The decision process for a suitable coastal adaptation pathway process is dependent on the local context and involves the complex considerations of all proposed alternatives.

5.1.4 Convergence of insights - answering the research question

. The main research question posed in the Introduction was:

What is the global potential of Modular Floating Structures and circular floating breakwaters as an alternative for sustainable urban expansion at sea and what could be the implications for the global steel flows based on this potential?

Based on the results and their interpretation, it can be stated that the global potential of MFS can be established by incorporating the technical potential and motivation perspective; together comprising the global potential. Firstly, the technical potential was developed considering the factors *bathymetry (water depth), wave statistics (significant wave height, wave period, wave length, wave energy, wave direction), wind velocity* and *hurricanes and cyclones*, *marine protected areas* and *shipping routes*. The technical potential was complemented by the motivation factor *proximity to coastal city*. This analysis resulted in global numbers representing the maximum achievable global potential of MFS: 84,000 km^2 of water could be used for MFS, which could grow up to 1.6 billion people; the associated material demand required to support this population would be 130,000 floating breakwaters - translating to 260,000 EOL ships. Moreover, for the construction of the sub structures 26 billion tons of steel would be needed.

Then, the motivation perspective was used to complement and interpret the results and establishing a more nuanced global potential. Motivation factors included in this thesis are *urban growth rates*, *slopes*, *exposure to SLR, exposure to earthquakes* and *land protected areas*. By assessing the established global potential under these potential drivers for MFS, I discovered that in global regions with high motivation, particularly Africa and Southeast Asia, the maximum potential was relatively high; opening doors to further investigating these areas as potential locations suitable for floating cities. Lastly, the results indicated that repurposing EOL ships as floating breakwaters could contribute to the circular economy within the shipbreaking industry. However, meeting the demand for EOL ships at the scale of the global maximum potential may challenge the capacity of 'green' certified shipyards and impact local economies in primary shipbreaking nations. Furthermore, the scale of magnitude of associated steel demand raises important questions about the alignment of such material demand with the contemporary challenges related to material depletion and resource sustainability.

With a comprehensive Literature Review and the established GIS model the main research question in regard to the global potential and associated material demand could be answered and discussed; whether the concept of floating cities is sustainable compared to other alternatives is a next step, which can build on the findings of this thesis.

5.2 Limitations and discussion of GIS model

5.2.1 Data availability and simplifications

The GIS model developed in this thesis proves useful for providing an exploration and first estimates of the global potential of MFS. However there is always room for improvement; the exclusion of certain factors relevant to implementation, due to data unavailability, could impact the model's ability to adequately represent the actual technical potential. For instance, the global scale wave statistics data was hard to obtain, especially the extreme values for the ULS. Consequently, only average coastal wave energy is considered as SLS input data. However, this is a rather vague classification and a proxy for the wave climate. Also, including wave period data would be useful, as this is a significant aspect of the wave climate that could potentially limit MFS performance as demonstrated in numerical studies by G. Wang, Drimer, and Goldfeld (2020) and G. Wang et al. (2023). For the ULS data, the most optimal dataset provided derived extreme values on a resolution of 2 x 2 degree, which is usually sufficiently detailed for global scale analysis. However, given the specific focus of this thesis on coastal waters, the limited resolution restricts the level of coastal detail in the ULS data, resulting in, for instance, overlooking small calm coastal bays. Regarding the ocean planning, global data was lacking. Important factors not considered in the analysis are military areas and existing infrastructure at sea such as wind farms. Windfarms are known to be widely implemented in the waters of Europe and could thus lead to overestimation of the global potential. As such, the GIS model does not capture all relevant factors, however, it still provides valuable estimates to assess the order of magnitude for proof of scale.

Conversely, for the data that was available and implemented, the used assumptions for the GIS analysis were rather conservative. For instance, only the boundaries of the wave statistics in which the MFS is proven to perform adequately are evaluated as suitable for MFS implementation. Moreover, the bathymetry boundaries are quite conservative due to the assumption that the floating breakwaters should maintain an substantial underwater keel clearance. The evaluation of shipping density data also takes a conservative stance, as AIS data encompasses all locations that are visited frequently, not only showing the actual theoretical shipping route. Also, it could be argued that shipping routes should not be automatically considered an exclusion, as re-routing might be considered a realistic option.

Additionally, some notable simplifications should be acknowledged. Firstly, the fixed global boundaries for bathymetry represent a simplification, as in reality, water depth limits for floating structures vary locally, as they should be primarily based on minimal disruption of the seabed ecosystem and interactions with waves and soil sediment types. Manmade floating structures should avoid interfering with natural coastal wave actions that lead to erosion and sediment deposition. Furthermore, MFS are designed as offshore structures for deployment in deep water, which is not defined by a straightforward depth boundary but is typically characterized as water deeper than half the wavelength. Secondly, the 35 km buffer around the city centre for motivation potential is open to discussion. It's important to acknowledge that cities come in various sizes, topographies, and characteristics, and a fixed 35 km buffer doesn't capture these diversities. For example, large, widespread cities with city centres located relatively far from the coast may have limited potential in the GIS model due to their centre location, while urban and suburban centres could extend to the coast. A more detailed examination of cities' sizes and extents, rather than representing them with a single centre point, could improve accuracy. The 35 km assumption also leads to a situation where delta cities, characterized by shallow nearby waters, have limited potential in the GIS model. However, these cities are often highly vulnerable and should not be overlooked in presenting solution for coastal urban challenges. Deepwater MFS may not be suitable for delta cities, necessitating the exploration of alternative solutions there. Lastly, the model's motivation potential simplification fails to capture the complex demographic factors underlying the issue of land scarcity – motivating the adoption of floating urban development. Evaluating land scarcity solely on urban growth provides an indication of potential issues in the future, however, in reality, land scarcity depends on various factors, as emphasized in the literature review. A more comprehensive local exploration of the motivation for MFS is required to assess motivations at the city level. This comprehensive exploration would consider factors such as rural-urban migration, metropolitan areas, city densities and limits, economic growth, land-use planning, and policies.

5.2.2 Future scenario's

The temporal scope of the technical potential is static and relies on current data of topographical, environmental, and ocean planning constraints. This static approach does not entirely align with the timeframe of the floating cities concept, which is still in its early developmental stage and is anticipated to be realized in the future rather than in the present. The model does not account for future changes in bathymetry – GSLR - wave climate data and future ocean planning projects. However, some of these climate-related factors are acknowledged to become more extreme in the future. Nevertheless, the model can be regularly updated if more recent data becomes available to keep it up to date. In contrast, the motivation potential does include data layers of future projections (SLR and urban growth), considering socio-economic and representative concentration pathways.

5.2.3 Adaptability of the GIS model

The GIS model is developed for the purpose of this thesis, specifically assessing the global potential of MFS. However, the application of this model can extend beyond this initial purpose. It is designed in an adaptable manner, allowing for the adjustment of boundary parameters and the option to include, exclude or view layers separately. As such, there is room for discussion regarding other potential uses for this GIS model. Other designs of floating structures, whether for urban development, energy generation or agriculture, could use this model by adjusting parameters. When for example comparing the floating urban development strategy to traditional land reclamation, it could prove valuable to explore the potential for floating urban development in areas where land reclamation is common practise. This can highlight the existence of an alternative to traditional land reclamation, encouraging further investigation into both alternatives.

5.3 Reflection on on research approach

The first note to reflect on the research approach must be made on the decision what factors to consider when establishing the global potential of MFS. As I limited the relevant factors based on my own rationale and assumptions, this should be carefully considered when interpreting the results. If a researcher decides to focus on other factors, the outcome may significantly differ. I think that the use of the Industrial Ecology perspective and GIS as a tool established a comprehensive framework of floating cities, placing it both in a technological and motivation context. The systems thinking approach revealed interconnections with multiple perspectives, such as the technological, environmental and social, which is, to my opinion, important to consider for the bigger picture and implications of urban development. Also, by using GIS as a tool for in the field of floating cities, it reveals significance of additional complex factors, such as the political and economic context, which may be challenging to assess spatially; giving rise to new research avenues.

In conclusion, I believe that the research approach has established a valuable tool for the field of floating cities and continues to foster discussions about floating urban development. This tool can for example be deployed to inform stakeholders and interested parties effectively since the results are visually accessible - and by fostering the discussions, the Industrial Ecology questions introduced in the beginning and, more broadly, the environmental and social impacts of this alternative will hopefully be addressed and deliberated upon in the future.

5.4 Conclusion

MFS are an proposed alternative for sustainable offshore urban dwelling, to combat the urban coastal challenges of urban growth, increased SLR exposure and land scarcity. This thesis has focussed on geographically exploring the global technical potential and motivation potential of MFS, integrating technical, environmental and social perspectives. The GIS analysis described in the methodology entailed:

1) establishing the SLS technical potential considering the factors *bathymetry, average wave energy, average wind speed* and *hurricane risk*;

2) establishing the ULS technical potential map based on the SLS map and the factors *100-year return significant wave height* and *100-year wind speed*;

3) establishing the ocean planning technical potential map based the ULS map and on the factors *marine protected areas* and *shipping routes*;

4) establishing the motivation potential maps, based on 1, 2, and 3 and the factor *'proximity to a coastal city'*; and

evaluation of the motivation layers based on demographic motivation – urban growth rate -, topographic motivation – slope hinterland -, environmental motivation – exposure to SLR, exposure to natural land hazards, such as earthquakes - and land use motivation – land protected areas.

Key insights of this thesis are that the global technical potential of urban offshore development can be explored by a GIS model, incorporating environmental and ocean zoning constraints. The GIS model developed in this thesis gives the following global results based on bathymetry, average wave energy, average wind speed, marine protected areas, shipping routes and proximity to coastal city centre constraints: 84 000 km^2 could potentially be used for MFS deployment, accommodating about 1.6 billion people. This would cover a fourth of the total urban population in 2050. However, substantial amounts of materials are associated with this potential, as approximately 261,000 end-of-life (EOL) ships would be required for floating breakwaters and 26 billion tons of steel for the construction of the MFS substructures. Based on the results, it can be concluded that MFS hold the potential to provide a global solution for global coastal challenges in terms of significant contribution to climate adaptive housing capacity, thereby addressing targets of SDG 11 “Sustainable cities and Communities”. The results show that in terms of material use the global potential greatly surpasses global yearly demand and supply in scale of magnitude, raising questions about the impact of global scale MFS implementation.

5.4.1 Future research directions

The results of this thesis open the door to even more interesting discussions and research directions. For example, now the substantial technical potential of MFS is discovered, it could also be considered to designate these areas to large-scale agricultural activities, food or energy generation. Future recommendations can go in the direction of improving, refining or extending the GIS model developed for this thesis. Taking the local case studies in this thesis as an example, this could be the starting point for more in-depth research into sustainable offshore urban development in specific cities or regions of interest. Also, the relevant factors used in the technical potential are limited and could be extended, especially regarding the ocean planning and motivation potential. When thinking beyond the technical potential used in this thesis, it would be relevant and interesting to move to the economical and market potential of this alternative in areas with a significant technical potential. For example, the list of leading cities includes some regions where political or economical potential may be considerably low; such as Syria and Yemen. As the results of this thesis show the high technical potential in Africa and Southeast Asia - including primarily developing nations - I also advocate for further research into the adaptability of the concept of MFS and/or floating cities to urban forms in developing nations. This research should investigate potential challenges and hurdles when implementing these concepts in developing nations, compared to high developed nations.

Additional future research building directly on the findings of this thesis could be:

- Comparing material requirements for MFS substructures to those of land-based building substructures.
- Investigating the hypothesis that the vast numbers associated with floating breakwaters and materials for the substructures are a limiting factor for global scale adoption of floating urban development.
- Conducting a Life Cycle Assessment (LCA) on a unit of land reclamation and a unit of MFS, to further investigate the environmental impact of both alternatives if the technical potential proves favorable for MFS.
- Micro, meso and macro-scale scenario based Material Flow Analysis (MFA) to uncover impact on the future global steel flow or ship breaking industry, using the local and global estimates of EOL ships and steel demand presented in this thesis as a guideline.

Bibliography

Ajibade, I. (2019). Planned retreat in Global South megacities: disentangling policy, practice, and environmental justice. *Climatic Change*, *157*(2), 299–317. https://doi.org/10.1007/s10584-019-02535-1

Amer, M., Mustafa, A., Teller, J., Attia, S., & Reiter, S. (2017). A methodology to determine the potential of urban densification through roof stacking. *Sustainable Cities and Society*, *35*(September), 677–691. https://doi.org/10.1016/j.scs.2017.09.021

Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000-2050. *Progress in Planning*, *75*(2), 53–107. https://doi.org/10.1016/j.progress.2011.04.001

Angel, S., Sheppard, S. C., & Civco, D. (2005). *The Dynamics of Global Urban Expansion. Transport and Urban Development Department* (tech. rep.). https://www.researchgate.net/publication/260317174

Arora, R., Paterok, K., Banerjee, A., & Saluja, M. S. (2017). Potential and relevance of urban mining in the context of sustainable cities. *IIMB Management Review*, *29*(3), 210–224. https://doi.org/10.1016/j.iimb.2017.06.001

Artz, M., & Baumann, J. (2009). What Is The Geographic Approach? https://www.esri.com/news/arcwatch/0809/feature.html

Barua, S., Rahman, I. M., Hossain, M. M., Begum, Z. A., Alam, I., Sawai, H., Maki, T., & Hasegawa, H. (2018). Environmental hazards associated with open-beach breaking of end-of-life ships: a review. *Environmental Science and Pollution Research*, *25*(31), 30880–30893. https://doi.org/10.1007/s11356-018-3159-8

Bell, M., Charles-Edwards, E., Ueffing, P., Stillwell, J., Kupiszewski, M., & Kupiszewska, D. (2015). Internal Migration and Development: Comparing Migration Intensities Around the World. *Population and Development Review*, *41*(1), 33–58. https://doi.org/10.1111/j.1728-4457.2015.00025.x

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010). Urban sprawl measurement from remote sensing data. *Applied Geography*, *30*(4), 731–740. https://doi.org/10.1016/j.apgeog.2010.02.002

Blue21. (2023a). BLUE REVOLUTION. https://www.blue21.nl/

Blue21. (2023b). Floating eco-homes Harnaschpolder. https://www.blue21.nl/portfolio/floating-eco-homes-harnaschpolder/

Bounoua, L., Nigro, J., Thome, K., Zhang, P., & Lachir, A. (2018). Mapping urbanization in the United States for 2020. *International Geoscience and Remote Sensing Symposium (IGARSS)*, *2018-July*, 854–857. https://doi.org/10.1109/IGARSS.2018.8517770

Brown, S., Nicholls, R., Lowe, J., & Hinkel, J. (2016). Spatial variations in sea level rise and global impacts: An application of DIVA. *Climatic Change*, *134*(3), 403–416.

