Politecnico di Torino
Department of Management and Production Engineering

Master's Degree Thesis in Engineering and Management

Comparative analysis of SEA*form* floating modular platform system and land reclamation In-fill and Hydraulic-fill techniques.

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Abstract

The scarcity of space in coastal towns due to rising sea levels and limited land availability in rapidly growing coastal communities has prompted the practice of land reclamation. The SEA*form* project aims to create settlements that are seamlessly integrated with the maritime environment using a system of modular floating platforms. This thesis seeks to evaluate and compare the SEA*form* technology solution with the current methods used in Land Reclamation (In-fill and Hydraulic-Fill land reclamation) to help decision-makers select the most appropriate option for their specific project needs.

This thesis intends to evaluate and compare the costs, marine environmental impact, and contribution to global warming of floating platforms and Land Reclamation In-fill and Hydraulic-fill methods to identify the most efficient approach for land reclamation projects.

Calculating the KPI values can be complex, especially when taking into account the land reclamation methods of In-Fill and Hydraulic Fill. The thesis includes simplifications in calculations and uses both bottom-up and top-down methods to estimate KPIs.

The thesis ultimately contrasts the outcomes obtained to give decision-makers a thorough understanding of the pros and cons of each technology within given boundary restrictions.

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1 Introduction

Currently, 50% of the global population resides in urban areas. It is projected that by 2050, almost 80% of the estimated 9 billion people on Earth will be living in urban zones [1]. Moreover, it is expected that half of the population would live within a distance of 100 kilometres or less from the coastline [2]. This trend is likely to result in a reduction of available land in metropolitan areas and an increase in the population at risk of flooding, hence exacerbating their susceptibility [3]. The ongoing trend of population concentration in urban regions is resulting in the conversion of rural land into urban areas, hence limiting the availability of land for essential purposes such as food production [4]. This extensive transformation not only changes the extent of land utilized for agricultural purposes but also influences the ability of the ground to allow the passage of fluids. The natural water filtration processes in urbanized soil are frequently hindered, resulting in an imbalance in the urban water cycle. The combination of sewer overflows and the greater volume of storm-water runoff increases the likelihood of flooding, therefore posing a risk [5].

Concerning the issues posed by climate change, coastal communities are more susceptible to floods due to the increased frequency of extreme weather events and sea level rise [6].

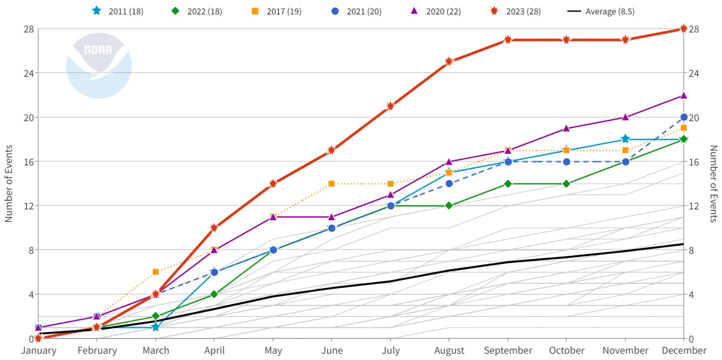


Figure 1: 1980-2023 United States Billion Dollar Disaster Year-To-Date Event Count [6].

The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019) [7] states that the anticipated increase in Global Mean Sea

Level (GMSL) is predominantly attributed to the melting of glaciers and ice sheets, thermal expansion of saltwater, and alterations in the storage of water on land. The magnitude of this increase is significantly influenced by the particular emission scenario referred to as the Representative Concentration Pathway (RCP). The RCPs provide four distinct trajectories for the release of greenhouse gases (GHGs), air pollutants, atmospheric concentrations, and land use over the 21st century [8].

The pathways encompass four distinct scenarios: a stringent mitigation scenario (RCP2.6), two moderate scenarios (RCP4.5 and RCP6.0), and one scenario characterized by exceptionally high greenhouse gas emissions (RCP8.5). These scenarios are linked to radiative forcings of 2.6, 4.5, 6, and 8.5 W/m^2, respectively. Baseline scenarios, which do not involve any measures to reduce emissions, are classified within the range of RCP6.0 and RCP8.5. Conversely, RCP2.6 is a scenario designed with the specific goal of limiting global warming to less than a 2°C increase compared to pre-industrial temperatures [8].

Projections indicate that sea levels will experience a more accelerated rise by the end of the century, irrespective of the Representative Concentration Pathway (RCP) scenarios. According to data from 1986-2005, it is estimated that the average sea level worldwide will increase by 0.43 m (with a probable range of 0.29-0.59 m under the RCP2.6 scenario) to 0.84 m (with a probable range of 0.61-1.10 m under the RCP8.5 scenario) by the year 2100 [7]. As per the RCP8.5 scenario, the projected sea level rise (SLR) rate is expected to be 15 mm year by 2100, and there is a potential for it to increase to multiple centimetres per year in the 22nd century [7].

The Shared Socioeconomic Pathway (SSP) paradigm examines seven possible trajectories that depict plausible scenarios for the development of global society, economics, and demographics in the coming century. The trajectories are influenced by the degree of implementation of climate policy [9]. Figure 2 illustrates the many scenarios of global sea-level rise (SLR) using the Shared Socioeconomic Pathways (SSP) framework [10].

The possible ramifications of this circumstance would be substantial since the projected increase in sea level might potentially exceed 5 meters by the year 2150 [9].

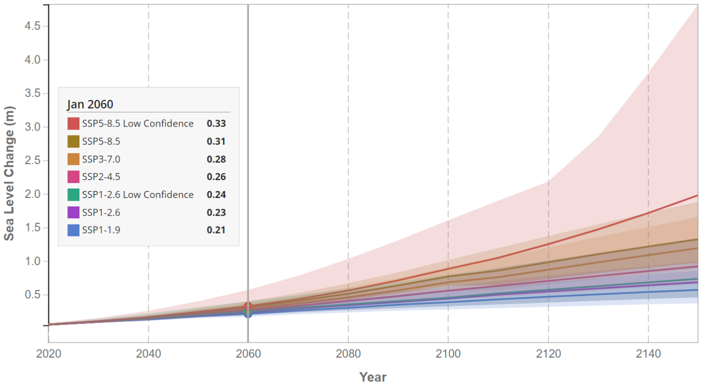


Figure 2: Projected sea level rise under different SSP scenarios [10].

Furthermore, over the past 50 years, there has been a substantial rise in the world's population, particularly in coastal areas which have become densely populated and highly urbanized.

Coastal zones encompass roughly 19.2% of the total land area, exhibiting a greater population density compared to inland areas. The majority of the 2 billion coastal residents reside in fewer than 40% of the global coastal areas, resulting in significant population density in those specific places [11].

More than half of the land characterized by a dense population was located in the coastal area. China, Bangladesh, and India exhibit significant population density in coastal regions, but Canada, Australia, and Russia experience minimal population pressure as their coastal locations are situated in polar or desert regions.

There are over 260 cities with populations over 100,000 that are situated in coastal areas across the globe. Among the ten most populous cities in the world, eight are found in coastal zones.

Anticipated future trends indicate a substantial rise in population density within coastal areas (Figure, rendering them favourable regions for both present and future population distribution and expansion [11].

Asset prices are expected to represent the level of risk associated with them accurately, but, the coastal real estate market has been defying this concept for a considerable period of time. The risk of sea level rise is not adequately accounted for, and furthermore, some of the most susceptible regions in the United States are also seeing excessive speculation, as seen, for example, by a 64% increase in housing prices in the Miami (US) area since 2019 [12].

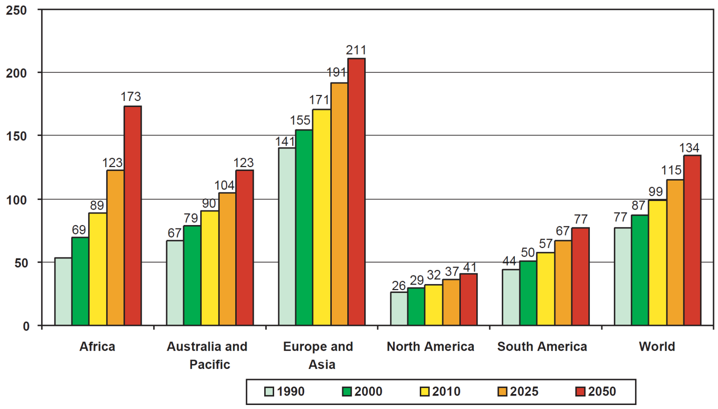


Figure 3: Population density trend in the coastal zones, by continent. $People/km^2$ [11].

Both the projected increase in sea level and the growing population density trend in the coastal zones, by continent pose a substantial threat to coastal communities since it will result in a further reduction of land availability and an elevated susceptibility to floods [3].

A viable strategy to tackle these concerns is the enlargement of urban areas through the reclamation of land from water, commonly referred to as "Land reclamation" [4].

This master's thesis aims to evaluate and contrast the technological solution put forward by the SEA*form* research project of the MOREnergy lab at the Politecnico di Torino with the prevailing solutions in the domain of land reclamation: Hydraulic-fill and In-fill.

2 Land Reclamation Overview

Land reclamation involves the process of creating new land from the sea, lakes or rivers by depositing large amounts of rock, cement, clay, and soil to achieve the desired height. This process is commonly known as filling and is the most common one. Another new technology involves the utilization of floating platforms.

Archaeological evidence suggests that land reclamation is not a modern innovation, but rather has been practiced for millennia. Approximately two millennia ago, the people residing in the marshy and tidal regions of the Wadden Sea in the northern parts of The Netherlands and Germany inhabited man-made housing mounds known as 'terpen' or 'wierden'. These mounds were constructed as a defence mechanism against floods during periods of elevated water levels. To mitigate the risk of sea flooding, they constructed dikes between the habitation mounds.

During the 1500s, a technique called "poldering" emerged as a means of reclaiming land. This involved constructing a circular embankment in places with shallow water, followed by the use of windmill-powered pumps to drain the contained low-lying region. In the 19th century, the availability of steam engines led to the replacement of certain windmills by pumping stations.

The advent of the modern centrifugal pump was a pivotal point that facilitated the implementation of large-scale reclamation projects by hydraulic-filling.

Due to the rapid increase in the global population and the resulting urbanization and economic progress, especially in densely populated coastal regions, there has been a growing need for additional land in recent decades. The desire for reclamation projects has led to the implementation of a wide range of projects, including both small-scale.

The International Association of Dredging Companies[13] reports that one of the earliest large-scale reclamation projects, known as the Bay of Abidjan in Ivory Coast, took place during the 1960s.

The age of land reclamation began in the 1970s with significant projects, such as the enlargement of the Port of Rotterdam in the Netherlands (fig.4). This project covered a vast area of 2000 hectares and required a significant quantity of 170 million cubic meters of construction materials [14].