Castro-Santos, L., Lamas-Galdo, M. I., & Filgueira-Vizoso, A. (2020). Managing the oceans: Site selection of a floating offshore wind farm based on GIS spatial analysis. *Marine Policy*, *113*, 103803. https://doi.org/10.1016/j.marpol.2019.103803

Church, J., Clark, P., Cazenave, A., Gregory, J., Jevrejeva, S., Levermann, A., Merrifield, M., Milne, G., Nerem, R., Nunn, P., Payne, A., Pfeffer, W., Stammer, D., & Unnikrishnan, A. (2013). *Chapter 13: Sea Level Change*. Jan H. van Angelen.

Churkina, G., Organschi, A., Reyer, C. P., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

Cohen, J. E. (2010). *Population and Climate Change* (tech. rep. No. 2). https://www.jstor.org/stable/41000096?seq=1&cid=pdf-

Cohen, M. (2017, November). A systematic review of urban sustainability assessment literature. https://doi.org/10.3390/su9112048

Conte. (2021). Visualizing 50 Years of Global Steel Production. https://www.visualcapitalist.com/visualizing-50-years-of-global-steel-production/

Dadashpoor, H., & Nateghi, M. (2017). Simulating spatial pattern of urban growth using GIS-based SLEUTH model: a case study of eastern corridor of Tehran metropolitan region, Iran. *Environment, Development and Sustainability*, *19*(2), 527–547. https://doi.org/10.1007/s10668-015-9744-9

Day, J. W., Gunn, J. D., & Burger, J. R. (2021). Diminishing Opportunities for Sustainability of Coastal Cities in the Anthropocene: A Review. *Frontiers in Environmental Science*, *9*(August), 1–15. https://doi.org/10.3389/fenvs.2021.663275

Dehghani, A., Alidadi, M., & Sharifi, A. (2022). Compact Development Policy and Urban Resilience: A Critical Review. *Sustainability (Switzerland)*, *14*(19), 1–19. https://doi.org/10.3390/su141911798

de Lima, R. L., de Graaf-Van Dinther, R. E., & Boogaard, F. C. (2022). Impacts of floating urbanization on water quality and aquatic ecosystems: a study based on in situ data and observations. *Journal of Water and Climate Change*, *13*(3), 1185–1203. https://doi.org/10.2166/wcc.2022.325

Díaz, H., Fonseca, R., & Guedes Soares, C. (2019). Site selection process for floating offshore wind farms in Madeira Islands. In *Advances in renewable energies offshore* (pp. 729–737). Taylor & Francis Group.

Díaz, H., & Guedes Soares, C. (2020). An integrated GIS approach for site selection of floating offshore wind farms in the Atlantic continental European coastline. *Renewable and Sustainable Energy Reviews*, *134*, 110328. https://doi.org/10.1016/j.rser.2020.110328

Ding, J., Tian, C., Wu, Y. s., Li, Z. w., Ling, H. j., & Ma, X. z. (2017). Hydroelastic analysis and model tests of a single module VLFS deployed near islands and reefs. *Ocean Engineering*, *144*, 224–234. https://doi.org/10.1016/j.oceaneng.2017.08.043

Ding, J., Wu, Y., Xie, Z., Yang, W., Wang, S., Yu, J., & Yu, T. (2021). Overview: Research on hydroelastic responses of VLFS in complex environments. *Marine Structures*, *78*(December 2020), 102978. https://doi.org/10.1016/j.marstruc.2021.102978

Du, R. (2016). Urban growth: Changes, management, and problems in large cities of Southeast China. *Frontiers of Architectural Research*, *5*(3), 290–300. https://doi.org/10.1016/j.foar.2016.04.002

Duan, H., Zhang, H., Huang, Q., Zhang, Y., Hu, M., Niu, Y., & Zhu, J. (2016). Characterization and environmental impact analysis of sea land reclamation activities in China. *Ocean and Coastal Management*, *130*, 128–137. https://doi.org/10.1016/j.ocecoaman.2016.06.006

Dube, K., Nhamo, G., & Chikodzi, D. (2022). Flooding trends and their impacts on coastal communities of Western Cape Province, South Africa. *GeoJournal*, *87*(s4), 453–468. https://doi.org/10.1007/s10708-021-10460-z

Esri. (2021). What is geodata? https://desktop.arcgis.com/en/arcmap/latest/manage-data/main/what-is-geodata.htm

Esri. (2023). What is GIS? https://www.esri.com/en-us/what-is-gis/overview

Esri, Airbus, USGS, NGA, NASA, CGIAR, NLS, OS, NMA, GSA, GSI, & Community, G. U. (2023). Terrain: Slope Map. https://www.arcgis.com/home/item.html?id=a1ba14d09df14f42ad6ca3c4bcebf3b4

Fan, T., & Chapman, A. (2022). Policy Driven Compact Cities: Toward Clarifying the Effect of Compact Cities on Carbon Emissions. *Sustainability (Switzerland)*, *14*(19), 1–19. https://doi.org/10.3390/su141912634

Flanders Marine Institute. (2023). MarineRegions.org. www.marineregions.org

GEBCO Compilation Group. (2023). GEBCO 2023 Grid. https://doi.org/doi:10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b

Glavovic, B. C., Dawson, R., Chow, W., Garschagen, M., Haasnoot, M., Singh, C., & Thomas, A. (2022). *Cross-Chapter Paper 2: Cities and Settlements by the Sea*. https://doi.org/10.1017/9781009325844.019.2163

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010, February). Food security: The challenge of feeding 9 billion people. https://doi.org/10.1126/science.1185383

GWA. (2023). Data mean wind-speed 10 obtained from the "Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, uti.

Haase, A., Bernt, M., Großmann, K., Mykhnenko, V., & Rink, D. (2016). Varieties of shrinkage in European cities. *European Urban and Regional Studies*, *23*(1), 86–102. https://doi.org/10.1177/0969776413481985

Habibi, S., & Asadi, N. (2011). Causes, results and methods of controlling urban sprawl. *Procedia Engineering*, *21*, 133–141. https://doi.org/10.1016/j.proeng.2011.11.1996

Hall, J. A., Gill, S., Obeysekera, J., Sweet, W., Knuuti, K., & Marburger, J. (2016). Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide. (April), 224. https://apps.dtic.mil/sti/citations/AD1013613

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., & Chateau, J. (2011). A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, *104*(1), 89–111. https://doi.org/10.1007/s10584-010-9977-4

Hennig, E. I., Schwick, C., Soukup, T., Orlitová, E., Kienast, F., & Jaeger, J. A. (2015). Multi-scale analysis of urban sprawl in Europe: Towards a European de-sprawling strategy. *Land Use Policy*, *49*, 483–498. https://doi.org/10.1016/j.landusepol.2015.08.001

Herburger, J. (2023). It's not about compact cities. *Dialogues in Human Geography*, *13*(1), 44–49. https://doi.org/10.1177/20438206221144822

Horton, B. P., Khan, N. S., Cahill, N., Lee, J. S., Shaw, T. A., Garner, A. J., Kemp, A. C., Engelhart, S. E., & Rahmstorf, S. (2020). Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey. *npj Climate and Atmospheric Science*, *3*(1), 1–8. https://doi.org/10.1038/s41612-020-0121-5

Hossain, M. S., Fakhruddin, A. N. M., Chowdhury, M. A. Z., & Gan, S. H. (2016). Impact of ship-Breaking activities on the coastal environment of Bangladesh and a management system for its sustainability. *Environmental Science and Policy*, *60*, 84–94. https://doi.org/10.1016/j.envsci.2016.03.005

IRP. (2018). *The weight of cities: resource requirements of future urbanization*. www.karlschulschenk.com

Jain, K. P., Pruyn, J. F., & Hopman, J. J. (2017). Material flow analysis (MFA) as a tool to improve ship recycling. *Ocean Engineering*, *130*, 674–683. https://doi.org/10.1016/j.oceaneng.2016.11.036

Jones, B., & O'Neill, B. C. (2016). Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. *Environmental Research Letters*, *11*(8). https://doi.org/10.1088/1748-9326/11/8/084003

Kennedy, C. (2016). Industrial Ecology and Cities. In *Taking stock of industrial ecology* (pp. 69–86).

Khosravi Kazazi, A., Rabiei-Dastjerdi, H., & McArdle, G. (2022). Emerging paradigm shift in urban indicators: Integration of the vertical dimension. *Journal of Environmental Management*, *316*. https://doi.org/10.1016/j.jenvman.2022.115234

KIT. (2023). Knowledge and Hospitality for a Sustainable World. https://www.kit.nl/

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The international best track archive for climate stewardship (IBTrACS). *Bulletin of the American Meteorological Society*, *91*(3), 363–376. https://doi.org/10.1175/2009BAMS2755.1

Knapp, K., Kruk, M., Levinson, D., Diamond, H., & Neumann, C. (2018). The International Best Track Archive for Climate Stewardship (IBTrACS) Project, Version 4. [ALL]. NOAA National Centres for Environmental Information. https://doi.org/doi:10.25921/82ty-9e16

Kong, X., Feng, K., Wang, P., Wan, Z., Lin, L., Zhang, N., & Li, J. (2022). Steel stocks and flows of global merchant fleets as material base of international trade from 1980 to 2050. *Global Environmental Change*, *73*. https://doi.org/10.1016/j.gloenvcha.2022.102493

Koziatek, O., & Dragićević, S. (2019). A local and regional spatial index for measuring three-dimensional urban compactness growth. *Environment and Planning B: Urban Analytics and City Science*, *46*(1), 143–164. https://doi.org/10.1177/2399808317703983

Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-12808-z

Kummu, M., De Moel, H., Salvucci, G., Viviroli, D., Ward, P. J., & Varis, O. (2016). Over the hills and further away from coast: Global geospatial patterns of human and environment over the 20th-21st centuries. *Environmental Research Letters*, *11*(3), 34010. https://doi.org/10.1088/1748-9326/11/3/034010

Lamas-Pardo, M., Iglesias, G., & Carral, L. (2015). A review of Very Large Floating Structures (VLFS) for coastal and offshore uses. *Ocean Engineering*, *109*, 677–690. https://doi.org/10.1016/j.oceaneng.2015.09.012

Lázaro, A. F., Serret, R. G., Negro, V., & López-Gutiérrez, J. (2013). Use of a scrapped ship as a floating breakwater for shore protection. *Journal of Coastal Research*, *65*(January), 225–230. https://doi.org/10.2112/si65-039.1

Li, M., Wang, Y., Rosier, J. F., Verburg, P. H., & van Vliet, J. (2022). Global maps of 3D built-up patterns for urban morphological analysis. *International Journal of Applied Earth Observation and Geoinformation*, *114*(September), 103048. https://doi.org/10.1016/j.jag.2022.103048

Lin, F. Y., Spijkers, O., & van der Plank, P. (2022). Legal Framework for Sustainable Floating City Development: A Case Study of the Netherlands. *Lecture Notes in Civil Engineering*, *158*, 433–460. https://doi.org/10.1007/978-981-16-2256-4{_}27

Lin, L., Feng, K., Wan, Z., Wang, P., Kong, X., Zhang, N., Hubacek, K., & Li, J. (2022). Unexpected side effects of the EU Ship Recycling Regulation call for global cooperation on greening the shipbreaking industry. *Environmental Research Letters*, *17*(4). https://doi.org/10.1088/1748-9326/ac5a68

Lin, Y. H., Chih Lin, Y., & Tan, H. S. (2019, August). Design and functions of floating architecture–a review. https://doi.org/10.1080/1064119X.2018.1503761

Lin, Z., & Gámez, J. (2018). *Vertical Urbanism: Designing Compact Cities in China*.

Mahtta, R., Mahendra, A., & Seto, K. C. (2019). Building up or spreading out? typologies of urban growth across 478 cities of 1 million+. *Environmental Research Letters*, *14*(12). https://doi.org/10.1088/1748-9326/ab59bf

Mandakini P. Bhatt. (2020). Modular Maritime Metropolis: A Review on Sustainable Floating City. *International Journal of Engineering Research and*, *V9*(05), 823–826. https://doi.org/10.17577/ijertv9is050600

Mao, X., Huang, X., Song, Y., Zhu, Y., & Tan, Q. (2020). Response to urban land scarcity in growing megacities: Urban containment or inter-city connection? *Cities*, *96*. https://doi.org/10.1016/j.cities.2019.102399

Mascarenhas, A., Haase, D., Ramos, T. B., & Santos, R. (2019). Pathways of demographic and urban development and their effects on land take and ecosystem services: The case of Lisbon Metropolitan Area, Portugal. *Land Use Policy*, *82*(October 2017), 181–194. https://doi.org/10.1016/j.landusepol.2018.11.056

Mawren, D., Hermes, J., & Reason, C. J. (2022). Marine heat waves and tropical cyclones - Two devastating types of coastal hazard in South-eastern Africa. *Estuarine, Coastal and Shelf Science*, *277*(August), 108056. https://doi.org/10.1016/j.ecss.2022.108056

Maxwell, S. M., Kershaw, F., Locke, C. C., Conners, M. G., Dawson, C., Aylesworth, S., Loomis, R., & Johnson, A. F. (2022). Potential impacts of floating wind turbine technology for marine species and habitats. *Journal of Environmental Management*, *307*(January), 114577. https://doi.org/10.1016/j.jenvman.2022.114577

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, *19*(1), 17–37. https://doi.org/10.1177/0956247807076960

McMichael, C., Dasgupta, S., Ayeb-Karlsson, S., & Kelman, I. (2020). A review of estimating population exposure to sea-level rise and the relevance for migration. *Environmental Research Letters*, *15*(12). https://doi.org/10.1088/1748-9326/abb398

Melissas, D., & Asprogerakas, E. (2022). Spatial parameters for the development of floating wind farms in Greece. *European Journal of Geography*, *13*(4), 1–17. https://doi.org/10.48088/ejg.d.mel.13.4.001.017

Merkens, J. L., Reimann, L., Hinkel, J., & Vafeidis, A. T. (2016). Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Global and Planetary Change*, *145*, 57–66. https://doi.org/10.1016/j.gloplacha.2016.08.009

Mouratidis, K. (2019). Compact city, urban sprawl, and subjective well-being. *Cities*, *92*(November 2018), 261–272. https://doi.org/10.1016/j.cities.2019.04.013

Nadeem, M., Khaliq, N., Akhtar, N., Al-Rashid, M. A., Asim, M., Codur, M. K., Mustafaraj, E., Codur, M. Y., & Baig, F. (2022). Exploring the Urban Form and Compactness: A Case Study of Multan, Pakistan. *Sustainability (Switzerland)*, *14*(23). https://doi.org/10.3390/su142316066

NEOM. (2023). Oxagon. https://www.neom.com/en-us/regions/oxagon

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, *10*(3). https://doi.org/10.1371/journal.pone.0118571

Nie, B., & Li, J. (2018). Technical potential assessment of offshore wind energy over shallow continent shelf along China coast. *Renewable Energy*, *128*, 391–399. https://doi.org/10.1016/j.renene.2018.05.081

NOAA. (2023a). Estimating Wind Speed. https://www.weather.gov/pqr/wind

NOAA. (2023b). Maritime Zones and Boundaries. https://www.noaa.gov/maritime-zones-and-boundaries

Notteboom, T., Pallis, A., & Rodrigue, J.-P. (2022). *Port Economics, Management and Policy* (Vol. 16). https://doi.org/https://doi.org/10.4324/9780429318184

Oceanix. (2023). Leading the next frontier for human habitation. https://oceanix.com/

O'Donnell, T. (2022). Managed retreat and planned retreat: a systematic literature review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *377*(1854), 23–29. https://doi.org/10.1098/rstb.2021.0129

OECD. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. https://doi.org/https://doi.org/10.1787/9789264307452-en

Ohmatsu, S. (2007). Model experiments for VLFS. In *Very large floating structures* (p. 24).