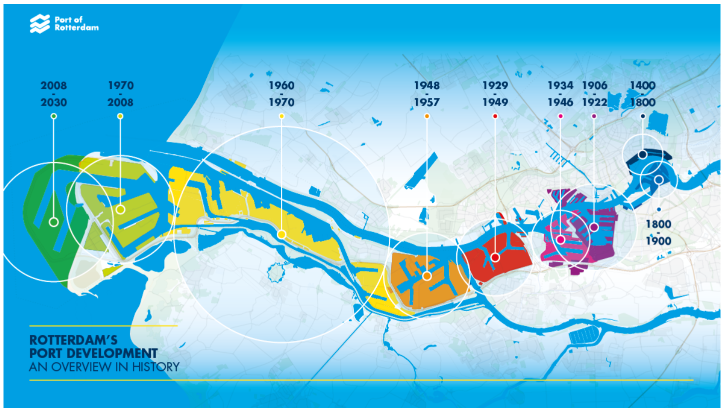


Figure 4: Rotterdam's port development history [15].

The approach quickly became popular globally, with notable examples in the Netherlands, Singapore, Hong Kong [14], and a significant portion of mainland China's coastline [16]. For instance, Singapore's Changi Airport (fig.5) was constructed by utilizing almost 40 million cubic meters of sand extracted from the seabed [17].

Figure 5: Singapore's Changi Airport in 2000 (left) and in 2023 (right) [18].

Artificial islands, like Kansai International Airport in Japan and Hong Kong International Airport, exemplify efforts to reclaim land through the process of land reclamation.

The Flevopolder, which covers an area of 970 km2 in the Netherlands, is recognized as the largest man-made island that has been reclaimed from the sea on a global scale [17].

3 Market Analysis

The solution presented by SEA*form* aligns with the expanding sector of the Blue Economy, which is a thriving global market, particularly in Italy. Recent estimates indicate that the maritime economy has a global total value of approximately $24 trillion. Nevertheless, it is anticipated that this number will experience exponential growth in the near future. Allocating $2.8 trillion at present towards four specific solutions related to the ocean is projected to generate a return on investment of almost $15.5 trillion by the year 2050. Moreover, the "Blue Economy Report" released by the European Commission in 2022 reveals that this industry employs 4.45 million individuals and generates €667.2 billion in sales just in Europe [19].

In Italy, the Blue economy is experiencing growth. In 2021, it generated €52.4 billion in value added. When taking into account the full direct and indirect supply chain, the total value reached €142.7 billion. The sector had a significant export surge between 2021 and 2022, with a growth rate of 37.4%. This expansion was supported by 228,000 enterprises, employing over 914,000 individuals [19].

The SEA*form* project operates under the Land Reclamation market, which encompasses the construction of structures, land, and projects on bodies of water. The Real Estate players currently hold a significant share in this market, with the Dredging sector being the main representative [19].

Recently, the Land Reclamation sector has been witnessing significant expansion, with investments surpassing billions of dollars. This growth is particularly evident in the development of creative ideas for new floating buildings, which are consistently being launched and promoted. These investments contribute to the growth of enterprises operating in the industry, including specialized investment funds, project execution companies, shipyards, design studios, transportation providers, and maintenance services [19].

3.1 Floating Projects

This section provides a list of organizations or initiatives that have been recognized as the main actors in the floating projects sector. These actors have a similar objective of facilitating the development of floating communities on water. The initiatives that are proposing an idea comparable to that of SEA*form* are currently in the design phase, and as of now, none of these projects have been implemented. In addition, the specific technological specifications of the solutions suggested by possible competitors are not disclosed to the public. Presented here are the most notable cases:

Neom is a state-controlled company responsible for the development of the floating metropolis of Oxagon. The design idea, which is the subject of debate and financed by the Public Investment Fund, seeks to establish a new model where individuals, industries, and technology coexist together with the natural environment. Upon its completion, the mega-city in northwestern Saudi Arabia would span an expansive area of 26,500 square kilometers. While a significant chunk of this area will be reclaimed land, the construction also incorporates a section of floating surface. The technologies employed appear to be interlinked modular platforms; however, no specific information is given regarding the technological solutions that would be utilized, leaving it as a conceptual endeavor. The technologies and solutions created by SEA*form* may be relevant to this project [19].

Oceanix is the initiative dedicated to creating the world's inaugural robust and sustainable floating village, designed to accommodate 10,000 residents. This project originates from the renowned BIG design company. Despite its significant technological advancements and seamless integration of the city with relevant technology, the available papers primarily focus on architectural concepts and visual representations. The Oceanix launch project is specifically tailored for the city of Busan in South Korea, located within a sheltered gulf. Similar to the last instance, there is a lack of information regarding the technological solutions, and neither the company nor the initiative currently possess any patents. Thus, given their desire to address the issue of connectivity, it can be inferred that they might have an interest in SEA*form* technologies [19].

Ocean Builders is a firm with the objective of developing environmentally-friendly floating Pods, which are self-contained units that enable persons to have their own living space on the water's surface. Their inaugural prototype was deployed earlier this summer along the coast of Panama, and interested parties have the option to make a down payment to acquire an initial pod. These constructions are characterized by their monolithic nature and their focus on utilizing state-of-the-art technologies [19].

Floating platform neighbourhoods in Northern Europe have a rich history and have emerged as leaders in this field over the past decade. One of the latest examples is Urban Riggers, a housing complex consisting of student residences located in the port of Copenhagen. Amsterdam has already finished building floating platform neighbourhoods like Waterbuurt and Schoonschip, with the latter being notable for its circular approach. These solutions consist of distinct projects that are tailored to serve a certain role and objective. They are physically linked to docks or specific locations on the landform. Consequently, they do not provide solutions that can be easily expanded or adjusted to accommodate growth [19].

The Copenhagen Islands project involves the construction of floating islands in the harbour of the Danish capital. The islands serve as a foundation for a floating park and are securely attached to the bottom, providing a durable habitat for the environment in the city centre. The maritime architectural firm (MAST) will construct the structures using traditional boat-building processes, employing wood and sustainable or recycled materials. Each island is an independent and self-contained construction; consequently, while this concept is unique and sustainable, it cannot be easily expanded or replicated [19].

3.2 Hydraulyc and In-fill

The key participants in the field of land reclamation, namely in relation to hydraulic-fill and in-fill technologies, remain unchanged. Both technologies share a significant portion of the implementation process and are thus utilized interchangeably by enterprises in the sector, depending on the unique instance and the reclamation site [20].

The Netherlands is home to the most significant corporations, owing to its long-standing legacy. Just like with floating platforms, the enterprises in this area are fairly limited in number due to the highly specialized skills necessary. The following list provides a description of the most significant ones [20]:

Royal Boskalis Westminster: The Dutch corporation is ranked first among the best dredging businesses. Founded in 1910, the corporation has expanded its operations to 50 countries worldwide over the course of more than a century. Royal Boskalis Westminster's unwavering emphasis on dredging since its inception has enabled it to build an unrivalled fleet of dredging vessels. Include projects focused on Europe, Asia, and Africa [20].

CHEC (China Harbour Engineering Company) is a prominent player in the dredging sector, solidifying China's dominance in this industry. Founded in 1980, the company has emerged as the top dredging contractor in China and the second-largest globally. The company is a subsidiary of CCCC - China Communications Construction Company Ltd. It is involved in projects across Asia and Africa [20].

Van Oord: is a Dutch dredging company that is collectively controlled by NPM Capital, the Van Oord business family line, and the construction behemoth Royal BAM. It is also one of the oldest in our compilation, having been founded in 1868. Currently, the organization has a significant global presence with numerous success stories that support this claim. Include programs that focus on Europe, Asia, and Africa [20].

DEME, short for Dredging, Environmental and Marine Engineering, is a Belgian consortium specializing in dredging. It is also known as Dredging International. DEME has a long history dating back to the 1800s. The company's first year of operations, however, is given as 1991. Reporting on initiatives in Europe, Asia, and Africa [20].

Jan de Nul is a Belgian dredging firm that was established in the late 1930s and is still family-owned. Initially focused on civic construction activities, the company later transitioned into a dredging contractor, which has led to global professional recognition for the conglomerate. Reporting on initiatives in Europe, Asia, and Africa [20].

Great Lakes Dredge and Dock is an American company that specializes in dredging. It was established in 1890. The corporation, currently based in Illinois, is the largest dredging contractor in the United States. It also operates in the international dredging industry. Focus on projects related to North America [20].

Weeks Marine Inc. is ranked seventh among the top-100 dredge operators worldwide. The American dredging conglomerate was established in 1919 and operates in both the United States and Canada. Boasting an extensive track record of successful dredging projects, the company ranks among the largest dredging companies in the entire United States. Focus on projects related to North America [20].

The Inai Kiara, a colossal Malaysian entity, was established in 1997. Over the span of more than a decade since its establishment, the business has made significant progress in elevating Asian dredge operators to global recognition. Reporting on projects in Malaysia, located in Southeast Asia [20].

The National Marine Dredging Company is a Middle Eastern corporation founded in 1976 and based in Abu Dhabi. The conglomerate is a subsidiary of the prominent petroleum business in Abu Dhabi and has been doing numerous significant operations in the Middle Eastern region. Reporting on initiatives in the Middle East and North Africa region [20].

Penta Ocean Construction is a specialist construction firm that focuses on building infrastructure and maritime civil engineering. It was originally established in Japan in 1896, but had a recovery phase in 1946 and now operates as a contractor for marine civil engineering projects. The Japanese corporation has undertaken numerous distinctive dredging and construction projects, both domestically and internationally. Reporting on initiatives in Asia and Africa [20].

4 Technological analysis

This chapter tries to present the technologies by providing a detailed description of their operation, main components, and primary phases.

4.1 SEA*form*

SEA*form* is a project developed by the Marine Offshore Renewable Energy Laboratory (MOREnergy Lab), a specialized research centre at Politecnico di Torino focused on offshore renewable energy [21]. The project aims to create a sustainable and environmentally friendly way of living on water. Its goal is to facilitate the transition to living at sea through the use of engineering solutions and technologies. The project attempts to address the Sustainable Development Goals (SDGs) depicted in Figure 6.

Figure 6: The Sustainable Development Goals (SDGs). The SEA*form* objectives are highlighted [19].

The primary objective of the SEA*form* project is to tackle the issues faced by coastal cities by developing self-sustaining communities that are seamlessly interwoven with the maritime environment. This will be achieved through the use of interconnected modular floating platforms [22]. The platforms are securely attached to the seabed and, if located in the open sea, shielded from the force of waves by floating breakwaters. To achieve self-sufficiency, the solution will integrate energy and food production, waste treatment, and water management. This integration will create floating communities that are built on the principles of sustainability and circular economy [19]. SEA*form*'s objective is to reduce the negative effects of its solution on the marine ecosystem, providing a practical answer for towns dealing with sea level rise and growing urbanization [22]. Figure 7 displays the concept designs [23].

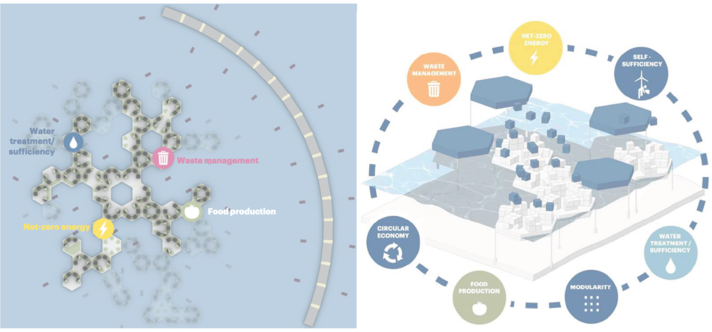


Figure 7: SEA*form* Design Concept [19].

The program defined by SEA*form* consists of three progressive stages: the project begins with the creation and construction of a small floating pavilion, which serves as a testing ground for both design and technology. The next phase involves the development of a larger floating complex that includes urban expansion. The ultimate vision is to establish a model for autonomous and sustainable floating cities that can be replicated, expanded, and scaled up [23] [24].

The advantages of SEA*form* compared to other land reclamation approaches are as follows [19]: A Minimal environmental impact, in contrast to the dredging technique, as the proposed solution does not disrupt the existing flow patterns and movement of silt. In addition, the mooring system differs from conventional floating constructions in that it exerts less pressure on the seabed, as it does not involve any mooring lines attached to the seafloor. The proposed approach has the ability to be installed at higher depths compared to dredging while incurring a far smaller cost increase [23].

Scalability and modularity refer to the ability to easily expand and adapt the systems to different functions: energy hubs, port facilities, vertical farming, residential spaces etc. By using a modular and standardized approach, as opposed to monolithic constructions, the system allows for flexible expansion according to investment needs. The platforms can be interconnected, smoothly changing from a small block size to the magnitude of a floating city. The buildings' structures are simply dismantled and recycled, and the entire project may be easily transported [22]. Standardizing the platform system enables replicability, resulting in cost savings by reducing construction costs and time-frames.

4.2 Hydraulic-Fill and In-Fill

"Hydraulic filling" refers to the process of creating additional land through a series of continuous activities (See figure 8).

1. **Dredging**: Excavation of sediment in a designated area using floating machinery (dredgers);
2. **Transportation**: Conveyance of the excavated sediment from the designated area to the reclamation site using a dredger, barge, or pipeline;
3. **Deposition** of the excavated sediment, mixed with water, in the reclamation area.

The three phases will be thoroughly examined in subsequent chapters.

"In-Fill", instead, does not include the dredging phase as the material is not extracted on site, but rather purchased and transferred to the reclamation site using barges.

The chapter primarily examines the dredging phase, which is a more intricate and distinctive stage in hydraulic-fill operations.

Expertise in multiple disciplines, including hydraulic, geotechnical, and environmental engineering, as well as practical experience in dredging and filling processes, is essential for the design and construction of a hydraulic-fill project [13]. Subsequent chapters will thoroughly examine each phase.

Boundary conditions are typically tailored to the unique site and project. The physical characteristics of a site, including factors such as wave climate, currents, water depth, subsoil properties, and environmental sensitivity to dredging and reclamation activities, will vary between different locations. The availability and suitability of fill material for construction will be significantly influenced by the project's location. These conditions will impact both the design of the reclamation and the selection of appropriate dredging equipment and construction process [13].

Figure 8: Hydraulic Filling Rainbowing technique example: a Trailing suction hopper dredger pumping sand [25].

In order to accurately determine the shape and characteristics of the fill mass, a rational design should incorporate the functional and performance requirements while taking into account the project's boundary circumstances. It is important to use the same logical thinking when it comes to building the reclamation. This means carefully choosing the right tools and method of operation [13].

The book "Environmental Aspects of Dredging" (Bray, 2008) [26] provides a comprehensive summary of the data needed to monitor the effects of dredging on the surrounding environment. A desk study is an economical and rational initial phase of a site inquiry conducted at the beginning of a project. Ideally, the desk study should be finished and documented before starting surveys and conceptual design. The subsequent phase in the design process involves creating a comprehensive list of the necessary data for the design process. The necessary data will vary based on the following factors: The specific area being investigated, which could be a designated borrow area, dredge area, or reclamation area. The type of soil present, whether it is cohesive, non-cohesive, or composed of rock. The design considerations that need to be examined, such as volume calculations, slope stability, settlement, abrasion, and potential dredging methods [13].

Using the information collected during the first research, a site investigation can be conducted to obtain the necessary data that is currently unavailable. A site investigation campaign can be divided into four primary areas of focus:

- Bathymetric or topographic survey;
- Geological and geotechnical investigations including geophysical investigations;
- Metocean survey and environmental investigations;
- Seabed scanning using side scan sonar and magnetometer survey.

A desk study is often the initial stage of a site assessment and is essential for achieving the best outcomes in the following phases. The process involves gathering, examining, and confirming existing information about a location, while also identifying possible discrepancies or gaps in the information. It is conducted during the initial phase of site evaluation to direct the subsequent site inquiry. The desk study must encompass a wide array of factors that have the potential to impact a project in terms of both practicality and logistics [13].

The desk research should encompass an examination of all pertinent sources of information, such as historical records, and the gathering and assessment of all accessible and relevant data for the site, including, for instance, bathymetric information. Precise bathymetric data is necessary to determine the amount of fill material that can be used in the designated region [13].

If the fill needs to be obtained from capital dredging activities, such as deepening the harbour basin, bathymetric studies are necessary to determine the exact amount of material that needs to be dredged:

- *Admiralty charts* and other marine charts that provide more specific information on local areas;
- *Geological data:* The examination of a borrow area and a reclamation area requires different sets of geological and geotechnical data. The tests conducted in the borrow area primarily focus on assessing the soil's quality, amount, and dredgeability. The soil characteristics, such as grading, may undergo alterations during dredging, rendering certain tests ineffective or requiring cautious interpretation, such as the Particle size distribution tests. Tests conducted in the reclamation

area primarily focus on assessing settlements resulting from the placement of the reclamation fill and verifying the stability, load-bearing capacity, and resistance to liquefaction of the reclamation area and its surrounding structures (such as revetments, retaining walls, and bunds). The data and records of seismic activities, including earthquake risk and magnitude, as well as tsunami activity, are available. Additionally, existing geotechnical and geohydrological data and information are accessible. Previous experiences with similar activities, such as dredging, or other activities of interest, such as foundations, in the area, are also documented [13].

- *Meteorological, oceanographic, and hydrological data*, which includes information on water levels, tides, currents, wind patterns, and wave conditions. The design of reclamation works relies heavily on water levels, which are the most significant data parameter. The heights of the defence structures and the level of the reclamation itself are mostly determined by the severe water levels. Currents in rivers, estuaries, and coastal locations are primarily influenced by gravity (in rivers), differences in density, fluctuations in tidal water levels, or wind shear during storms (known as surge currents) [13].
- *Non-technical data:* includes information about underwater pipes, prohibited areas, shipping movements, fishing or military activity, the sailing distance between the borrow area and reclamation area, site accessibility, permits, housing, and office facilities [13].
- *Ecology:* The existence of marine reserves and the presence of indications that suggest the presence of protected species [13].

This chapter provides a concise overview of dredging equipment, covering the types of soils that can be dredged and the operational constraints associated with it [13].

Dredging can be categorized into two primary types: suction dredging and mechanical (cutting) dredging. These dredging techniques can also be combined, for example, by using a cutter suction dredger with a cutter head and a trailing suction hopper dredger with a draghead equipped with a cutting edge. The many categories of suction dredgers include the plain suction dredger, the cutter suction dredger, and the trailing suction hopper dredger. The two types of mechanical dredgers are the hydraulic backhoe dredger and the grab dredger [13].

Plain Suction Dredger (SD) Suction dredging relies on the erosive force of water flow that enters the suction pipe of the dredger due to the vessel's pumping action. Frequently, jets connected to the suction nozzle are employed to dislodge the material that needs to be dredged. The eroded material is combined with water to form a sand-water combination. This mixture is then sent through a discharge pipeline to either the reclamation site or a barge located next to the dredger, using a spreader discharge system. The dredging principle employed by the "plain suction dredger" and the "dustpan dredger" is referred to as the "plain" dredging principle. The plain suction dredger is commonly employed for extracting sand whereas the dustpan dredger is widely utilized in the United States for the purpose of maintaining dredging operations. During the process of dredging, the location of the simple suction dredger is regulated using a wire anchor system (see figure 9) [13].

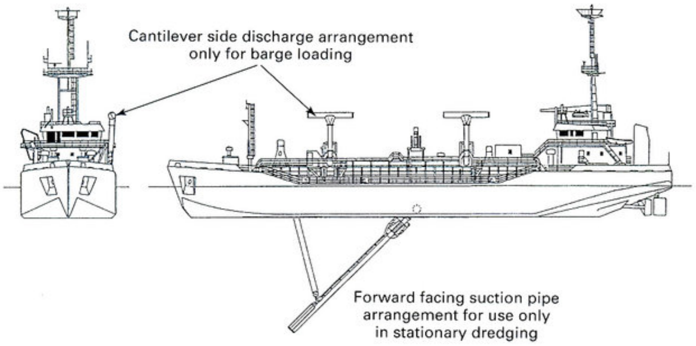


Figure 9: Plain Suction Dredger [27].

Cutter Suction Dredger (CSD) The cutter suction dredger operates by utilizing a combination of mechanical and suction dredging techniques. The dredger's cutter head slices through and loosens the material to be dredged, while the water's erosive force is directed towards the suction mouth by the vessel's pumping action. Furthermore, jets affixed to the cutter head, located at the bottom extremity of the cutter ladder, can be employed to dislodge the debris. The sand-water mixture is conveyed through the discharge pipeline to the reclamation area. Occasionally, the substance is transported via a distribution system and transferred into a barge located next to the dredger. Cutter suction dredgers (CSDs) are extensively utilized in dredging and reclamation endeavours. Their capacity to dredge various materials, such as silt, soft clay, and even moderately hard rock, is contingent upon their installed power. During the process of dredging, the cutter suction dredger rotates laterally around a fixed point using the working spud located at the rear of the vessel. The lateral movement is regulated by a wire anchoring system connected to the lowest part of the cutting ladder. While larger cutter suction dredgers may have the ability to propel themselves, the majority of cutter suction dredgers do not possess this capability (see figure 10) [13].