Oppenheimer, M., Glavovic, B., Hinkel, J., van de Wal, R., Magnan, A., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., & Sebesvari, Z. (2019). *Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities*. https://doi.org/10.1017/9781009157964.006

Oxford University Press. (2023). Territorial waters. *Oxford Online Dictionary*.

Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013). The steel scrap age. *Environmental Science and Technology*, *47*(7), 3448–3454. https://doi.org/10.1021/es303149z

Peduzzi, P. (2014). Sand, rarer than one thinks. *Environmental Development*, *11*, 208–218. https://doi.org/10.1016/j.envdev.2014.04.001

Pelling, M., & Blackburn, S. (2013). *Megacities and the Coast: Risk, Resilience and Transformation* (tech. rep.). https://www.researchgate.net/publication/261511434

Peponi, A., & Morgado, P. (2020, April). Smart and regenerative urban growth: A literature network analysis. https://doi.org/10.3390/ijerph17072463

Perez, O. M., Telfer, T. C., & Ross, L. G. (2005). Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research*, *36*(10), 946–961. https://doi.org/10.1111/j.1365-2109.2005.01282.x

Peters, J. L., Remmers, T., Wheeler, A. J., Murphy, J., & Cummins, V. (2020, August). A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices. https://doi.org/10.1016/j.rser.2020.109916

Pisut, D. (2020). Global Active Earthquake Faults - Living Atlas of the World. https://livingatlas-dcdev.opendata.arcgis.com/datasets/37a384d4c1ef4f56a33a40f291a634e9/explore

Priyanka, B., & Mahesha, A. (2015). Parametric Studies on Saltwater Intrusion into Coastal Aquifers for Anticipate Sea Level Rise. *Aquatic Procedia*, *4*, 103–108. https://doi.org/10.1016/j.aqpro.2015.02.015

Rasmussen, P., Sonnenborg, T. O., Goncear, G., & Hinsby, K. (2013). Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer. *Hydrology and Earth System Sciences*, *17*(1), 421–443. https://doi.org/10.5194/hess-17-421-2013

Ray, R. D., & Foster, G. (2016). Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future*, *4*(12), 578–587. https://doi.org/10.1002/2016EF000423

Ritchie, H., & Roser, M. (2018). Urbanization. *Our World in Data*. https://ourworldindata.org/urbanization

Sankalp, A., & De Leeneer, Y. (2020). Mooring Systems for Very Large Floating Structures. In *Lecture notes in civil engineering* (pp. 253–273, Vol. 41). Springer. https://doi.org/10.1007/978-981-13-8743-2{_}14

Sayre, R., Martin, M., & Cress, J. (2021). Earth's coastlines. In *Gis for science: Maps for saving the planet, volume 3* (pp. 4–27). Esri Press.

Schallenberg-Rodríguez, J., & García Montesdeoca, N. (2018). Spatial planning to estimate the offshore wind energy potential in coastal regions and islands. Practical case: The Canary Islands. *Energy*, *143*, 91–103. https://doi.org/10.1016/j.energy.2017.10.084

Schiller, G., & Roscher, J. (2023). Impact of urbanization on construction material consumption: A global analysis. *Journal of Industrial Ecology*, *27*(3), 1021–1036. https://doi.org/10.1111/jiec.13392

Senavirathna, G. R., Galappaththi, U. I., & Ranjan, M. T. (2022, June). A review of end-life management options for marine structures: State of the art, industrial voids, research gaps and strategies for sustainability. https://doi.org/10.1016/j.clet.2022.100489

Sengupta, D., Chen, R., & Meadows, M. E. (2018). Building beyond land: An overview of coastal land reclamation in 16 global megacities. *Applied Geography*, *90*(May 2017), 229–238. https://doi.org/10.1016/j.apgeog.2017.12.015

Seto, K. C., Fragkias, M., Güneralp, B., & Reilly, M. K. (2011). A meta-analysis of global urban land expansion. *PLoS ONE*, *6*(8). https://doi.org/10.1371/journal.pone.0023777

Shaiful Fitri Abdul Rahman, N., Khairuddin Othman, M., & Ismail, A. (2018). Introduction of Floating Vessel Breakwater System for Coastal and Tourism Sustainability using Re-Use Vessel, 46–57. www.jmr.unican.es

Silva, A. N., Taborda, R., Bertin, X., & Dodet, G. (2012). Seasonal to Decadal Variability of Longshore Sand Transport at the Northwest Coast of Portugal. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *138*(6), 464–472. https://doi.org/10.1061/(asce)ww.1943-5460.0000152

Solakivi, T., Kiiski, T., Kuusinen, T., & Ojala, L. (2021). The European Ship Recycling Regulation and its market implications: Ship-recycling capacity and market potential. *Journal of Cleaner Production*, *294*. https://doi.org/10.1016/j.jclepro.2021.126235

Somansundar, S., & Panneer Selvam, R. (2019). Hydroelastic responses of a pontoon-type VLFS in different water depths. *Lecture Notes in Civil Engineering*, *22*, 319–331. https://doi.org/10.1007/978-981-13-3119-0{_}18

Stauber, J., Chariton, A., & Apte, S. (2016). *Global Change*. https://doi.org/10.1016/B978-0-12-803371-5.00010-2

Stedenbouw. (2019). Schoonschip Amsterdam. https://www.stedenbouw.nl/artikel/schoonschip-amsterdam/

Sylla, G., Coulibaly, T. J. H., Coulibaly, N., Kouadio, K. C. A., Coulibaly, H. S. J. P., Cissé, S., Sie, K., Camara, I., & N'guessan, K. H. J. (2023). Urban expansion of Korhogo City (Côte d'Ivoire) using gis and nocturnal remote sensing. *Computational Urban Science*, *3*(1). https://doi.org/10.1007/s43762-023-00099-6

Takbash, A., Young, I. R., & Breivik, Ø. (2019). Global wind speed and wave height extremes derived from long-duration satellite records. *Journal of Climate*, *32*(1), 109–126. https://doi.org/10.1175/JCLI-D-18-0520.1

The World Bank. (2023). Global Shipping Traffic Density [Ship Density - Commercial]. Version 5. https://datacatalog.worldbank.org/search/dataset/0037580/Global-Shipping-Traffic-Density

Ulgiati, S., & Zucaro, A. (2019). Challenges in Urban Metabolism: Sustainability and Well-Being in Cities. *Frontiers in Sustainable Cities*, *1*. https://doi.org/10.3389/frsc.2019.00001

Umar, T. (2020, December). Making future floating cities sustainable: A way forward. https://doi.org/10.1680/jurdp.19.00015
Umoh, K., & Lemon, M. (2020). Drivers for and barriers to the take up of floating offshore wind technology: A comparison of Scotland and South Africa. *Energies*, *13*(21). https://doi.org/10.3390/en13215618
UNEP-WCMC & IUCN. (2023). Protected Planet: The World Database on Protected Areas (WDPA). www.protectedplanet.net.
United Nations. (2022a). Global Issues: Population. https://www.un.org/en/global-issues/population
United Nations. (2022b, April). *THE SECOND UN ROUNDTABLE ON SUSTAINABLE FLOATING CITIES Meeting the Rising Seas with Floating Infrastructure* (tech. rep.). UN Habitat.
United Nations. (2022c). *World Population Prospects 2022: Summary of Results* (tech. rep.).
United Nations. (2023). The 17 Goals. https://sdgs.un.org/goals
United Nations Department of Economic and Social Affairs. (2018). Population Division. *World Urbanization Prospects: The 2018 Revision, Online Edition*. https://population.un.org/wup/Download/
van de Wal, R. S., Nicholls, R. J., Behar, D., McInnes, K., Stammer, D., Lowe, J. A., Church, J. A., DeConto, R., Fettweis, X., Goelzer, H., Haasnoot, M., Haigh, I. D., Hinkel, J., Horton, B. P., James, T. S., Jenkins, A., LeCozannet, G., Levermann, A., Lipscomb, W. H., . . . White, K. (2022). A High-End Estimate of Sea Level Rise for Practitioners. *Earth's Future*, *10*(11), 1–24. https://doi.org/10.1029/2022EF002751
von Thenen, M., Maar, M., Hansen, H. S., Friedland, R., & Schiele, K. S. (2020). Applying a combined geospatial and farm scale model to identify suitable locations for mussel farming. *Marine Pollution Bulletin*, *156*. https://doi.org/10.1016/j.marpolbul.2020.111254
Wan, Z., Wang, L., Chen, J., & Sperling, D. (2021). Ship scrappage records reveal disturbing environmental injustice. *Marine Policy*, *130*. https://doi.org/10.1016/j.marpol.2021.104542
Wang, C. M., & Tay, Z. Y. (2011). Very large floating structures: Applications, research and development. *Procedia Engineering*, *14*, 62–72. https://doi.org/10.1016/j.proeng.2011.07.007
Wang, G., Bar, D., & Schreier, S. (2023). Preprint: Floating Seawall and the Circular Economy of End-of-life Ships. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4390642
Wang, G., Drimer, N., & Goldfeld, Y. (2020). Modular floating structures (MFS) for offshore dwelling a hydrodynamic analysis in the frequency domain. *Ocean Engineering*, *216*. https://doi.org/10.1016/j.oceaneng.2020.107996
Wang, G., Goldfeld, Y., & Drimer, N. (2019). Expanding coastal cities – Proof of feasibility for modular floating structures (MFS). *Journal of Cleaner Production*, *222*, 520–538. https://doi.org/10.1016/j.jclepro.2019.03.007
Wang, G., Rosenfeld, Y., Drimer, N., & Goldfeld, Y. (2020). Occupant comfort analysis for rigid floating structures–methodology and design assessment for offshore dwelling module. *Ships and Offshore Structures*, *16*(2), 184–199. https://doi.org/10.1080/17445302.2020.1718267
Water-based communities. (2022, November).
Waterstudio.NL. (2023). Waterstudio.NL Architecture, urban planning and research. https://www.waterstudio.nl/
Wdowinski, S., Bray, R., Kirtman, B. P., & Wu, Z. (2016). Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach, Florida. *Ocean and Coastal Management*, *126*, 1–8. https://doi.org/10.1016/j.ocecoaman.2016.03.002
World Resources Institute. (2020). Aqueduct Floods Hazard Maps Data Set. https://www.wri.org/data/aqueduct-floods-hazard-maps
Xu, L., Cui, S., Wang, X., Tang, J., Nitivattananon, V., Ding, S., & Nguyen Nguyen, M. (2021). Dynamic risk of coastal flood and driving factors: Integrating local sea level rise and spatially explicit urban growth. *Journal of Cleaner Production*, *321*. https://doi.org/10.1016/j.jclepro.2021.129039
Yang, H., Zhao, S., & Kim, C. (2022). Analysis of floating city design solutions in the context of carbon neutrality-focus on Busan Oceanix City. *Energy Reports*, *8*, 153–162. https://doi.org/10.1016/j.egyr.2022.10.310
Yang, X., Hu, M., Zhang, C., & Steubing, B. (2022). Urban mining potential to reduce primary material use and carbon emissions in the Dutch residential building sector. *Resources, Conservation and Recycling*, *180*(January), 106215. https://doi.org/10.1016/j.resconrec.2022.106215
Yılmaz, M., & Terzi, F. (2021). Measuring the patterns of urban spatial growth of coastal cities in developing countries by geospatial metrics. *Land Use Policy*, *107*. https://doi.org/10.1016/j.landusepol.2021.105487
Zhang, J., & Wang, H. (2022). Development of offshore wind power and foundation technology for offshore wind turbines in China. *Ocean Engineering*, *266*. https://doi.org/10.1016/j.oceaneng.2022.113256
Zhou, Q., Du, Z., Liu, J., Liang, J., & Jiao, Y. (2021). Factors influencing green ship recycling: A conceptual framework and modeling. *Journal of Cleaner Production*, *322*. https://doi.org/10.1016/j.jclepro.2021.129155

Zitti, M., Ferrara, C., Perini, L., Carlucci, M., & Salvati, L. (2015). Long-term urban growth and land use efficiency in Southern Europe: Implications for sustainable land management. *Sustainability (Switzerland)*, *7*(3), 3359–3385. https://doi.org/10.3390/su7033359

Zucaro, A., Maselli, G., & Ulgiati, S. (2022). Insights in Urban Resource Management: A Comprehensive Understanding of Unexplored Patterns. *Frontiers in Sustainable Cities*, *3*(February), 1–6. https://doi.org/10.3389/frsc.2021.807735

Appendix A

Complete overview factors for MFS implementation

Table A.1: Factors relating to the technical and motivation potential, based on literature and expert consultations

Factor	Description	Relevance to this thesis
	TECHNICAL	
Bathymetry	Water depth could constrain the deployment of MFS, as there could be a minimal and maximal depth for floating structures. MFS deployment in deep water waves.	Assumed relevant from a technical perspective.