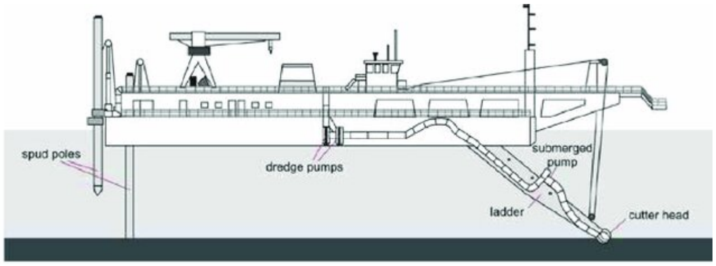


Figure 10: Cutter Suction Dredger [28].

Trailing Suction Hopper Dredger (TSHD) The trailing suction hopper dredge employs a mix of mechanical dredging (cutting) and suction power to dislodge the material that needs to be dredged. This particular dredger possesses the unique characteristic of being able to propel itself, setting it apart from the majority of other dredgers. During operation, one or two suction pipes are lowered to the bottom to extract soil through dredging. The material is loosened through a mix of cutting using the draghead connected to the bottom part of the suction pipe, jetting, and the erosive effect of water moving towards the suction mouth. The substance is injected into the container's receptacle, while the water used in the process is released into the adjacent water through a regulated overflow mechanism. After the hopper is full of dredged material, the vessel navigates to a specified dumping area or reclamation site and unloads its cargo. Discharging can be accomplished by opening doors or valves located at the bottom of the vessel's hopper, or by using a method known as rainbowing or pumping through a discharge pipeline. The choice of discharge mechanism is contingent upon various criteria such as prevailing environmental limitations, proximity to the reclamation site, and water depth. The trailing suction hopper dredger is suitable for dredging sand, silt, or clayey material. Even the largest dredgers have the capability to dredge weak rock. The productivity of dredging operations will fluctuate depending on the hardness and resistance of the material being dredged (see figure 11) [13].

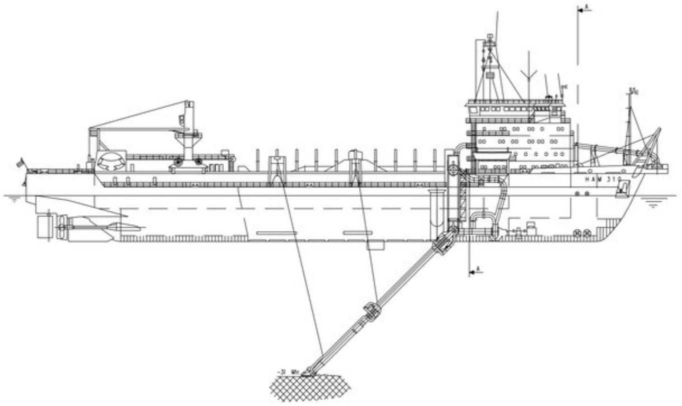


Figure 11: Trailing Suction Hopper Dredger [29].

Mechanical dredging Material is extracted and collected using a grab or a bucket during the process of mechanical dredging. The dredged material can be deposited either on a barge positioned next to the dredger, in a separate container on the dredger itself, or on land located next to the dredger. Common types of mechanical dredgers include the backhoe dredger, grab dredger, and bucket dredger. These dredgers are known as stationary dredgers and they are secured in the dredging position either by spuds or an anchor system (see figure 12) [13].

Finally, the dredged material can be transferred using three methods: Pumping it through a discharge pipeline straight into the fill area, using barges and using the dredger itself, namely the trailing suction hopper dredger.

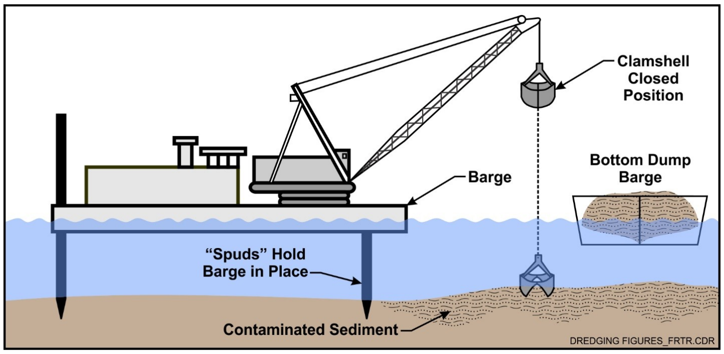


Figure 12: Mechanical dredging [30].

5 KPIs

As with Hydraulic-fill and In-fill land reclamation works, the modular platforms proposed by SEA*form* aim to provide new land by subtracting it from the sea.

The two technologies are, as shown in 4, very different. To compare them the thesis identifies three characteristics:

1. Costs.
2. Environmental Sustainability.
3. Technological Performances or Quality.

For reasons of complexity, it was chosen to focus the thesis work on the first two characteristics: Cost and Environmental Sustainability. It was then also decided to spin off Environmental Sustainability into two separate categories:

1. Marine Environmental Impact.
2. Carbon Footprint.

This thesis primarily examines the effects on the marine ecosystem and defers the investigation of the carbon footprint study up to future developments.

5.1 Costs

To compare the two technologies' costs, the thesis focuses on the cost of the floating platform under-structure and the hydraulic and in-fill land reclamation realization.

In hydraulic and in-fill, it is always necessary to build an Edge Protection to contain the fill material and protect it from the erosion of tides and waves. In the case of SEA*form* floating platforms, instead, the need for a floating breakwater depends on the reclamation site conditions of tides and waves.

For this reason, edge protection is always considered in hydraulic and in-fill cost estimation while the cost of the floating breakwater is estimated separately.

In both cases, it was decided to ignore:

- the costs of any upper structure which depend on the final use of the land reclaimed;
- VAT, which is related to the fiscal regulation of the reclamation site;
- maintenance costs;
- any other costs that are not included in the following list.

After estimating the costs, a tool in Excel is developed to compare the technologies' costs in the same conditions. Specifically the following will be compared:

- $Cost/m^2$
- Total Cost

5.1.1 SEA*form* costs

Unlike Hydraulic-fill and In-fill, the cost of floating platforms, as the SEA*form* solution, is relatively constant regardless of the varying conditions of the reclamation site. The primary cost element of a land reclamation project conducted using floating platforms is indeed the building costs associated with the platforms.

SEA*form* floating platforms are modular solutions, meaning that their dimensions and characteristics are standardized. As a result, the cost per square meter of these platforms may be deemed constant [19].

The sole factors that influence the estimation of platform costs are directly related to the socio-economic conditions of the building site at the time of their development. These costs are inherently changing over time, but they are not influenced by the location or characteristics of the reclamation site. These costs can be categorized as follows:

- Labour costs;
- Costs for raw materials;
- Costs for the required equipment to construct the platforms;
- Costs for the energy required to construct the platforms.

In this thesis, the cost of concrete is emphasized, as will be discussed further in this chapter.

The cost components that contribute to the final cost of a land reclamation project using floating platforms, besides the construction of the platforms, depend on the specific reclamation site characteristics, but cannot, however, be neglected. These components primarily include transport costs, anchoring costs, and the costs associated with creating a potential floating breakwater. The requirements and characteristics of the latter will be examined in detail in the upcoming chapter [19].

The transportation costs are contingent upon the number of platforms to be transported and the distance between the site where the platforms are produced and the site where they are reclaimed. In this thesis, the transport costs are calculated as a fixed proportion of the total expenditures. The reason for this is that it is inconceivable to envision a specific range of distance due to the absence of defined geographical constraints on the potential locations for constructing a floating platform production facility [19].

The costs associated with **anchoring and installation** are determined by the number of platforms as well as the specific characteristics and depth of the seabed. Placing anchors at significant depths poses more challenges due to the increasing complexity of rock anchors. Nevertheless, the influence of factors such as the depth and type of seabed on the total costs for anchoring and installation is little. Therefore, for simplicity, these costs are regarded as constant [19].

Cost Estimation

The under-structure costs of realization of a land reclamation project carried out through SEA*form* floating platforms are calculated as the cost of one platform multiplied by the number of platforms needed to reach the surface of land reclamation required [19].
The platform cost is composed of:

- Hull
- Technical equipment and Connectors
- Mooring
- Installation
- Other Costs

The **hull** cost is calculated as the cost of the concrete needed to ensure the structural characteristics of the hull multiplied by the cost per unit volume of the concrete.

After literature analysis, the volume of concrete was calculated as 17% of the volume of the hull. Similarly, the cost of the concrete was set as 1200 €/m^3.

$$HullCost = HullVolume \cdot 0,17 \cdot 1200 \tag{1}$$

The cost of the **technical components** and connectors was extrapolated from literature studies. The cost is a function of hull volume (0.015 ton//m^3 and cost per unit weight of components (5 €/kg) [19].

$$TechnicalComponents\&Connectors = HullVolume \cdot 0,0189 \cdot 3.89 \tag{2}$$

Mooring, **Installation** and **Other costs** are estimated by this thesis to be respectively 15%, 15% and 5% of the Total Costs [19].

A single platform cost results to be 6,341 M€. (See Table 1)

Element	*Value*	*UoM*
Hull	3,013	m^2
Technical Equipment and Connectors	1,108	M€
Mooring	0,951	M€
Installation	0,951	M€
Other Costs	0,317	M€
Total Costs	6,341	M€

Table 1: Single SEA*form* Floating Platform Costs

The total cost of a land reclamation project via SEA*form* floating platform is calculated as the single platform cost multiplied by the number of platforms (np) needed to achieve the surface requested [19].

$$FloatingTotCost = SinglePlatformCost \cdot \frac{ProjectSurface}{PlatformSurface} \tag{3}$$

It is important to note that the only driver for the platform cost estimation is the requested surface of the project. The reclamation site bathymetry contribution in the mooring and installation cost is, indeed, negligible.

Floating Breakwater

Floating breakwaters are typically required when the floating platforms are located offshore rather than in inland or protected waters.

The design of the floating breakwaters can be tailored to accommodate the precise requirements of the reclamation site. Breakwaters can be designed in different ways: as an open line, which protects against waves coming from one direction, as a closed line with gates, which allows access to internal waters and protects against waves arriving from all directions, or as a compromise between the two alternatives [19].

In this thesis, the breakwater is set as an open line whose length strictly depends on the platform layout and can be estimated as the length of the platform group multiplied by a length coefficient (LC). The length of the group of platforms can be estimated, in first approximation, as the diameter of one platform multiplied by the number of total platforms (np) divided by the number of rows (nr) of the platform chain [19].

$$BreakwaterLegth = \frac{PlatformDiameter \cdot np \cdot LC}{nr} \tag{4}$$

The cost of the breakwater is composed by:

- Hull
- Mooring
- Installation
- Other Costs

The **hull** cost of the breakwater is estimated, as the floating platform, computing the cost of the concrete needed to ensure the structural characteristics of the breakwater.

$$BreakwaterHullCost = BreakwaterVolume \cdot 0,17 \cdot 1200 \tag{5}$$

Mooring, **Installation** and **Other costs** are estimated by this thesis to be respectively 15%, 15% and 5% of the Total Costs.

The Breakwater cost for the "n" platform is calculated as:

$$BreakwaterTotCost = \frac{BreakwaterSingleCost \cdot np}{nr} \tag{6}$$

with np=number of platform and nr=number of rows of the platforms layout.

The floating breakwater, with nr=3, results to be 4,293 M€. (See Table 2)

Element	*Value*	*UoM*
Hull	2,791	m^2
Mooring	0,644	M€
Installation	0,644	M€
Other Costs	0,215	M€
Total Costs	4,293	M€

Table 2: Breakwater Cost for single Platform

The value of the Cost of a Land Reclamation project via Floating Platforms with a floating Breakwater is estimated as:

$$FloatingWithBWTotCost = FloatingTotCost + BWTotCost \tag{7}$$

To make an overall comparison with hydraulic and in-fill technology, the thesis analyzes both cases:

- Land reclamation without floating breakwater.
- Land reclamation with floating breakwater.

5.1.2 Hydraulic Fill Costs

This chapter wants to give, in the first part, an overview of the hydraulic-fill Land Reclamation cost composition to thereafter explain the construction of the cost per unit of surface function using the regression analysis technique.

The expense of a hydraulic fill project is directly connected to the choice of the main dredging equipment and the selection of the most suitable transportation and deposition method. Paragraph 4.2 provides a non-comprehensive selection of equipment choices. Every category of equipment has its own set of operational constraints and certain conditions under which it may be a more favourable option compared to other categories of equipment.

The factors for choosing the most suitable equipment are numerous and are outlined below:

- Characteristics of the area to be dredged: Exposed or in a sheltered area;
- Distance between the excavation site and the restoration location;
- Geological characteristics of the material present in the borrow area: sand, rock, mud or other substances;
- Thickness of the stratum that can be dredged;
- Volume of sediment available for dredging in the borrow area;
- Equipment accessibility at the reclamation site;
- Waves and Current;
- Depth of the seabed;
- Size of the area to fill;
- Soil conditions;

- Presence of Ships;
- Temporary limitations on work;
- Compensation received on a weekly basis by the crew members of the dragger ships and the workers on shore;
- Fuel costs incurred at the reclamation site at the time of the project.

After selecting the optimal equipment from the available options, the costs can be determined by adding together the fixed and variable costs.

The majority of fixed expenses are non-operational. These consist of the following costs:

- Preliminary study
- Design
- Equipment mobilization and demobilization

The operational expenses associated with a dredging and reclamation project are commonly measured in a specific currency unit per cubic meter. The term used to describe this is the unit rate. The unit rate can be represented as a mathematical function that depends on the weekly production of the dredging vessel (equation 8).

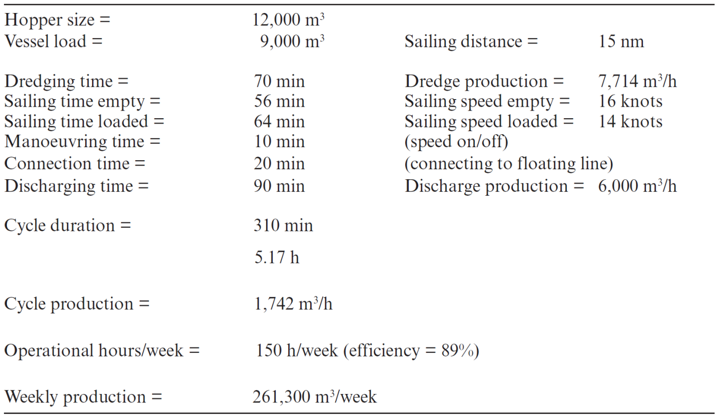
$$UniteRate = \frac{WeeklyCostsOfEquipment}{WeeklyProductionOfDredger} \tag{8}$$

Thus, by multiplying the unit rate by the whole volume of the land reclamation project, it is possible to get the variable cost estimation.

In addition to the intricacy of selecting the appropriate equipment, it has to be considered the intricacy of forecasting the real working conditions that the hydraulic-fill operations will face.

An extensive analysis of the characteristics of the reclamation site end of the borrow area minimizes but does not eliminate, the chances of encountering conditions that are significantly different and then potentially worse than anticipated. This can result in significant variations, particularly in the calculation of the "Unit Rate," leading to cost increases of up to 96% for a single variable.

Figure 13 shows an example of the calculation of the weekly production of a Trailing Suction Hopper Dredger (TSHD). Figure 14 illustrates, instead, several examples of how the change of boundary conditions are reflected in changes in the unit rate.



Hopper size =	12,000 m^3		
Vessel load =	9,000 m^3	Sailing distance =	15 nm
Dredging time =	70 min	Dredge production =	7,714 m^3/h
Sailing time empty =	56 min	Sailing speed empty =	16 knots
Sailing time loaded =	64 min	Sailing speed loaded =	14 knots
Manoeuvring time =	10 min	(speed on/off)	
Connection time =	20 min	(connecting to floating line)	
Discharging time =	90 min	Discharge production =	6,000 m^3/h
Cycle duration =	310 min		
	5.17 h		
Cycle production =	1,742 m^3/h		
Operational hours/week =	150 h/week (efficiency = 89%)		
Weekly production =	261,300 m^3/week		

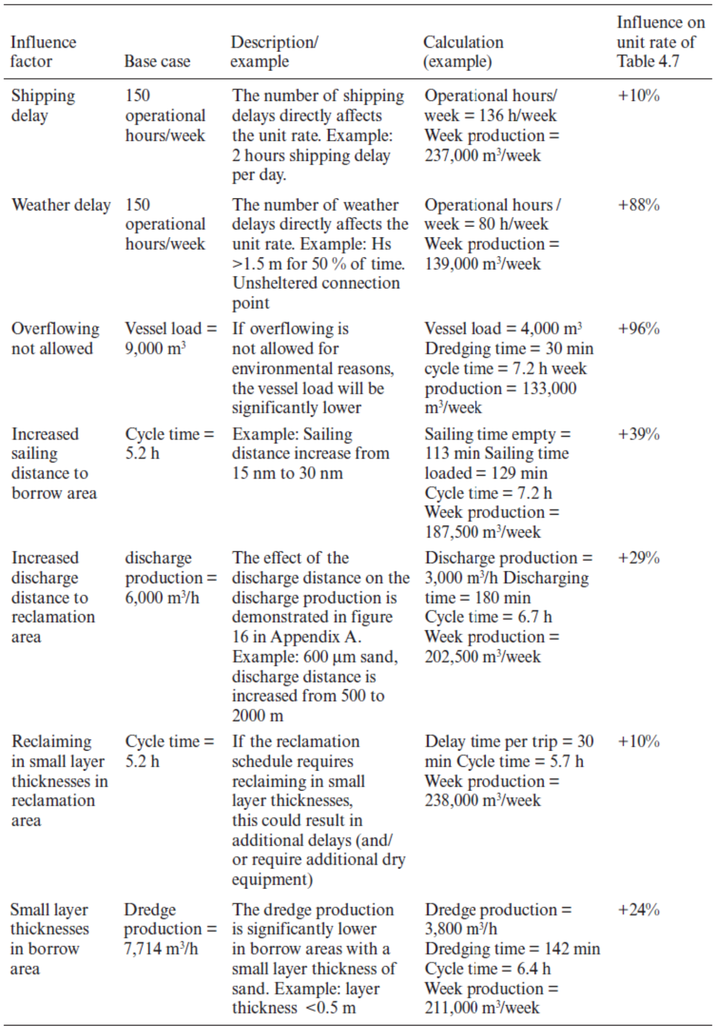
Figure 13: Calculation of the weekly production of a TSHD [13].

To address the challenges associated with estimating the costs of a hydraulic-fill land reclamation project using a bottom-up strategy, this thesis employs a top-down approach. It derives the costs of implementing a hydraulic-fill land reclamation by utilizing data from two land reclamation studies: a study conducted on behalf of the Government of Malta [31] and a study examining the feasibility of land reclamation by in-fill in Jakarta [32].

The Malta research conducted on behalf of the Government of Malta examines 12 design hypotheses in different maritime habitats within Maltese waters. Out of the total of 12 projects, 10 include extending land, while the remaining 2 projects involve actual offshore land reclamation.

It is crucial to emphasize that the Maltese study proposes a highly specific In-fill technique that utilizes construction waste material as fill material. This specific option enables the Maltese studio to ignore the expenses associated with obtaining the fill material, regardless of whether it is material extracted on-site using hydraulic-fill procedures or material procured outside and delivered to the reclamation site.

Considering the intricate nature discussed earlier in the chapter on accurately measuring the expenses associated with dredging, this thesis utilizes the cost of 44,267 €/m^3 per unit volume of dredged sand as determined in the Jakarte research [32].



Influence factor	Base case	Description/ example	Calculation (example)	Influence on unit rate of Table 4.7
Shipping delay	150 operational hours/week	The number of shipping delays directly affects the unit rate. Example: 2 hours shipping delay per day.	Operational hours/ week = 136 h/week Week production = 237,000 m^3/week	+10%
Weather delay	150 operational hours/week	The number of weather delays directly affects the unit rate. Example: Hs >1.5 m for 50 % of time. Unsheltered connection point	Operational hours / week = 80 h/week Week production = 139,000 m^3/week	+88%
Overflowing not allowed	Vessel load = 9,000 m^3	If overflowing is not allowed for environmental reasons, the vessel load will be significantly lower	Vessel load = 4,000 m^3 Dredging time = 30 min cycle time = 7.2 h week production = 133,000 m^3/week	+96%
Increased sailing distance to borrow area	Cycle time = 5.2 h	Example: Sailing distance increase from 15 nm to 30 nm	Sailing time empty = 113 min Sailing time loaded = 129 min Cycle time = 7.2 h Week production = 187,500 m^3/week	+39%
Increased discharge distance to reclamation area	discharge production = 6,000 m^3/h	The effect of the discharge distance on the discharge production is demonstrated in figure 16 in Appendix A. Example: 600 µm sand, discharge distance is increased from 500 to 2000 m	Discharge production = 3,000 m^3/h Discharging time = 180 min Cycle time = 6.7 h Week production = 202,500 m^3/week	+29%
Reclaiming in small layer thicknesses in reclamation area	Cycle time = 5.2 h	If the reclamation schedule requires reclaiming in small layer thicknesses, this could result in additional delays (and/ or require additional dry equipment)	Delay time per trip = 30 min Cycle time = 5.7 h Week production = 238,000 m^3/week	+10%
Small layer thicknesses in borrow area	Dredge production = 7,714 m^3/h	The dredge production is significantly lower in borrow areas with a small layer thickness of sand. Example: layer thickness <0.5 m	Dredge production = 3,800 m^3/h Dredging time = 142 min Cycle time = 6.4 h Week production = 211,000 m^3/week	+24%

Figure 14: Influence change of factors on unit rates [13].