Table A.1: (continued)

Factor	Description	Relevance to this thesis
Wave statistics	Wave statistics are used to describe the wave climate. Certain wave characteristics limit the deployment of MFS - occupant comfort criteria must be met. The wave climate can also be used to determine whether floating breakwaters should be deployed. - Average significant wave height (H_s) – average of highest 1/3 of waves (height from crest to trough) - 100-year return Hs ($H_s^1$00) – a H_s that is on average exceeded only once every 100 year - Wave energy – energy depends on wave height, wave period, water depth - Wave direction - Wave length - length crest to crest or through to through - Average wave period (T) - time it takes for one wavelength to pass a specific point, relates to wave frequency (f = 1/T) - Average peak period (T_p) - the T associated with the most energetic waves in the total wave spectrum at a specific point	All wave statistics assumed relevant, except wave direction. Wave statistics are key parameters in testing feasibility of MFS (G. Wang, Drimer, & Goldfeld, 2020; G. Wang, Rosenfeld, et al., 2020; G. Wang et al., 2019). Wave direction is presumed to be addressed when placing the MFS modules and is therefore not assumed relevant in this stage of research.
Wind velocity	MFS might not meet occupant criteria with certain wind velocities. - Average wind speed (U_{10}) – wind speed 10 meters above Earth's surface - 100-year return U10 (U_{10}^{100}) – a U_{10} that is on average exceeded only once every 100 year	Assumed relevant, as this is related to the horizontal mean forces as described in G. Wang, Rosenfeld, et al. (2020).
Hurricanes and cyclones	During cyclones high significant wave height and wind speed can be reached, influencing the occupant comfort of MFS.	High hurricane risk areas are assumed relevant, as these areas might require extra consideration for MFS such as hurricane-proof design.
Sea current and tides	Sea current causing drift could be important for type and strength of mooring system. Tides influence water depth.	Assumed not relevant, as drifting of modules is not for this stage of research, and tides are assumed to not have a significant contribution in deep water, relevant to MFS implementation.
Sea ice extent	Sea ice extent is the measurement of the area covered by sea ice in polar regions, and could hinder floating structures.	Assumed not relevant, as this is presumed to be addressed in costs; certain design parameters should be considered in ice regions.
(Coastal) seabed slope	Coastal seabed slope refers to the angle of the ocean floor as it extends from the shoreline into deeper waters. Links to wave energy and coastal deposition and erosion processes.	Assumed not relevant, as this thesis focuses on MFS implementation in deep water.
Seabed sediment	The (mixture of) material that accumulates on the ocean floor. Links to coastal deposition and erosion.	Assumed not relevant, as this thesis focuses on MFS implementation in deep water.
Marine protected areas	MFS cannot be deployed in marine protected areas / restricted areas, unless scientific evidence proves potential for mutualism.	Assumed relevant from an environmental perspective.

Table A.1: (continued)

Factor	Description	Relevance to this thesis
Shipping routes	MFS cannot be deployed crossing commonly used shipping routes.	Assumed relevant from a zoning perspective.
Military areas	MFS cannot be deployed in army waters because of safety considerations.	Assumed relevant from a zoning perspective.
Existing infrastructure (offshore wind parks, cables / pipelines, oil / gas platforms, mineral extraction sites, stationary fishing nets..)	MFS cannot be deployed in areas with existing permanent marine infrastructure.	Assumed relevant from a zoning perspective.
	MOTIVATION	
Proximity of (mega)city	The proximity of a coastal (mega)city could be motivating for MFS expansion. Existing city infrastructure available.	Assumed relevant as MFS is promoted as an expansion of existing coastal cities (G. Wang et al., 2019).
City population growth	The proximity of an existing, growing city could be motivating for MFS expansion, as more people will need space.	Assumed relevant due to the observed local variation in the growth of coastal cities, which is assumed to be a crucial driver for the need for additional space.
Land protected areas	Spatial factor that could restrict spatial city expansion to hinterland.	Assumed relevant as it could motivate expanding to the sea.
Slope	Spatial factor that restricts or enables urban expansion to hinterland, depending on the steepness of the slope and cultural believes.	Assumed relevant, as literature indicates that this factor significantly constrains urban expansion (Dadashpoor & Nateghi, 2017; Du, 2016).
Exposure to SLR	Low-lying coastal cities face an increasing risk of coastal flooding.	Assumed relevant as cities most exposed to SLR in the future could benefit from urban expansion at sea, a climate-adaptive alternative.
Natural land hazards	Cities at land are exposed to natural land hazards such as earthquakes, wildfires and volcano's.	Assumed relevant as cities facing a high risk of natural land hazards may find potential advantages in expanding their urban infrastructure into sea areas, reducing their exposure.
Other land-use factors, soil quality, elevation, distance to road networks or other infrastructure	All of these factors could also influence urban growth, and / or constrain or enable expansion to hinterland.	Assumed not relevant as the global scope of this thesis does not accommodate such specific details at city level.

Note: MFS = Modular Floating Structures; SLR = Sea Level Rise. Relevance was based on literature (Literature Review; Table 2.2), expert consultations and supplementary literature if mentioned explicitly.

Table A.2: Data availability and description of relevant factors for technical potential and motivation potential

Factor		Data source	Data attributes	Description
Geographical scope		Flanders Marine Institute (2023)	**Data files:** main.eez_12nm_v3 main.eez_internal_waters_v3 eez_archipelagic_waters_v3.shp **Format:** shapefile (polygon) **Coordinate System:** WGS 1984	Shapefiles representing World's territorial, internal and archipelagic waters.
			TECHNICAL	
Bathymetry (m)		GEBCO Compilation Group (2023)	**Data files:** gebco_sub_ice_n0.0_s-90.0_w0.0_e90.0.tif gebco_sub_ice_n0.0_s-90.0_w-90.0_e0.0.tif gebco_sub_ice_n0.0_s-90.0_w90.0_e180.0.tif gebco_sub_ice_n0.0_s-90.0_w-180.0_e-90.0.tif gebco_sub_ice_n90.0_s0.0_w0.0_e90.0.tif gebco_sub_ice_n90.0_s0.0_w-90.0_e0.0.tif gebco_sub_ice_n90.0_s0.0_w90.0_e180.0.tif gebco_sub_ice_n90.0_s0.0_w-180.0_e-90.0.tif **Format:** raster **Resolution:** 0.00416 x 0.00416 **Coordinate System:** WGS_unknown	Raster files that together represent global bathymetry data.
Wave statistics	Average significant wave height (H_s)		*No data available on global scale.*	
	100-year return Hs (H_s^{100}) (m)	Takbash et al. (2019)	**Data file:** Hs_100_young.tif **Format:** raster **Resolution:** 2 x 2 **Coordinate System:** WGS 1984	A raster layer representing the 100-year return significant wave height of World's oceans and seas.
	Wave energy	U.S. Geological Survey (USGS) in partnership with Esri (Sayre et al., 2021)	**Data file:** Esri Living Atlas - Ecological Coastal Units (ECU) 1km Segments **Format:** shapefile (line) **Coordinate System:** WGS 1984	A shapefile representing World's shoreline characteristics: Mean Significant Wave Height, Tidal Range, Chlorophyll-α, Turbidity, Temperature and Moisture, Marine Physical Environment, Regional Sinuosity, Global Human Modification Index, Max Slope, Erodibility. Based on these attributes, for each segment a Chlorophyll-α Descriptor, River Descriptor, Sinuosity Descriptor, Slope Descriptor, Tidal Descriptor, Turbid Descriptor, and Wave Descriptor is assigned.

Table A.2: (continued)

Factor		Data source	Data attributes	Description
	Wave length		*No data available on global scale.*	
	Average wave period (T)		*No data available on global scale.*	
	Average peak period (T_p)		*No data available on global scale.*	
Wind velocity (m/s)	Average wind speed (U_{10})	GWA (2023)	**Data file:** gwa3_250_windspeed_10m.tif **Format:** raster **Resolution:** 0.0025 **Coordinate System:** WGS 1984	A raster file representing the average wind speed from 2008 to 2017 at 10 meters above Earth's surface.
	100-year return U10 (U_{10}^{100})	Takbash et al. (2019)	**Data file:** U10_100_young.tif **Format:** raster **Resolution:** 2 x 2 **Coordinate System:** WGS 1984	A raster layer representing the 100-year return wind speed at 10 meters above Earth's surface of World's oceans and seas.
Hurricanes and cyclones		K. R. Knapp et al. (2010) and K. Knapp et al. (2018)	**Data file:** IBTrACS.ALL.list.v04r00.lines **Format:** shapefile (line) **Coordinate System:** WGS 1984	A shapefile representing historical hurricane and cyclone tracks from 1842 to 2023.
Marine protected areas		UNEP-WCMC and IUCN (2023)	**Data file:** Esri Living Atlas - L1WDPA_poly_Latest **Format:** shapefile (polygon) **Coordinate System:** WGS 1984 Web Mercator (auxiliary sphere)	A shapefile representing World's Natura2000 Marine Protected Areas.
Shipping routes		The World Bank (2023)	**Data file:** ShipDensity_Commercial1.tif **Format:** raster **Resolution:** 0.005 x 0.005 **Coordinate System:** WGS 1984	A raster layer representing World's shipping density. The raster provides an analysis of hourly AIS (Automatic Identification System) positions over the period from 2015 to 2021, representing the total number of AIS positions received from ships in each raster cell.
Military areas			*No data available on global scale.*	
Existing infrastructure (offshore wind parks, cables / pipelines, oil / gas platforms, mineral extraction sites, stationary fishing nets..)			*No data available on a global scale.*	
			MOTIVATION	
Proximity of (mega)city City population growth		United Nations Department of Economic and Social Affairs (2018)	**Data file:** WUP2018-F14-Growth_Rate_Cities.xls **Format:** Excel file	An excel file listing World's cities (>300,000 inhabitants in 2018) and their historical and projected growth rates up to 2035. Use worksheet ArcGIS_data$.

Table A.2: (continued)

Factor	Data source	Data attributes	Description
Exposure to sea level rise	World Resources Institute (2020)	**Data file:** inuncoast_rcp8p5_wtsub_2050_rp0100_0.tif **Format:** raster **Resolution:** 0.0083 x 0.0083 **Coordinate System:** WGS 1984	
Land protected areas	UNEP-WCMC and IUCN (2023)	**Data file:** Esri Living Atlas - WDPA_poly_Latest **Format:** shapefile (polygon) **Coordinate System:** WGS 1984 Web Mercator (auxiliary sphere)	A shapefile representing all World's Natura2000 Protected Areas, land and marine.
Slope	Esri et al. (2023)	**Data file:** Esri Living Atlas - Terrain: Slope Map **Format:** raster **Resolution:** 0.25 x 0.25 **Coordinate System:** WGS 1984 Web Mercator (auxiliary sphere)	
Natural hazards at land - Earthquakes	Pisut (2020)	**Data file:** Active Faults **Format:** shapefile (line) **Coordinate System:** WGS 1984	

Note: MFS = Modular Floating Structures; AIS = Automatic Identification System; SLR = Sea Level Rise. Hs_100_young.tif and U10_100_young.tif were derived from the raw data of Takbash et al. (2019), obtained via Prof. I. Young. The Matlab script that was created for this thesis to convert the raw data files to georeferenced .tif raster files is attached in the zip folder of this thesis.

Appendix B

Comprehensive Methodology GIS Model

Figures B.2, B.3, B.4, B.5, B.6, B.7, B.8, B.9, and B.10 illustrate a step-by-step workflow, which is further complemented by Tables B.3, B.4, B.5, B.6, B.7. If not mentioned or explained explicitly in the tables, tools are using default settings by ArcGIS Pro 3.1.

Preprocessing

The raster files Hs_100_young.tif and U10_100_young.tif used as input for the preprocessing model were derived from the raw data of Takbash et al. (2019), obtained via Prof. I. Young. The Matlab script that was created for this thesis to convert the raw data files to georeferenced .tif raster files is attached in the zip folder of this thesis, as well as all input files for the preprocessing model.

Table B.3: Metadata preprocessing model

Input model	**Output model**	**Description**
eez_archipelagic_waters_v3.shp	waters_shp	
main.eez_12nm_v3	waters_shp	A merged shapefile (polygon) of World's archipelagic, territorial and internal waters.
main.eez_internal_waters_v3	waters_shp	
gebco_sub_ice_n0.0_s-90.0_w0.0_e90.0.tif gebco_sub_ice_n0.0_s-90.0_w-90.0_e0.0.tif gebco_sub_ice_n0.0_s-90.0_w90.0_e180.0.tif gebco_sub_ice_n0.0_s-90.0_w-180.0_e-90.0.tif gebco_sub_ice_n90.0_s0.0_w0.0_e90.0.tif gebco_sub_ice_n90.0_s0.0_w-90.0_e0.0.tif gebco_sub_ice_n90.0_s0.0_w90.0_e180.0.tif gebco_sub_ice_n90.0_s0.0_w-180.0_e-90.0.tif	wd	A raster layer of the water depth for each raster cell, at a resolution of 0.0125 x 0.0125 degree.
Ecological Coastal Units (ECU) 1km Segments	we	A raster layer of World's average coastal wave energy for each raster cell, at a resolution of 0.0125 x 0.0125.

Table B.3: (continued)

Input model	Output model	Description
gwa3_250_windspeed_10m.tif	ws	A raster layer representing World's average wind speed at 10 meter above Earth's surface for each raster cell, at a resolution of 0.0125 x 0.0125 degrees.
IBTrACS.ALL.list.v04r00.lines	hur	A raster layer representing high hurricane and cyclone risk areas for each raster cell, at a resolution of 0.0125 x 0.0125 degrees.
Hs_100_young.tif	hs100	A raster layer representing the 100-year return significant wave height of World's oceans and seas for each raster cell, at a resolution of 0.0125 x 0.0125 degrees.
U10_100_young.tif	u100	A raster layer representing the 100-year return wind speed at 10 meters above Earth's surface of World's oceans and seas for each raster cell, at a resolution of 0.0125 x 0.0125 degrees.
ShipDensity_Commercial1.tif	ship_dens	A raster layer representing World's shipping density for each raster cell, at a resolution of 0.0125 x 0.0125 degrees.
L1WDPA_poly_Latest	wdpa	A raster layer representing World's Natura2000 Marine Protected Areas, at a resolution of 0.0125 x 0.0125 degrees. Each raster cell is classified into '0' = Restricted; Marine Protected Area; or '1' = Not restricted; No Marine Protected Area.
ArcGIS_data$	prox_cities	A shapefile (polygon) layer representing World's coastal cities (>300,000 inhabitants; <15 km from shoreline) and the area within 35 km of the city centres.