Furthermore, to generalize the findings of the Maltese study to a broader context, the thesis calculates the expenses for a hydraulic-fill land reclamation per unit of area and then increases the costs of land extension projects by 50%. Land extension projects inherently entail less difficulty and hence incur cheaper expenses compared to offshore ones. The costs per unit of surface area calculated using this approach are subsequently modified to reflect the year 2024 by applying a discount rate of 2.44%, which corresponds to the average inflation rate of the euro area over the previous two decades.

Significant attention should also be directed to the design and construction of the breakwater, which is consistently important in Hydraulic-fill projects.

The reclamation fill can be protected by a variety of edge structures. Some of the possible edge protection structure types are shown below:

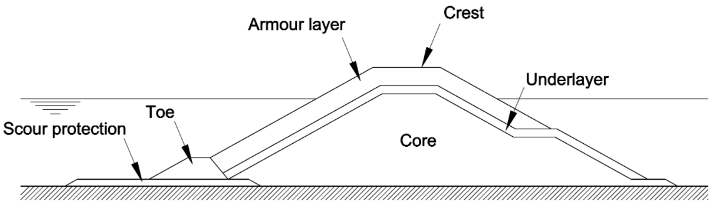


Figure 15: Cross-section of a typical rubble mound breakwater [33].

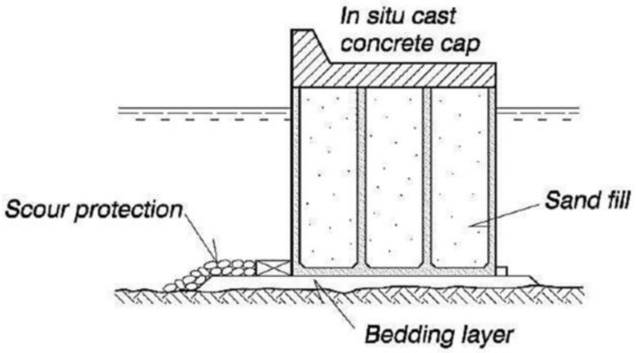


Figure 16: Cross-section of a typical concrete cassion breakwater [34].

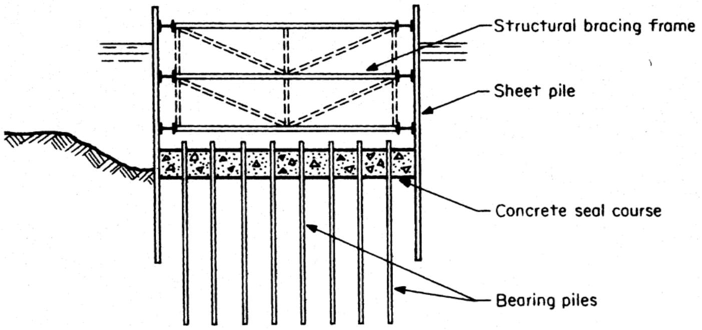


Figure 17: Cross-section of a typical steel cofferdams breakwater [35].

All the possible types of edge structures have exponentially higher construction costs as depth increases. This is the element that has the greatest impact on the increase in hydraulic-fill Land Reclamation costs per m^3 as the depth of the seabed increases. Edge protection costs are incorporated in the Total Costs/m^3 but are not estimated individually.

The final costs per m^2 of each project are then illustrated in figure 18. The graph shows the correlation between the cost per square meter of the 12 Maltese projects and the depth of the seabed of each project. The thesis utilizes then exponential regression to establish a cost function that correlates the cost per unit of surface area to the depth of the seabed for the 12 Maltese projects. This function is:

$$y = 1019,9e^{0,0662x} \tag{9}$$

The Total Cost of a land reclamation project via hydraulic-fill is then calculated as the surface of the land reclamation project multiplied by the $cost/m^2$

$$TotalCost : Surface \cdot Cost/m^2 \tag{10}$$

Nevertheless, these estimated costs serve as a close approximation due to the limited availability of reliable data in the scientific literature.

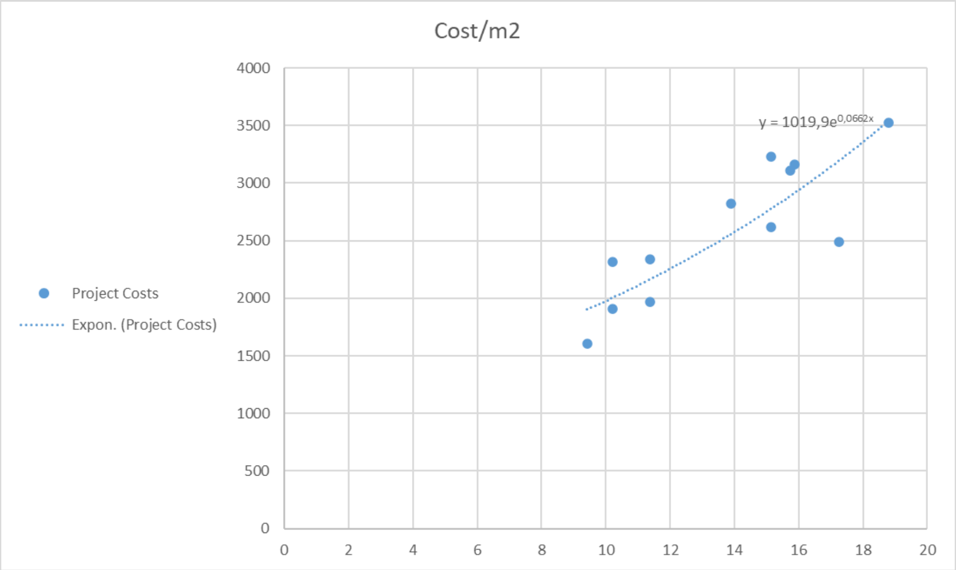


Figure 18: Hydraulic-fill land reclamation Total Cost/m^3 Regression.

5.1.3 In-Fill Costs

The assessment of in-fill land reclamation costs closely resembles the estimation of hydraulic-fill costs mentioned in paragraph 5.1.2. The primary distinction lies in the omission of the dredging step. Nevertheless, the expense of dredging is substituted by the cost of acquiring the in-fill material. Estimating the cost of the fill material, such as in the case of hydraulic-fill, is quite intricate since it is heavily influenced by the geographical location of the reclamation site.

The cost of obtaining the fill material primarily relies on the expenses associated with procuring the material and transporting it to the reclamation site. Both costs can vary significantly depending on the potential scarcity of the item in the specific geographical area and its distance from the reclamation site.

To maintain simplicity, the thesis assumes that both technologies have equal costs.

5.1.4 Cost Comparison

After the estimation of the costs for both SEA*form* Floating Platform and Hydraulic In-fill, the thesis work obtained three cost functions: two cost functions for Floating Platforms and one equation for Hydraulic In-fill:

- Floating Total Cost (equation 3)
- Floating+Breakwater Total Cost (equation 7)
- Hydraulic and In-fill Total Cost (equation 10)

It can be noticed that the Costs for floating platforms are a function of the surface of the land reclamation project alone, while the Costs for Hydraylic and In-fill are a function of the surface of the land reclamation project but also of the depth of the reclamation site.

In the figure below (Figure 19) the cost/m^2 functions per unit of depth are plotted.

It is crucial to emphasize that the costs of the floating platform does not begin at a depth of zero meters. This occurs due to the fact that the technology necessitates a minimal depth to operate. This depth is called draft. The cost curve for hydraulic and in-fill operations does not start at zero at zero meters of depth. This happens due to the presence of fixed costs associated with mobilization and demobilization, which are incurred even at low depths.

As expected, the costs for floating platforms are constant since they do not depend on depth while the costs of In-fill and Hydraulic-fill grow exponentially with depth.

The two intersection points between the Floating Costs and the hydraulic-fill and In-fill costs are the depth at which the hydraulic-fill and In-fill overrun the Cost of floating platforms. Table 3 shows the isocost depth.

	Depth
Floating without Breakwater	16
Floating with Breakwater	19

Table 3: Isocost Depth [m]

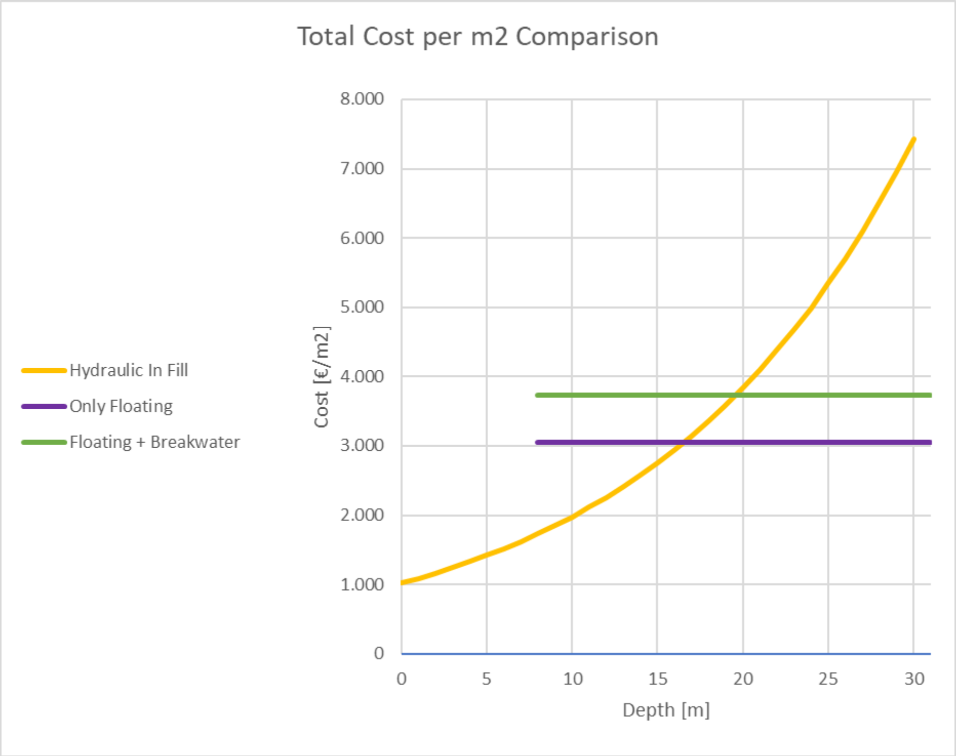


Figure 19: Total Cost/m^2 Comparison

5.2 Marine Environmental Impact

The assessment of marine environmental impact caused by floating SEA*form* platforms, in-fill, and hydraulic-fill originates from Letizia Pincetti's Master's Degree thesis in Environmental and Land Engineering Climate Change titled "Sustainable coastal development: a comparative analysis of environmental impacts between floating platforms and dredging" [23].