Note: Description of the input files can be found in Table A.2.

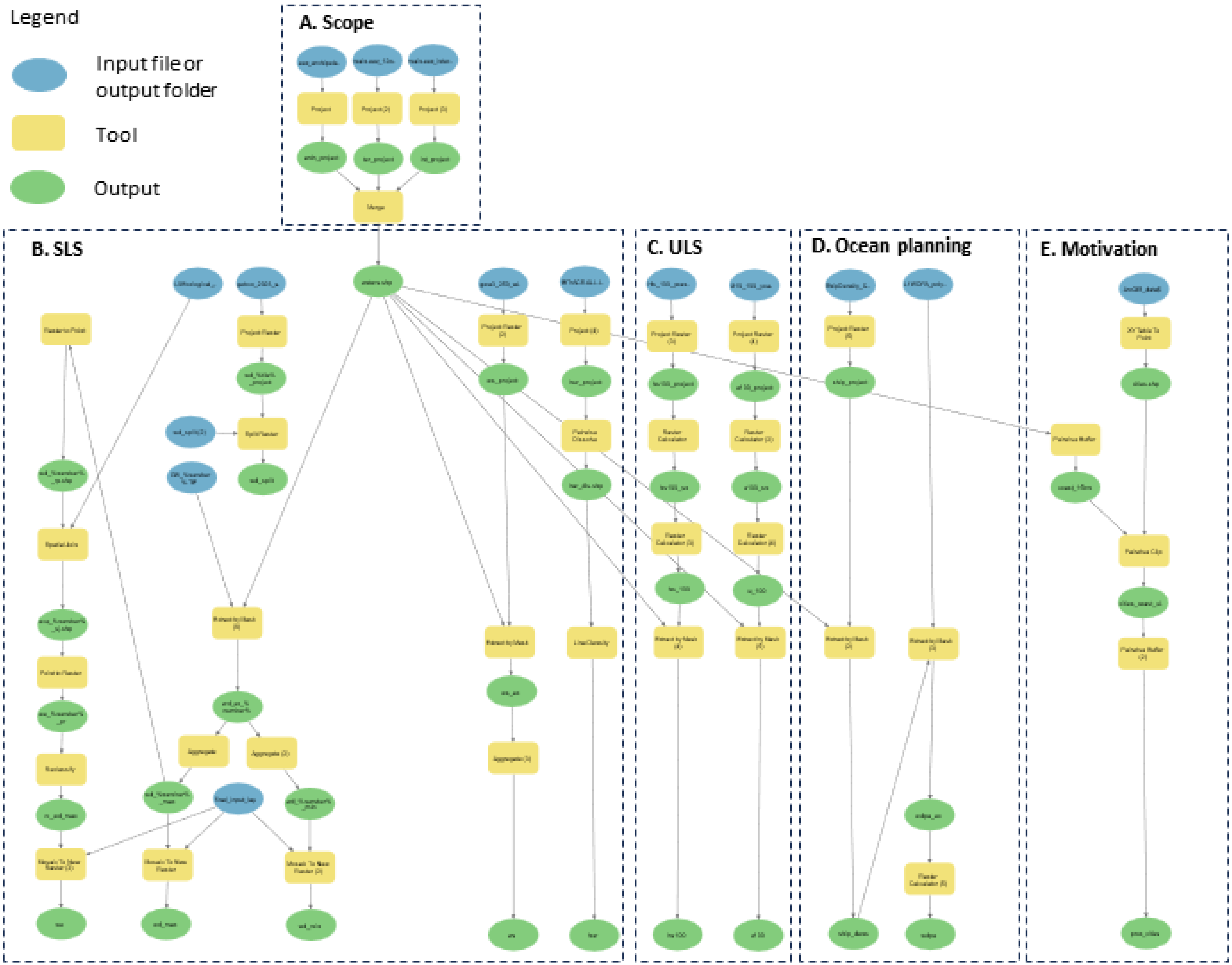

Figure B.3: Complete step-by-step overview of the preprocessing methodology

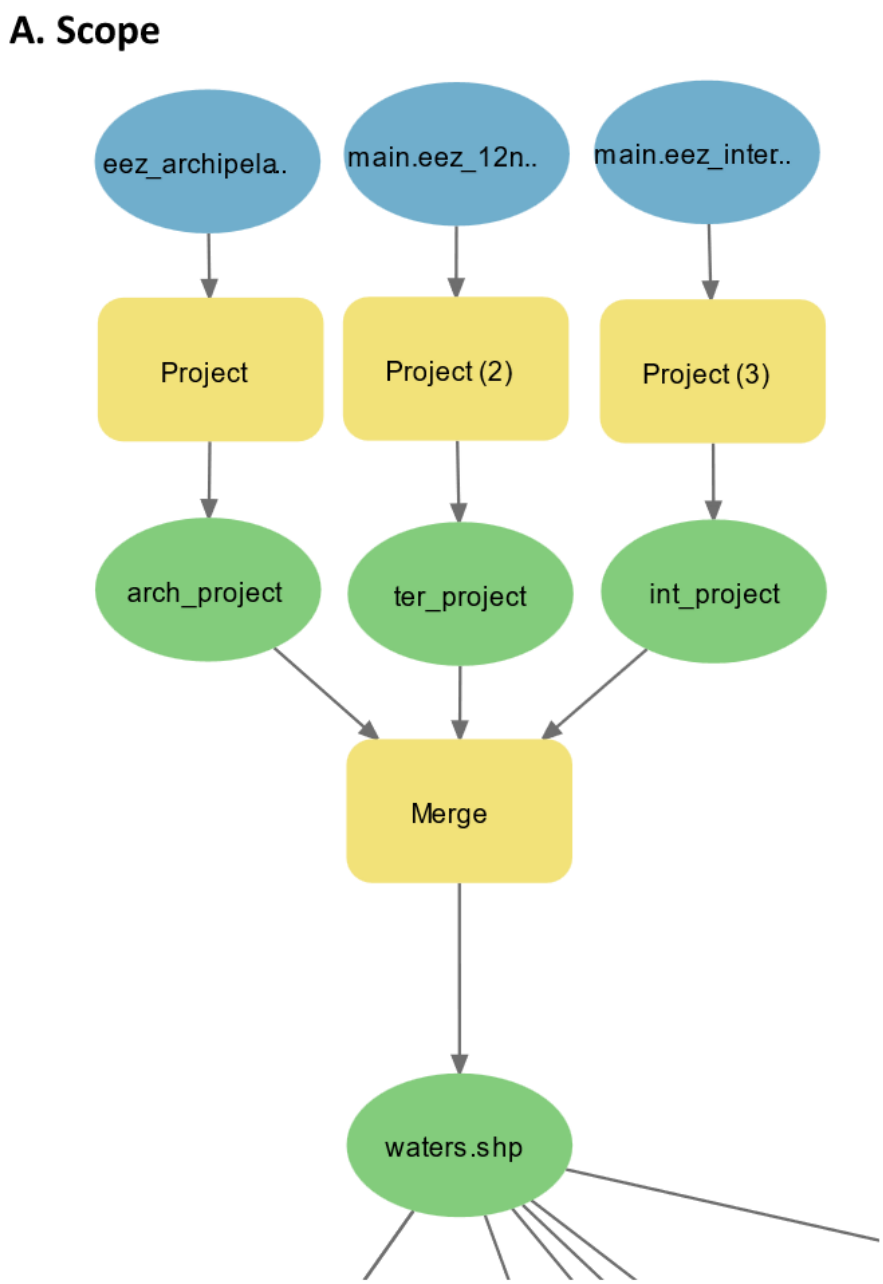

Figure B.4: Geographical scope preprocessing step-by-step. Sub figure of Figure B.2.

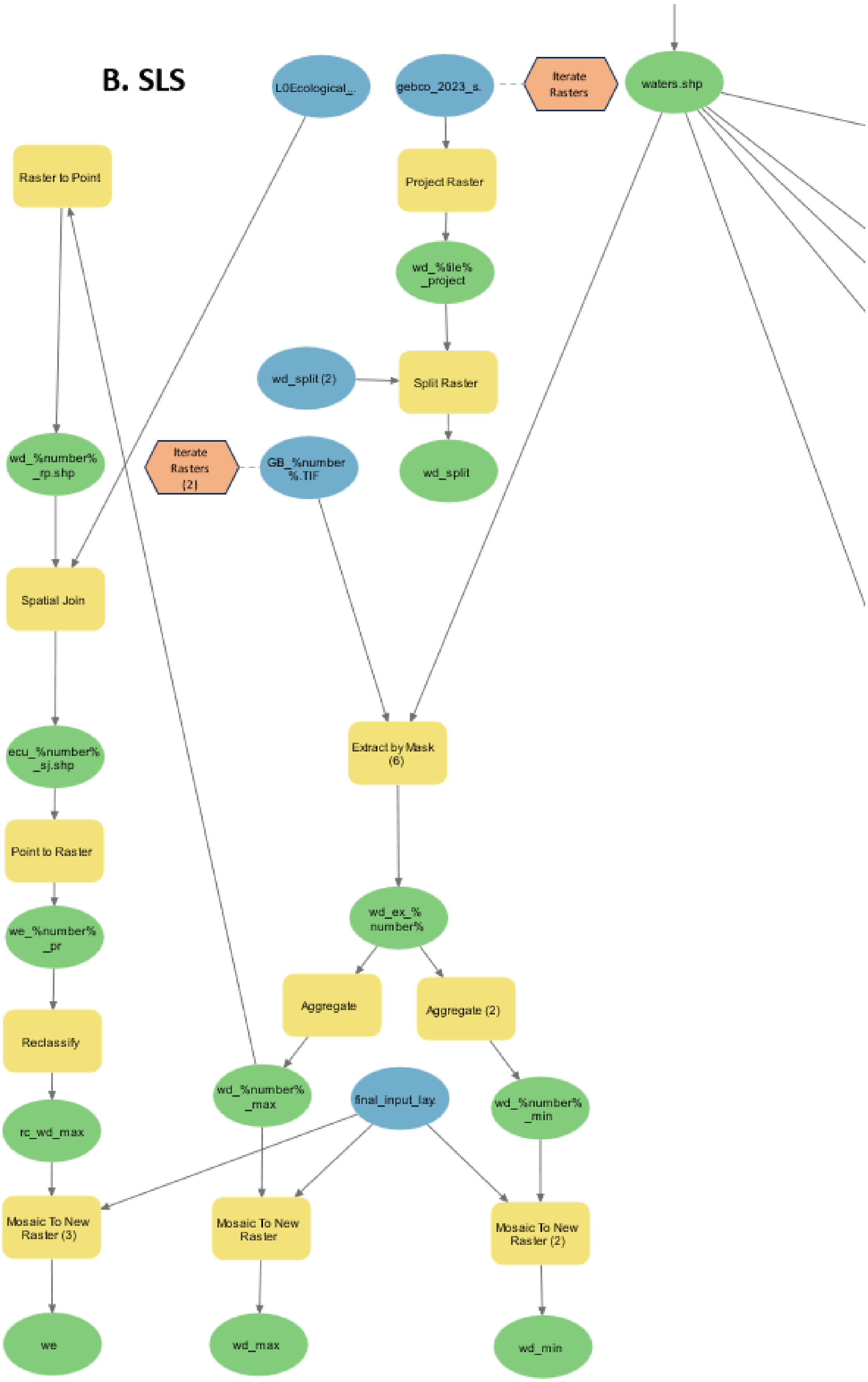

Figure B.5: Service Limit State (SLS) preprocessing step-by-step. Sub figure of Figure B.2.

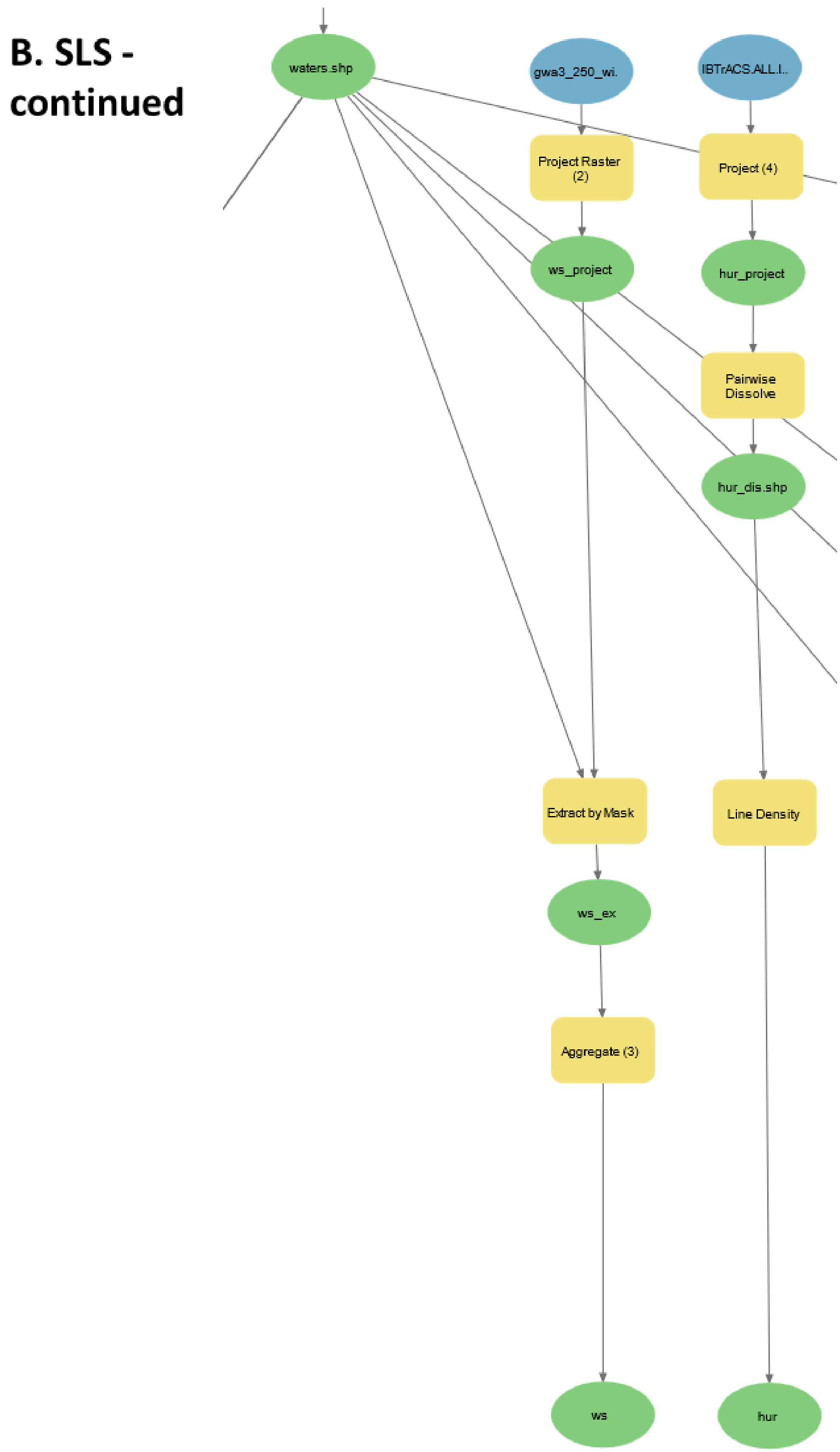

Figure B.6: Service Limit State - continued - preprocessing step-by-step. Sub figure of Figure B.2.