The cited thesis provides an overview of interactions between floating platforms, hydraulic-fill and in-fill land reclamation techniques, and the marine environment. It identifies and evaluates non-site-specific main stressors that can occur during the construction or operational phase of floating platforms and hydraulic-fill and in-fill, assigning a score based on their spatial extent and duration.

A stressor, usually referred to as pressure, is a factor that can lead to changes in the environment due to physical, chemical, or biological influences. It is vital to emphasize that a stressor does not inevitably have a negative influence on the environment [36]. Stressors are:

- **Turbidity:** is an optical characteristic of water that results in the scattering or absorption of light instead of its transmission [48]. Suspended sediments consist of both organic matter, such as algae and plankton, and inorganic particles, including sand, silt, and clay [69]. Turbidity-induced reduction in underwater light availability can result in diminished photosynthetic activity, leading to decreased quantities of dissolved oxygen in water. Furthermore, animals that depend on vision for their ability to determine direction, navigate their surroundings, and identify prey may be negatively affected by an extreme reduction in transparency [23].

- **Noise:** Sound is a form of vibration that travels through a flexible substance, like a gas, liquid, or solid. It happens when particles in the substance are stimulated by an external force, causing them to move back and forth from their original position. Marine organisms can be responsive to either the pressure or the movement of particles in water, depending on the mechanism of their receptors [23].

- **Physical destruction of habitat:** refers to the direct and often irreversible modification, harm, or extinction of a natural environment or ecosystem that serves as a habitat for creatures and is crucial for their survival. Habitat destruction has significant consequences, such as the reduction of biodiversity, disturbance of ecological equilibrium, and the risk of extinction for species that cannot adjust or locate adequate alternative habitats [23].

- **Hydro-morphological changes:** Hydro-morphological changes pertain to modifications in the physical configuration and shape of the seafloor. These changes entail alterations in the patterns of water movement, the movement of particles in the water, the shape of the channel, and the general characteristics of the landscape that are influenced by the movement of water. These modifications can have substantial effects on aquatic ecosystems, such as shifts in habitat configuration, sediment composition, and water quality and can even cause coastal erosion and alteration of coastal ecosystems. Gaining a comprehensive understanding of hydro-morphological changes is essential for efficiently managing water resources, conserving the environment, and minimizing any adverse impacts on ecosystems and their biodiversity [23].

- **Physical-chemical properties:** Alterations in the hydromorphological regime have the potential to influence the physical and chemical characteristics of the water body, hence impacting the quality of water, due to changes in water mixing rate and also modifying the open water surface, where exchanges between air and water occur. The most crucial qualities to monitor are *temperature*, *dissolved oxygen*, *salinity*, and *pH fluctuations* [23].
- **Collisions:** Vessel activity occurs during the whole building phase of dredged land and during the transportation phase of floating platforms. Additionally, the existence of the reclaimed land or platform is expected to result in a rise in vessel activity during the operational stage. The probability of a collision is influenced by various factors, including the kind and speed of the vessel, the behaviour of the species, and the amount of marine traffic [37].
- **Shading:** The presence of floating structures obstructs direct sunlight from penetrating the water column. Consequently, the photosynthetic activities may be diminished or even halted, both on the seabed and in the upper layers of the water column, affecting the benthic population, macrophytes, phytoplankton, and macroalgae [38].
- **Artificial lightning:** The nocturnal emission of artificial light might impact the natural light cycle of the surrounding environment [39]. This phenomenon is usually referred to as ”light pollution” [40], although in recent years the word has primarily been used to describe the deterioration of the visibility of the night sky. Longcore and Rich (2004) [40] provide a more precise definition of this phenomenon as ”artificial light pollution,” while the impact on the ecology is referred to as ”ecological light pollution.” The sources of ecological light pollution are many and encompass various factors such as sky glow (the reflection of light from the sky), illuminated buildings and towers, streetlights, fishing boats, security lights, car lights, flares on offshore oil platforms, and even lights on undersea research vessels [40].

The relevance of each stressor will be then determined by combining the spatial and temporal extent values. Finally, a list of potential receptors that may be impacted will be provided and their susceptibility to the identified stressors analyzed [23].

Once the primary impacts have been identified, it is imperative to assign a numerical score to each of them. Each impact has been assessed based on two specific attributes: spatial extent and duration. Other attributes that can be used to assess environmental impacts are magnitude and likelihood; however, these parameters are strongly influenced by the particular location, while spatial and temporal extent can be more easily assessed in a non-site-specific way. Hence, this thesis only emphasizes the spatial and temporal scope, aiming for a comparison that is not limited to specific locations. To guarantee the autonomy of the allocated indices from the particular place, percentages have been selected instead of absolute values [23].

The spatial extent refers to the area that is influenced by the impact and can take on the values [23]:

1. From 0 to 100% of the area that has been dredged, filled with new material or the area occupied by the floating platform;
2. From 100 to 200%The coverage extends from the entire reclaimed land or floating platform to twice its size, ranging from 100 to 200%;
3. From 200 to 1000%, it encompasses an area that ranges from 2 times to 10 times the size of the dredged land or the floating platform;
4. More than 1000%, the area covered is more than 10 times larger than the land that was dredged or the floating platform.

The duration refers to the period during which the impact occurs and can take on the following values [23]:

1. From 0-25% of each phase duration;
2. From 25-75% of each phase duration;
3. From 75-100% of each phase duration: the impact lasts up to the whole duration of the phase;
4. More than 100% of each phase duration: the impact duration extends beyond the phase duration, resulting in its persistence even after the phase has concluded.

The significance is determined by multiplying the duration by the spatial area, resulting in values ranging from 1 to 16.

The environmental impacts of Hydraulic-fill, In-fill and floating platforms are categorized based on the various project phases (see figure 20):

- **Construction:** Hydraulic-fill entails dredging, transporting, and placing material to create land. in-fill entails only transporting and placing material while floating platforms require transport and installation using mooring anchors and lines [23];
- **Operational phase:** During this phase, interactions take place between floating platforms or hydraulic-fill and in-fill efforts and the marine environment where they are situated. The interactions and their impacts can be categorized into those induced by the structure in the maritime environment and those coming from activities above the land or platform. The first class can be generalized to some extent, but the second class is very dependent on the objective of the land reclamation project, as a diverse range of activities might occur on the platforms or land. The full description of stressors will not include the impacts that activities can have on the marine environment [23];
- **Decommissioning:** in hydraulic-fill and in-fill, refers to the end of activities conducted on the land and their associated effects because the impacts from the land itself persist as the land cannot be removed. Floating platforms, instead, can be removed or relocated as necessary [23].

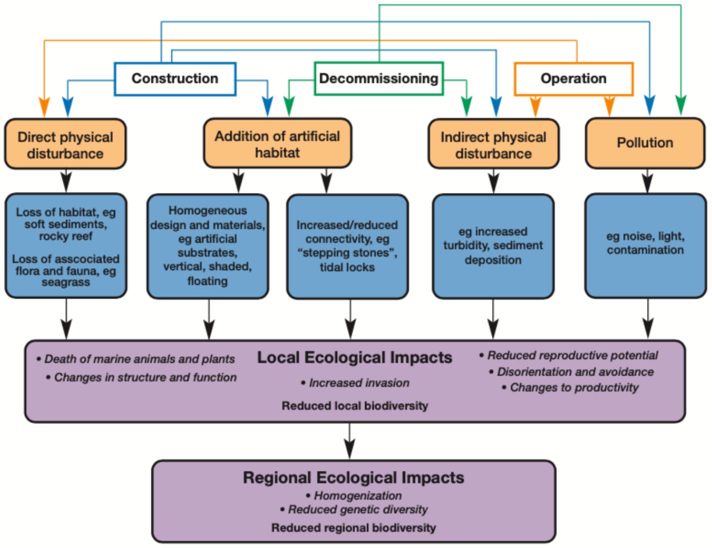


Figure 20: Engineering phases and their impacts. Habitat alteration (orange), physical/chemical modifications (blue), potential ecological impacts at local and regional scale (purple) [41].

5.2.1 Floating platforms marine environmental impact

Floating platforms are primarily constructed on land, with marine interaction limited to transportation and installation stages. Possible impacts of these operations include increased noise levels from ships transporting platforms and installing mooring anchors, which can affect animal physiology and behaviour depending on the level of increase. Additionally, water turbidity may occur due to the installation of mooring anchors, leading to temporary suspension of sediment and a decrease in water transparency. Furthermore, vessels used for transportation may directly collide with marine mega-fauna. Mega-fauna could also be entangled in mooring line [23].

Following its installation, the platform's interactions with the marine environment and the subsequent effects are:

- Reduced light exposure due to the platform blocking incident sunlight, leading to decreased photosynthesis in both the upper layers of water, where phytoplankton and tiny algae thrive and at the bottom [3], [42];

- Minor fluctuations in water temperature patterns (less than $0.5°C$) are influenced by the platform's obstruction of solar radiation, which warms the water, and its ability to absorb and release heat, resulting in a delayed temperature peak with minimal impact.

- Surface currents may slow down, leading to silt accumulation, or speed up, causing enhanced erosion [42];

- Reduced dissolved oxygen levels due to restricted water flow, colonization of sessile species on the shelf bottom absorbing oxygen, and diminished photosynthesis from shading, leading to decreased water quality [43];

- Discharge of hazardous compounds into the water from construction materials such concrete, plastics, wood, and steel components, which can significantly affect the ecosystem if heavy metals are released, even in small amounts [42];

- Establishing a new habitat beneath the platform for sessile organisms to occupy, hence enhancing biodiversity and offering refuge and food for many species [3]. Bivalves at the bottom of the platforms filter plankton and suspended particles in water by devouring or rejecting them, reducing suspended sediment while increasing sediment deposition on the bottom. Bivalve shells, both alive and dead, gather under the shelf, providing a surface for sessile species to grow on. This collection also enhances decomposition, leading to decreased oxygen levels near the bottom of the sea.

The table 4 displays the duration and spatial extent values identified by Letizia Pincetti's thesis after an intensive literature review. This thesis provides, instead, significance values, calculated by multiplying the two indexes.

Impact	**Spatial extent**	**Duration**	**Significance**
	Construction phase		
Turbidity and suspended sediments	2	3	6
Noise	3	3	8
Collision vessel-wildlife	1	3	3
	Operational phase		
Shading	2	3	6
Hydromorphological changes	2	3	6
Dissolved oxygen and temperature	2	3	6
pH	1	3	4
Artificial light	2	2	4

Table 4: Impact matrix of SEA*form* floating platforms [23].

5.2.2 Hydraulic-fill marine environmental impact

The process of creating new land through dredging occurs in multiple phases, each of which can exert a significant influence on the surrounding ecosystem. Undoubtedly, it is imperative to dig out the necessary material, hoist it up to the surface, transfer it to the designated location, and subsequently place it [44].

The main environmental impacts at these stages include:

- The rise in water turbidity and sedimentation leads to a decrease in water clarity, visibility, and light availability. This has significant effects on bottom-dwelling species, resulting in reduced rates of feeding and reproduction. In certain cases, these organisms may be buried or suffocated [45] [46] [47].
- The resuspension of sediment and the potential release of organic compounds can have both positive and negative effects on the benthic habitat. On one hand, it can be advantageous by improving the habitat. On the other hand, it can lead to eutrophication, reduced oxygen lev-

els due to increased oxygen demand, and overall degradation of water quality [46] [48];

- The possibility of releasing harmful substances if the suspended sediments are polluted, which might result in death and impact the food chain [46] [49].
- The loss or damage to the physical structure of the seafloor environment, including benthic animals, coral reefs, and seagrass beds, leads to a decrease in both the variety of species and the availability of adequate locations for shelter and breeding for many animal species. This has an impact on the interconnected food chain [49] [50];
- The noise generated by machinery used for digging and moving sediments may impact the behaviour of marine mammals and their reproductive abilities, as indicated by references [51] [45] [52];
- There is an elevated danger of collisions between marine megafauna and vessels used for sediment transportation, as mentioned in reference [37].

Upon completion of the construction phases, the primary interactions that the new landmass will have with its surrounding ecosystem are as follows:

- modifications in the hydromorphological regime, encompassing variations in currents, water circulation, wave motion, tides, and bathymetry [46]. These modifications have the potential to result in diminished water quality, coastal erosion, and alterations to habitat [53];
- alterations in the physical-chemical characteristics of water, including temperature, salinity, and pH [54] [55] [56].

Furthermore, it is crucial to take into account the effects on the surrounding ecosystem resulting from activities conducted on the developed property. This land has the potential to be used for more than just residential reasons. It may also be used for the construction of important infrastructure like ports, airports, and industrial zones. However, it is important to note that these developments can have a considerable influence on the environment. These activities commonly impact the marine ecosystem through variables such as noise, artificial light, substantial fluctuations in water temperature, and water pollution caused by inadequate management of household wastewater and the discharge of harmful substances from enterprises.

Impact	**Spatial extent**	**Duration**	**Significance**
	Construction phase		
Turbidity and suspended sediments	4	4	16
Noise	4	3	13
Physical destruction and entrainment	1	4	4
Dissolved oxygen	2	4	8
Collision vessel-wildlife	1	3	3
	Operational phase		
Hydromorphological changes	4	4	16
Physical-chemical water parameters (T, salinity, pH)	2	3	6
Artificial light	2	2	4

Table 5: Hydraulic-Fill Impact matrix [23].

5.2.3 in-fill marine environmental impact

The estimation of stressor values for in-fill is based on the values established by Letizia Pincetti for hydraulic-fill. While the values for the operating phase are equal, the values of the construction phase are slightly lower in spatial extent since the impact is confined solely to the reclamation area. The values presented in this thesis are derived and should be understood as approximate, rather than serving as the central objective estimate of the thesis.

Impact	Spatial extent	Duration	Significance
	Construction phase		
Turbidity and suspended sediments	3	4	12
Noise	3	3	9
Physical destruction and entrainment	1	4	4
Dissolved oxygen	2	4	8
Collision vessel-wildlife	1	3	3
	Operational phase		
Hydromorphological changes	4	4	16
Physical-chemical water parameters (T, salinity, pH)	2	3	6
Artificial light	2	2	4

Table 6: In-Fill Impact matrix.

5.2.4 Marine Environmental Impact Comparison

The stressors found and calculated by Letizia Pincetti are constructed to be non-site specific. In order to conduct a site-specific evaluation, it is necessary to apply the total stressors' significance of the three technologies to receptors, such as mobile animals, benthos, macroplants and plankton. This thesis suggests, as a first approximation, to categorize the maritime environment of the reclamation site into four distinct groups, with the first category being the critical one:

- **Extremely sensitive** marine environment (e.g. protected areas);
- **Highly sensitive** marine environment;
- **Moderately sensitive** marine environment;
- **Relatively sensitive** marine environment (e.g. port areas).

The weight of each category was determined by applying two distribution laws (See figure 21):

- Halving:

$$w(j) = \frac{1}{f_w(j)} \quad \forall j \in N \cap [1, n] \tag{11}$$

$$f_w(1) = 1 \tag{12}$$

$$f_w(j) = 2f_w(j-1) \quad \forall j \in N \cap [2, n] \tag{13}$$

- Quadratic:

$$w(j) = \frac{1}{f_w(j)} \quad \forall j \in N \cap [1, n] \tag{14}$$

$$f_w(j) = 2j^2 \quad \forall j \in N \cap [2, n] \tag{15}$$

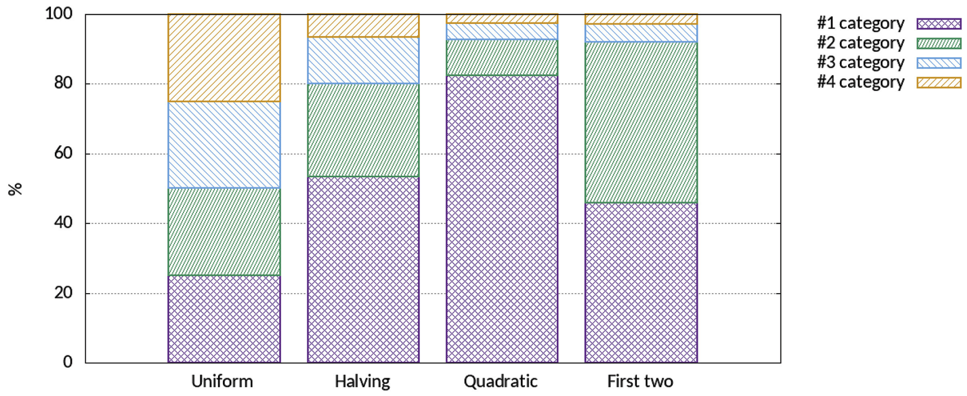


Figure 21: Distribution of weights on a percentage basis for the pre-defined laws of the proposed MCDA methodology. Example with four categories used as criteria [57].

The figures 22 and 23 provide evidence that, both in halving and in quadratic distribution, as the sensitivity of the marine environment of the reclamation site rises, the use of floating platforms becomes increasingly advantageous.

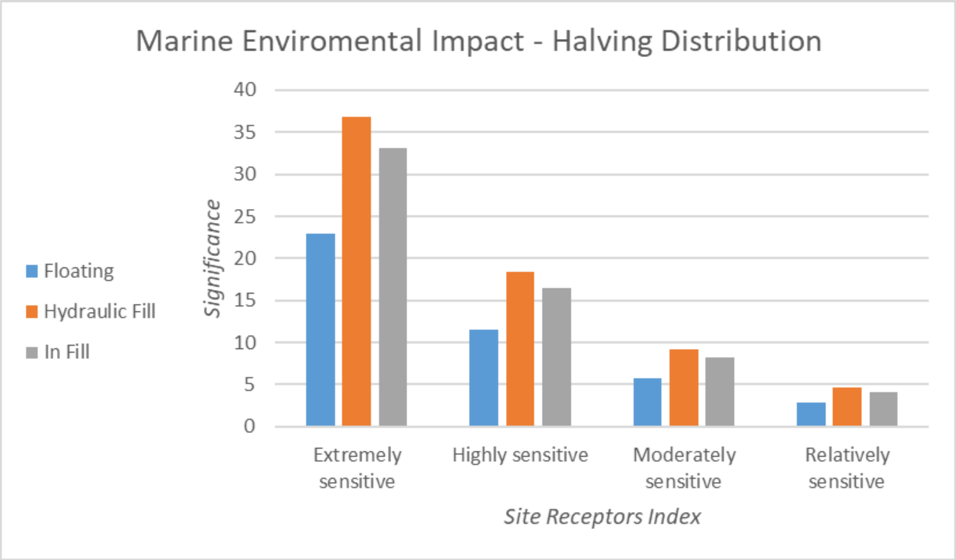


Figure 22: Marine Enviromental Impact - Halving Distribution.

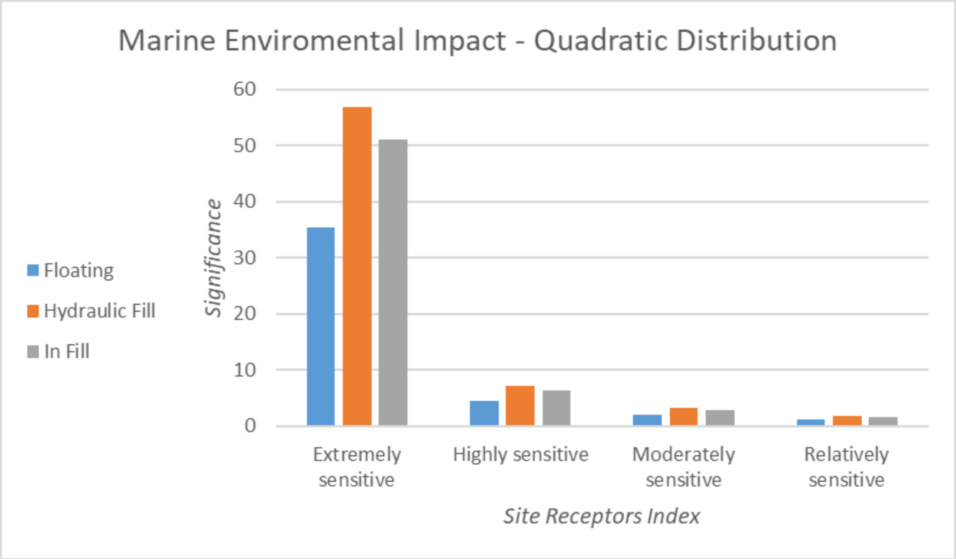


Figure 23: Marine Enviromental Impact - Quadratic Distribution.

6 Conclusions

An examination of the floating platform technologies created by SEA*form* and the hydraulic-fill and in-fill technologies led to a comparison of key performance indicators (KPIs) that assess the economic aspects and effects on the maritime environment.

Regarding costs, as shown in figure 19, the costs per square meter of hydraulic and in-fill materials, while initially lower at shallow seabed depths, significantly rise as the bathymetry increases. The cost of floating platforms, however, remains unchanged, disregarding little fluctuations that this thesis deems inconsequential.

As indicated by the table 3, in fact, the intersection points correspond to depth values at which floating platforms become more economically advantageous.

Instead, the examination of the marine impact revealed that while floating platforms have a lesser impact overall, the specific impact on the marine environment varies significantly depending on the location of the reclamation site. Hydraulic-fill and in-fill technologies have a significantly greater influence on sites with more fragile environmental circumstances compared to floating platform technology.

The thesis defers the task of providing a more precise estimation of prices and analyzing the carbon impact of various technologies on future developments.

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