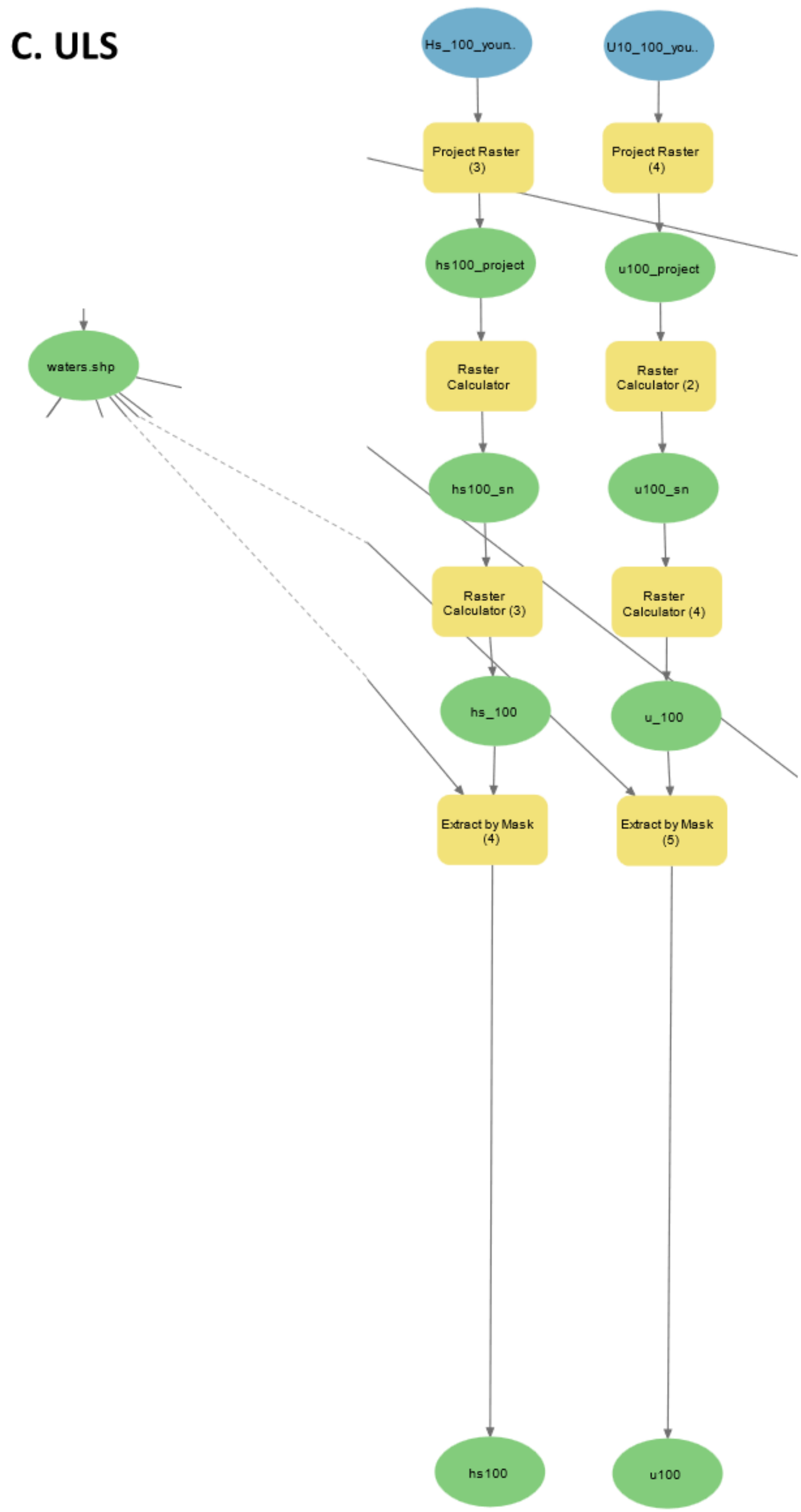

Figure B.7: Ultimate Limit State preprocessing step-by-step. Sub figure of Figure B.2.

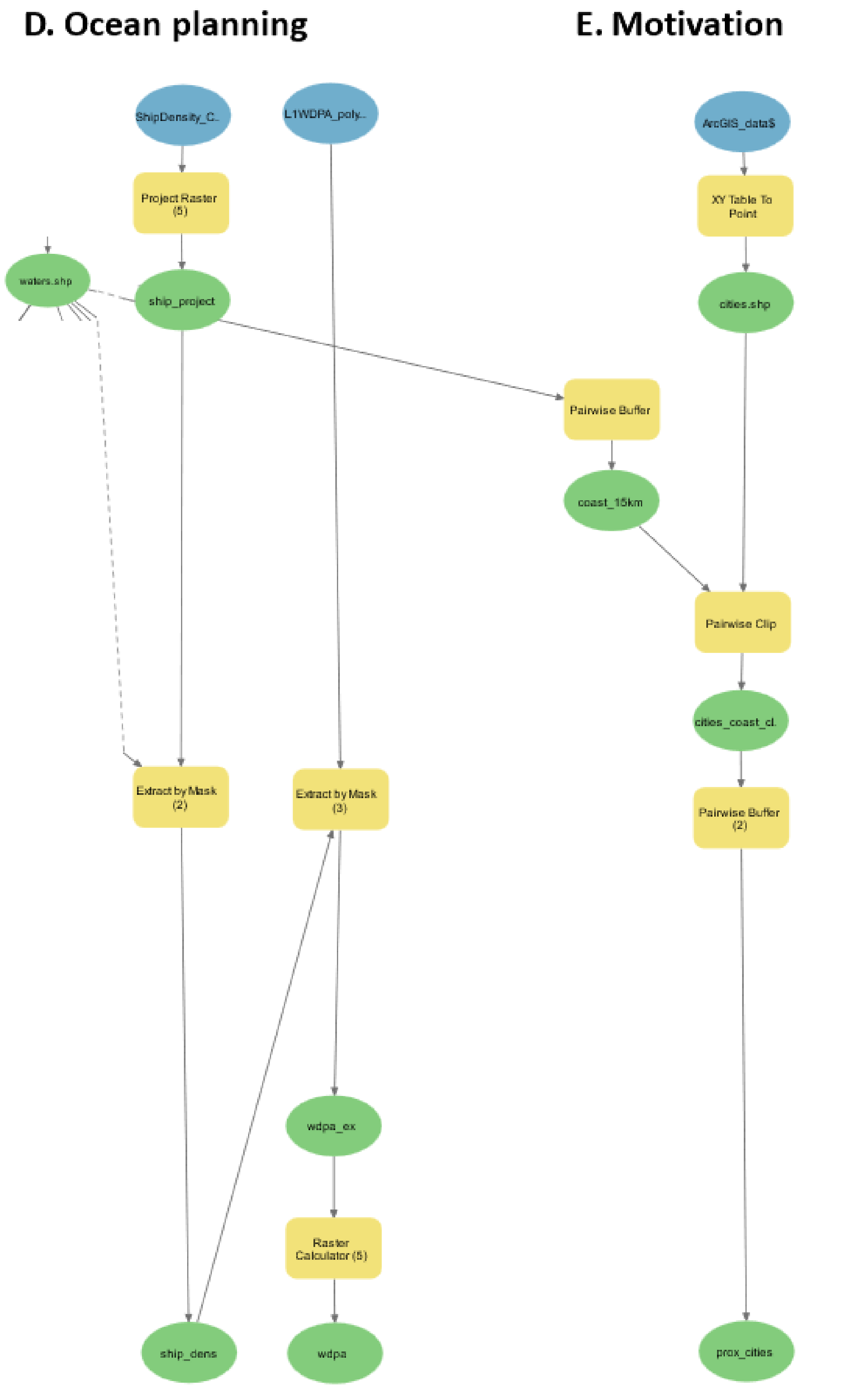

Figure B.8: Ocean planning and motivation preprocessing step-by-step. Sub figure of Figure B.2.

Table B.4: Detailed description of Iterator commands presented in Figure B.4

Command	Description
Iterate Rasters	This iteration block iterated over every raster in the GEBCO input folder. This folder includes eight GEBCO raster files, together comprising the whole world. %number% ranges from 1 to 8.
Iterate Rasters (2)	This iteration block iterated over every raster in the wd_split folder. This folder includes 128 raster files, together comprising the whole world. %number% ranges from 10 to 89 and from 110 to 115; from 210 to 215; from 310 to 315; from 410 to 415; from 510 to 515; from 610 to 615; from 710 to 715; from 810 to 815.

Table B.5: Detailed description of tools and settings presented in Figure B.3, B.4, B.5, B.6, B.7

Factor	Tool	Settings	Short explanation
Geographical scope	Project	Output Coordinate System: GCS_WGS_1984	
	Project (2)	Output Coordinate System: GCS_WGS_1984	
	Project (3)	Output Coordinate System: GCS_WGS_1984	
Bathymetry	Project Raster	Output Coordinate System: GCS_WGS_1984	
	Split Raster	Split Method: Number of tiles Resampling Technique: Bilinear Number of Output Rasters: X: 4 ; Y: 4	This was done to create manageable bathymetry tiles to deal with computational limits. Total tiles are 128 (8 * 16)
	Extract by mask (6)	Environment - Snap Raster: GB_%number%.TIF Extraction Area: Inside	
	Aggregate	Cell factor: 3 Aggregation technique: Maximum	The aggregation was based on the numerical minimum depth (numerical maximum; closest to 0). The resulting cell represents the minimum depth there; crucial for for the upper depth limits.
	Mosaic To New Raster	Number of Bands: 1 Input Rasters: All bathymetry max rasters of all pieces the World was divided in.	All bathymetry tiles are put together after preprocessing, to obtain one global bathymetry raster layer representing the minimum depth in each raster cell.
	Aggregate (2)	Cell factor: 3 Aggregation technique: Minimum	The aggregation was based on the maximum depth (numerical minimum; furthest from 0). The resulting cell represents the maximum depth there; crucial for for the lower depth limits.
	Mosaic To New Raster (2)	Number of Bands: 1	All bathymetry tiles are put together after preprocessing, to obtain one global bathymetry raster layer representing the maximum depth in each raster cell.

Table B.5: (continued)

Factor	Tool	Settings	Short explanation
		Input Rasters: All bathymetry min rasters of all pieces the World was divided in.	
	Raster to Point		A shapefile was used as starting point for the preprocessing of the wave energy layer. A shapefile (point) was obtained by converting the cells of a raster layer to points, thereby retaining the resolution of 0.0125 x 0.0125 degrees when converting back. These points were used to attach wave energy values to.
Average wave energy	Spatial Join	Join Operation: Join one to one Match Option: Closest geodesic Search Radius: 10 Decimal Degrees	To obtain a raster layer representing the shapefile input, average wave energy was assigned to each point covering the territorial, internal and archipelagic waters, based on closest shoreline segment containing the wave energy.
	Point to Raster	Value field: wave_label Cellsize: wd_min	To obtain a raster layer from the shapefile (point), the points were converted to raster cells while retaining the values of of the wave energy field.
	Reclassify	Reclass field: "WAVE_LABEL" Reclassification: Value: "quiescent"; New: 0 Value: "very low wave energy"; New: 1 Value: "low wave energy"; New: 2 Value: "moderate wave energy"; New: 3 Value: "moderately high wave energy"; New: 4 Value: "high wave energy"; New: 5 Value: "very high wave energy"; New: 6 Value: NoData; New: NoData Change missing values to NoData: checked	
	Mosaic To New Raster (3)	Number of Bands: 1 Input Rasters: All wave energy rasters of all pieces the World was divided in.	All wave energy tiles were put together after preprocessing, to obtain one global wave energy raster layer representing the average coastal wave energy in each raster cell.
Average U_{10}	Project Raster (2)	Output Coordinate System: GCS_WGS_1984	
	Extract by Mask	Environment - Snap Raster: gwa3_250_windspeed_10m.tif Extraction Area: Inside	
	Aggregate (3)	Cell factor: 5 Aggregation technique: Maximum	The aggregation was based on the maximum average wind speed. The resulting cell represents the maximum wind speed there; crucial for the wind speed limit.

Table B.5: (continued)

Factor	Tool	Settings	Short explanation
Hurricanes and cyclones	Project (4)	Output Coordinate System: GCS_WGS_1984	
	Pairwise Dissolve	Dissolve Fields: SID	Lines associated with the same hurricane (SID) are dissolved so that one single line represents one hurricane or cyclone.
	Line Density	Ouput cell size: 0.0125	A Line Density analysis was done to create high risk areas for hurricanes and cyclones, based on the frequency of historical tracks.
100-year return H_s	Project Raster (3)	Output Coordinate System: GCS_WGS_1984	
	Raster Calculator	Map Algebra expression: ”hs100_project” * 1	To set every cell with no data to NoData.
	Raster Calculator (3)	Map Algebra expression: Con(IsNull(”hs100_sn”), FocalStatistics(”hs100_sn”, NbrRectangle(20,20, ”CELL”), ”MEAN”), ”hs100_sn”)	To fill up NoData cells at coasts, extrapolatoion based on the mean of neighbouring cell values was executed as a type of estimation.
	Extract by Mask (4)	Environment - Snap Raster: hs_100	
		Extraction area: Inside	
100-year return U_{10}	Project Raster (4)	Output Coordinate System: GCS_WGS_1984	
	Raster Calculator (2)	Map Algebra expression: ”u100_project” * 1	To set every cell with no data to NoData.
	Raster Calculator (4)	Map Algebra expression: Con(IsNull(”u100_sn”), FocalStatistics(”u100_sn”, NbrRectangle(20,20, ”CELL”), ”MEAN”), ”u100_sn”)	To fill up NoData cells at coasts, extrapolatoion based on the mean of neighbouring cell values was executed as a type of estimation.
	Extract by Mask (5)	Environment - Snap Raster: u_100	
		Extraction area: Inside	
Shipping density	Project Raster (5)	Output Coordinate System: GCS_WGS_1984	
	Extract by Mask (2)	Environment - Snap Raster: ShipDensity_Commercial1.tif	
		Extraction area: Inside	
Marine protected areas	Extract by Mask (3)	Extraction Area: Inside	
	Raster Calculator (5)	Con(”wdpa_ex” >= 0, 0)	To set every raster cell that represents a marine protected area to ’0’.
Proximity to coastal cities	XY Table To Point	X Field: Longitude	
		Y Field: Latitude	
		Coordinate System: GCS_WGS_1984	
	Pairwise Buffer	Distance [value or field]: 15 Kilometers	To create a polygon that represents the area within a 15-kilometer buffer of the shoreline, the waters_shp was used to generate a 15 km buffer extending from the shoreline borders.
		Method: Geodesic (shape preserving)	
		Dissolve Type: Dissolve all output features into a single feature	
	Pairwise Buffer (2)	Distance [value or field]: 35 Kilometer	To create a polygon that represents the area within 35 km of the city centre, a buffer was created around the coastal city centre points.

Table B.5: (continued)

Factor	Tool	Settings	Short explanation
		Method: Geodesic (shape preserving)	
		Dissolve Type: No Dissolve	

Note: SLS = Service Limit State; ULS = Ultimate Limit State

Technical Potential

Table B.6: Metadata technical potential and motivation model

Input model	Output model	Description
wd we ws hur	tech_sls	A raster layer of World's technical potential based on the exclusion boundaries of bathymetry, average wave energy, average wind speed and the evaluation of hurricane risk. Each raster cell is classified into '0' = Not suitable; '1' = Suitable; and '2' = Suitable, but hurricane risk. The individual classified input layers that together comprise the tech_sls are also saved.
hs100 u100 tech_sls	tech_sls_uls	A raster layer of World's technical potential based on the exclusion boundaries the 100-year return H_s, the 100-year return U_{10} and the tech_sls. Each raster cell is classified into '0' = Not suitable; '1' = Suitable; and '2' = Suitable, with floating breakwaters. The individual classified input layers that together comprise the tech_sls_uls are also saved.
ship_dens wdpa tech_sls_uls	tech_all	A raster layer of World's technical potential based on the exclusion boundaries of the shipping density, the marine protected areas and the tech_sls_uls. Each raster cell is classified into '0' = Not suitable; '1' = Suitable; and '2' = Suitable, with floating breakwaters. The individual classified input layers that together comprise the tech_allare also saved.
prox_cities tech_all	tech_mot	A raster layer of World's technical potential, motivated by the proximity of a coastal city (>300 000 inhabitants, <15 km from coast). Each raster cell is classified into '0' = Not suitable; '1' = Suitable; and '2' = Suitable, with floating breakwaters. The individual classified input layers that together comprise the tech_mot are also saved.

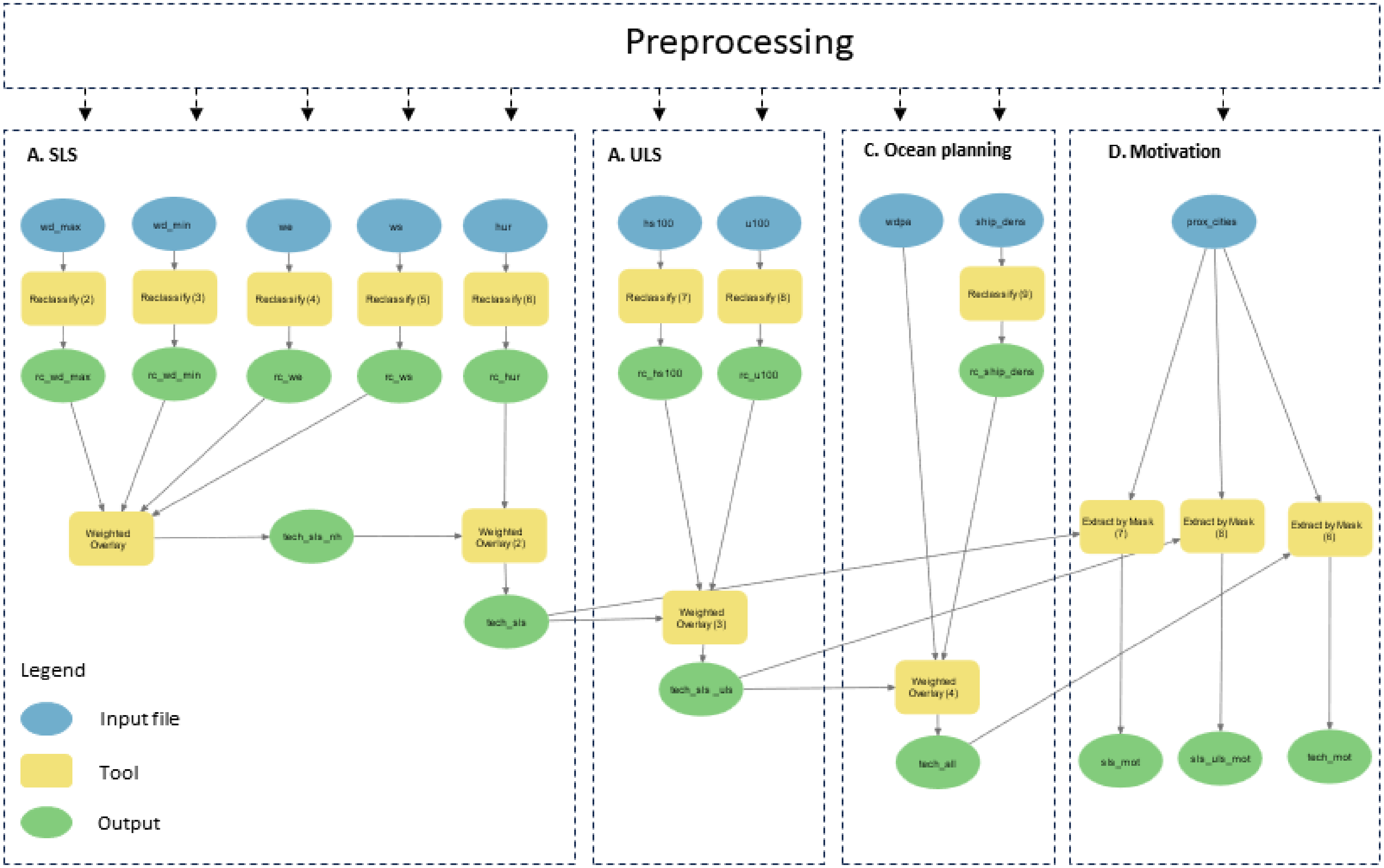

Figure B.9: Complete step-by-step overview of the technical potential and motivation methodology. Note: SLS = Service Limit State, ULS = Ultimate Limit State

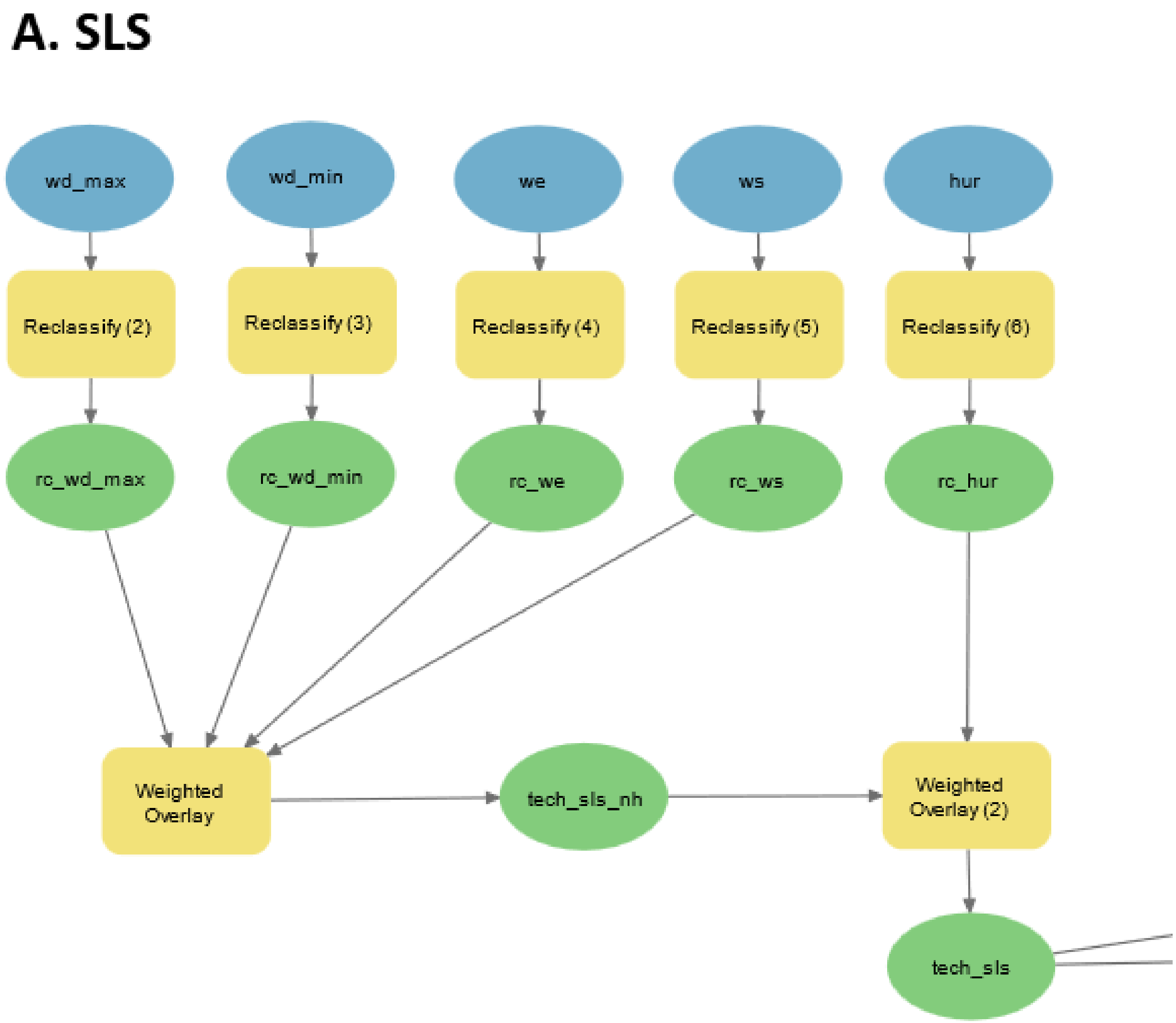

Figure B.10: Service Limit State model step-by-step methodology. Sub figure of Figure B.8.

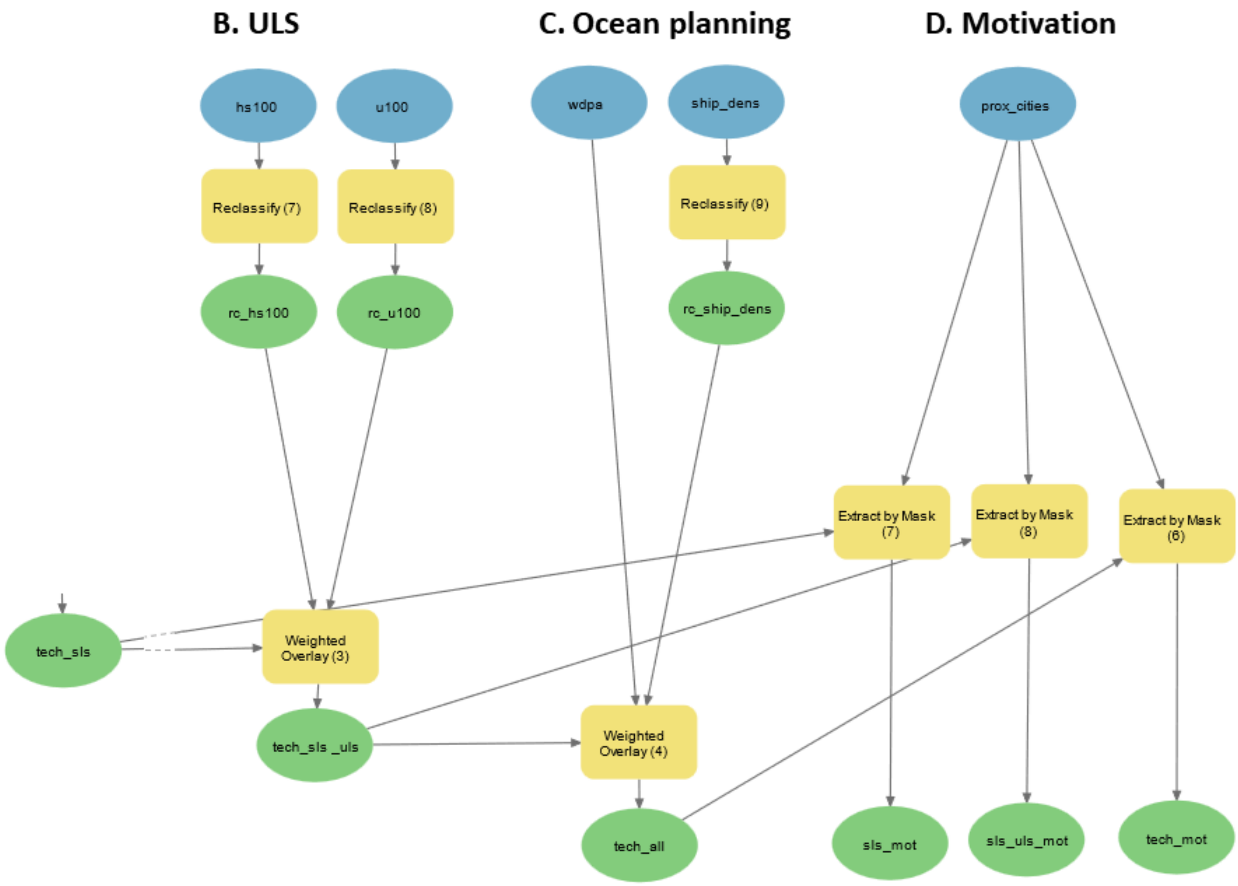

Figure B.11: Ultimate Limit State, ocean planning and motivation model step-by-step methodology. Sub figure of Figure B.8

Table B.7: Detailed description of tools and settings presented in Figure B.9, B.10

Factor	Tool	Settings
Bathymetry	Reclassify (2)	Reclass field: VALUE
		Reclassification: Start: -12000; End: -35; New: 1 Start: -35; End: 425; New: 0 Start: NoData; End: NoData; New: NoData
		Change missing values to Nodata: checked
	Reclassify (3)	Reclass field: VALUE
		Reclassification: Start: -12000; End: -2500; New: 0 Start: -2500; End: 501; New: 1 Start: NoData End: NoData New: NoData
		Change missing values to Nodata: checked
Average wave energy	Reclassify (4)	Reclass field: WAVE_LABEL

Table B.7: (continued)

Factor	Tool	Settings
		Reclassification: Value: 0; New: 1 Value: 1; New: 1 Value: 2; New: 1 Value: 3; New: 1 Value: 4; New: 0 Value: 5; New: 0 Value: 6; New: 0 Value: NoData; New: NoData
		Change missing values to Nodata: checked
Average U_{10}	Reclassify (5)	Reclass field: VALUE
		Reclassification: Start: 0; End: 9; New: 1 Start: 9; End: 25; New: 0 Start: NoData; End: NoData; New: NoData
		Change missing values to Nodata: checked
Hurricanes and cyclones	Reclassify (6)	Reclass field: VALUE
		Reclassification: Start: 0; End: 14; New: 1 Start: 14; End: 145; New: 2 Start: NoData; End: NoData; New: NoData
		Change missing values to Nodata: checked
100-year return H_s	Reclassify (7)	Reclass field: VALUE
		Reclassification: Start: 0; End: 4; New: 1 Start: 4; End: 8.5; New: 2 Start: 8.5 End: 30; New: 0 Start: NoData; End: NoData; New: NoData
		Change missing values to Nodata: checked
100- year return U_{10}	Reclassify (8)	Reclass field: VALUE
		Reclassification: Start: 0; End:30; New: 1 Start: 30; End: 70; New: 0 Start: NoData; End: NoData; New: NoData
		Change missing values to Nodata: checked
Shipping density	Reclassify (9)	Reclassification: Start: 0; End: 1300000 New: 1 Start: 1300000 End: 70000000 New: 0 Start: NoData End: NoData New: NoData
		Change missing values to Nodata: checked
-	Weighted Overlay	Weighted overlay table: All equal weight ('%=')
		Scales: 1-9
		Remap Table: rc_wd_max [0, Restricted] [1, 1] [NoData, NoData] rc_wd_min [0, Restricted] [1, 1] [NoData, NoData] rc_we [0, Restricted] [1, 1] [NoData, NoData] rc_ws [0, Restricted] [1, 1] [NoData, NoData]
	Weighted Overlay (2)	Weighted overlay table: All equal weight ('%=')
		Scales: 1-9
		Remap Table: tech_sls_nd [0, Restricted] [1, 1] [2, 1] [NoData, NoData] rc_hur [1, 1] [2, 3] [NoData, NoData]
	Weighted Overlay (3)	Weighted overlay table: All equal weight ('%=')

Table B.7: (continued)

Factor	**Tool**	**Settings**
		Scales: 1-9 Remap Table: rc_hs100 [0, Restricted] [1, 1] [2, 3] [NoData, NoData] rc_u100 [0, Restricted] [1, 1] [NoData, NoData] tech_sls [0, Restricted] [1, 1] [2, 1] [NoData, NoData]
	Weighted Overlay (4)	Weighted overlay table: All equal weight ('%=') Scales: 1-9 Remap Table: wdpa [0, Restricted] [1, 1] [NoData, NoData] rc_ship_dens [0, Restricted] [1, 1] [NoData, NoData] tech_sls_uls [0, Restricted] [1, 1] [2, 3] [NoDAta, NoData]
Technical Potential based on SLS, ULS and Ocean Planning	Extract by Mask (6)	Environment - Snap raster: tech_mot Extraction Area: Inside

Note: SLS = Service Limit State; ULS = Ultimate Limit State. Boundaries in Table 3.1 used for reclassification of each layer.

Appendix C

Comprehensive Additional Methodology

Figure C.11 illustrates a step-by-step workflow, which is further complemented by Table C.8. If not mentioned or explained explicitly in Table C.8, tools are using default settings by ArcGIS Pro 3.1.

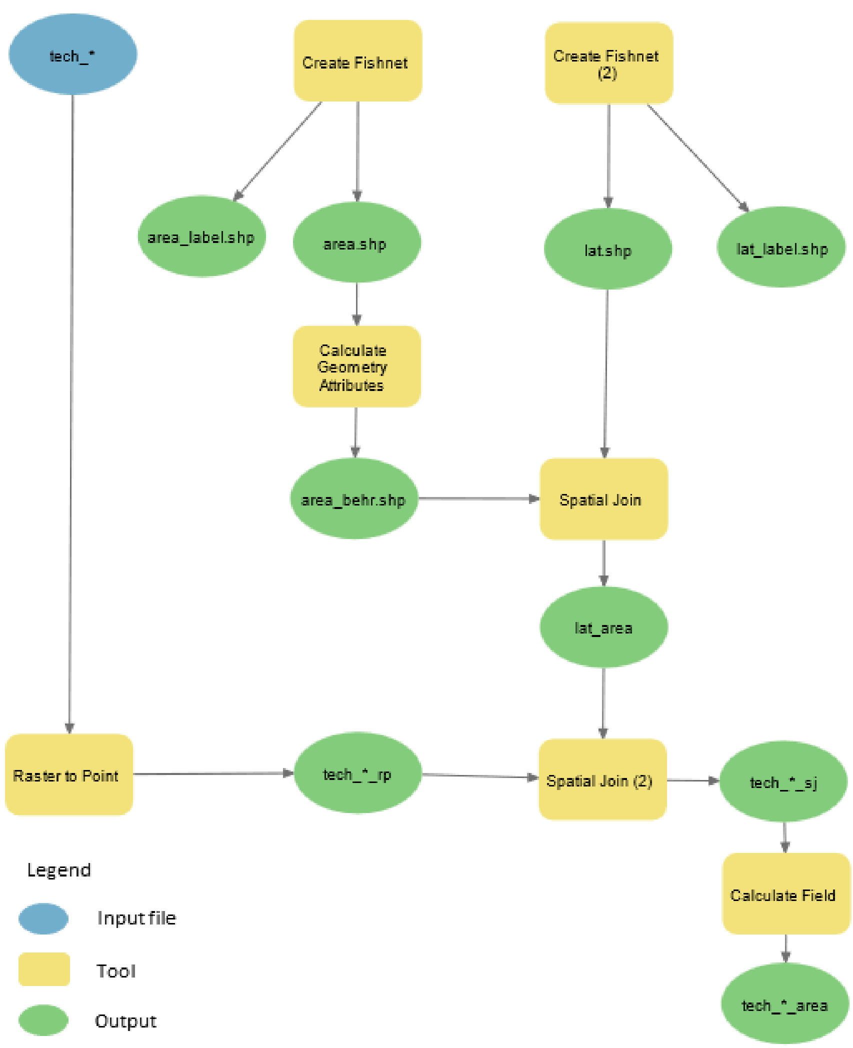

Figure C.12: Comprehensive step-by-step methodology km^2 conversion. Note: * input can be any map of which conversion is desired

Table C.8: Detailed description of tools and settings presented in Figure C.11.

Tool	Settings	Description
Create Fishnet	Output Feature Class: area.shp Fishnet Origin Coordinate: Y: -180; X: -56 Y-axis coordinate: Y: -180; X: -46 Number of rows: 11250 Number of columns: 1 Opposite corner of fishnet: Y: -179.9875; X: 84 Create Label Points: unchecked Geometry Type: polygon	To create a series of polygons that represents a single vertical column (North to South) from the technical potential maps, with the area of one polygon corresponding to the area of one raster cell (0.0125 x 0.0125 degree).
Calculate Geometry Attributes	Field (Existing or New): area_behr Property: Area (geodesic) Area Unit: Square Kilometers Coordinate System: Behrmann World	The area of each polygon is calculated with the Behrmann projection.
Create Fishnet (2)	Output Feature Class: lat.shp Fishnet Origin Coordinate: Y: -180; X: -56 Y-axis coordinate: Y: -180; X: -46 Number of rows: 11250 Number of columns: 1 Opposite corner of fishnet: Y: 180; X: 84 Create Label Points: unchecked Geometry Type: polygon	To create a series of polygons that represent East to West horizontal rows, each having a width of 0.0125 degrees to match the raster cells in the technical potential maps.
Spatial Join	Join Operation: Join one to one Match Option: Intersect	Each polygon row now contains the information of the area of one raster cell on this latitude.
Spatial Join (2)	Join Operation: Join one to many Match Option: Intersect	Each polygon row now contains the information of the area of one raster cell on this latitude, the number of cells on this latitude and their corresponding classification (0, 1, 2).
Calculate field	Field Name: total_area Expression: Join_Count(1)*geom_behr	The total area is calculated by multiplying the number of cells (Join_Count(1)) with the area of one raster cell in that row (area_behr). The contained information of the classification can later be used to filter each classification.

Table C.9: Global region selection for GIS analysis.

Global region	Included countries
Southeast Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam, Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Republic of) Maldives, Nepal, Pakistan, Sri Lanka
East Asia	China, Hong Kong SAR, China, Macao SAR, Dem. People's Republic of Korea, Mongolia, Republic of Korea, China, Taiwan Province of China, Japan
West Asia	Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, State of Palestine, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara, Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Réunion, Rwanda, Somalia, Sudan, Uganda, United Republic of Tanzania, Zambia, Zimbabwe, Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Botswana, Lesotho, Namibia, South Africa, Swaziland, Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo
Europe	Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Montenegro, Poland, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, The former Yugoslav Republic of Macedonia, Ukraine, Austria, Belgium, Channel Islands, Denmark, Finland, France, Germany, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom
Latin America and Caribbean	Aruba, Bahamas, Barbados, Cuba, Dominican Republic, Grenada, Guadeloupe, Haiti, Jamaica, Martinique, Netherlands Antilles, Puerto Rico, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, United States Virgin Islands, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
Oceania	Fiji, French Polynesia, Guam, Micronesia (Federated States of), New Caledonia, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu, New Zealand, Australia
North America	North America Canada, United States of America

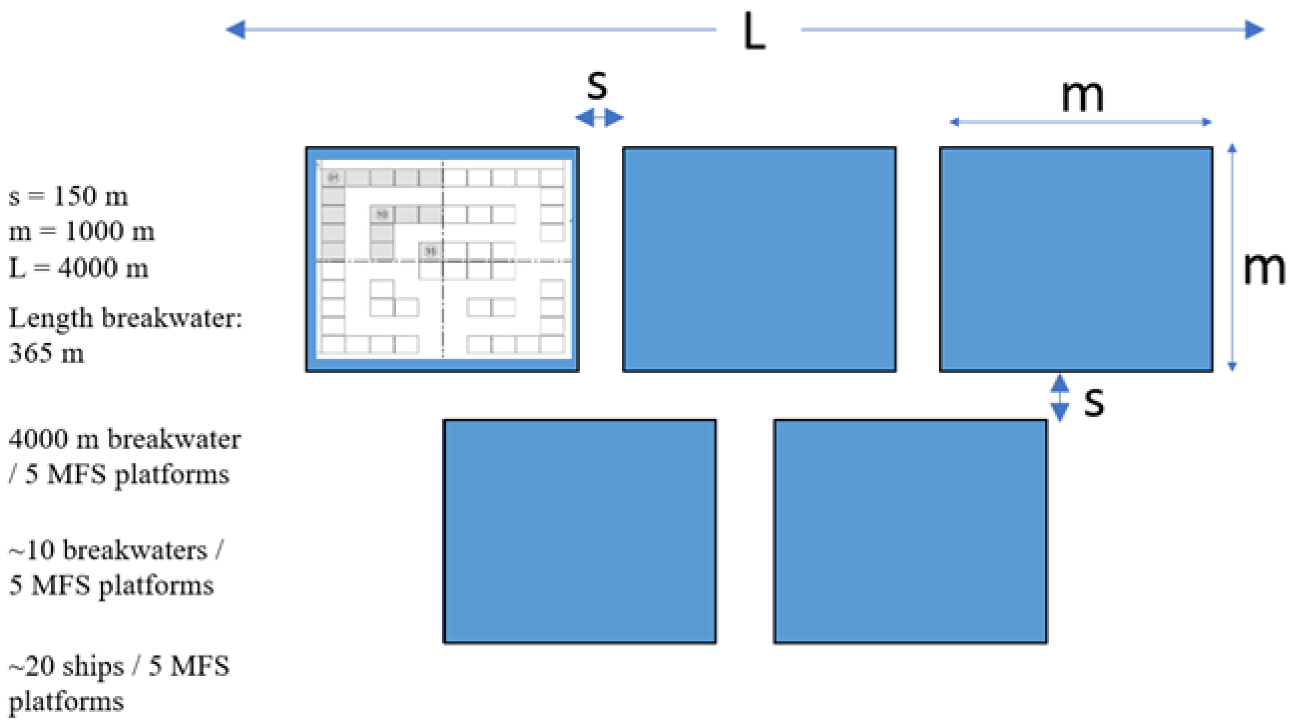

Figure C.13: Ratio floating breakwaters per MFS platform.