Quantifying Sustainability of Coastal Engineering Solutions

Development of an Assessment Framework to Quantify Sustainable Aspects of Coastal Engineering Solutions

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TU Delft

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by

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TU Delft

Preface

This thesis represents the culmination of my academic journey in pursuit of a Master's degree in coastal and environmental engineering—a journey that has been both challenging and rewarding. It is with great gratitude and appreciation that I reflect on the support and guidance I have received along the way.

First and foremost, I extend my heartfelt thanks to my esteemed supervisors, José Antonio Álvarez Antolínez, Erik Mostert, Jeroen van den Bos, and Irena Doets. Their invaluable guidance, unwavering support, and profound expertise have been instrumental in shaping my research. Their insights have not only enhanced the quality of my work but have also significantly contributed to my academic and professional growth. I am deeply grateful for their encouragement and the time they invested in mentoring me through this process.

I would also like to express my deepest gratitude to my dear family. Their unwavering love, constant encouragement, and steadfast belief in me have been the bedrock of my strength. They have been my pillars of support, providing me with the motivation to persevere through the challenges and obstacles that accompanied this academic endeavour. Their faith in my abilities has been a source of immense inspiration and has played a crucial role in the successful completion of this thesis.

I would like to acknowledge the contributions of Kees Koejemans and many other individuals who have supported me. I extend my sincere thanks to everyone involved. This thesis is a testament to the collective efforts, patience, and dedication of all those who have contributed.

Finally, I dedicate this thesis to all those who strive for knowledge and understanding, and to those who support them in their pursuit.

Mazen Al-Qadi
Delft, June 2024

Abstract

This thesis reviewed current methods for monetarily quantifying the sustainable aspects of coastal engineering solutions. It developed a holistic monetary valuation framework that integrates the Ecosystem Services Assessment (ESA) and Life Cycle Assessment (LCA) to evaluate the impacts and benefits of coastal engineering interventions. The framework offers a comprehensive approach to assessing the economic, social, and environmental impacts and benefits of coastal solutions, thereby enabling informed decision-making.

Applying the framework to a case study in the Netherlands demonstrated its effectiveness in providing valuable insights into the sustainability of coastal protection measures. The sensitivity analysis underscored the importance of accurately valuing ecosystem services and environmental impacts, as well as the influence of economic parameters, materials, and modes of operation on project viability. Additionally, the framework's potential for broader application was illustrated through a feasibility study in Suriname.

The study's findings highlight the need for improved data collection, stakeholder engagement, methodological refinements, and consideration of policy environments to enhance the framework's applicability and effectiveness. Future research should address these areas to further improve the informed decision-making process regarding the sustainability of coastal engineering alternatives.

Summary

The thesis by Mazen Al-Qadi, conducted at Delft University of Technology's Faculty of Civil Engineering and Boskalis - a leading dredging and marine contractor, aims to create a monetary valuation framework for coastal engineering solutions that account for their sustainable aspects. This is done by integrating the well-known Ecosystem Services Assessment (ESA) and Life Cycle Assessment (LCA) methodologies to evaluate these interventions' economic, social, and environmental impacts and benefits. The primary objective is facilitating informed decision-making in coastal engineering by providing a robust tool for assessing sustainability.

The literature review - chapter 2 - of the thesis identifies existing methodologies for monetizing ecosystem services (ES) and life cycle impacts (LCA) relevant to coastal engineering and highlights gaps in current research. The review employs both systematic and narrative analysis methods, with a systematic literature review (SLR) following the Reporting Standards for Systematic Evidence Syntheses (ROSES) framework to identify peer-reviewed articles on the monetary valuation of coastal ecosystem services (CES). The review reveals that ES are categorized into provisioning, regulating, and cultural services and uses the Total Economic Value (TEV) framework to assess these services comprehensively. Various methods to assess and monetize the environmental impacts of construction projects are also reviewed, highlighting the need for standardized approaches. Existing frameworks that integrate ES and LCA are explored, revealing a gap in comprehensive valuation methods for coastal engineering projects.

Building on insights from the literature review, chapter 3 develops a framework that integrates ESA and LCA for comprehensive or quick economic valuation of coastal engineering interventions. This framework incorporates data collection, scoping, impact assessment, and monetization and is designed to evaluate the full range of economic, social, and environmental impacts and benefits. The framework provides a structured approach to quantify and monetize the impacts and benefits of coastal engineering solutions, facilitating a holistic assessment that can be used by contractors, their clients, and policymakers to make informed decisions.

To validate the developed framework, the thesis applies it to a hypothetical case study in the Netherlands, comparing two coastal solution alternatives: sea dike and sand nourishment, Chapter 4. This chapter details the steps of Life Cycle Assessment (LCA) and Ecosystem Services Assessment (ESA), followed by a comprehensive financial analysis. The LCA identifies and monetizes significant environmental impacts, providing a clear picture of the project's environmental footprint. The ESA quantifies and monetizes the benefits provided by ecosystem services. Financial analysis—including Net Present Value (NPV) and Return on Investment (ROI) analysis—demonstrates the project's overall economic feasibility. For the hypothetical numbers used in the case study, the analysis revealed that, although sand nourishment incurs higher maintenance and environmental impact costs compared to the sea dike, its enhanced ecosystem services value can lead to a more favourable economic outcome under certain conditions. Moreover, the sensitivity analysis underscored the critical role of accurately valuing ecosystem services and environmental impacts in determining project viability, indicating that small changes in these values could significantly alter the preferred alternative.

The thesis evaluates the feasibility of the framework in an international setting by using Suriname as a case study. In chapter 5, the framework is adapted to the local context of Suriname, focusing on data collection, LCA, ESA, and financial analysis. The results demonstrate that the framework can be customized to different geographical and socio-economic situations. However, for better quality results, it is essential to have access to local data, involve stakeholders, and consider policy environments when defining and selecting LCA and ESA values.

The discussion chapter - Chapter 6 - interprets and analyzes the findings from the literature review and case studies, evaluating the strengths and weaknesses of the framework. The critical analysis reveals that the comprehensive approach of the framework provides valuable insights into some sustainability aspects of coastal engineering solutions. However, it also identifies areas needing improvement, such as data collection and methodological refinements. The potential for international application is demonstrated, but the need for local adaptation is underscored.

In conclusion, the thesis combines the research findings and provides recommendations based on the identified gaps and limitations, Chapter 7. The developed framework serves as a strong tool for assessing the sustainability of coastal engineering solutions. Future research should concentrate on enhancing data collection methods, refining valuation techniques, and improving stakeholder engagement. It is recommended to conduct additional case studies to validate the framework's applicability and effectiveness across different contexts.

Overall, this thesis presents a novel framework that integrates Ecosystem Services Assessment and Life Cycle Assessment to value coastal engineering projects comprehensively. Applying the framework to a case study demonstrated its potential for enhancing informed decision-making in coastal engineering, promoting sustainable development, and balancing economic, social, and environmental considerations.

Contents

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Nomenclature

Abbreviations

Abbreviation	Definition
BwN	Building with Nature
CBA	Cost-Benefit Analysis
CES	Coastal Ecosystem Services
ECI	Environmental Cost Indicator
ESA	Ecosystem Services Assessment
ES	Ecosystem Services
ESVD	Ecosystem Services Valuation Database
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEAT	Most Economically Advantageous Tender
MKI	MilieuKostenIndicator
MVCs	Monetary Valuation Coefficients
NBS	Natural-Based Solutions
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
ROI	Return on Investment
ROSES	Reporting Standards for Systematic Evidence Syntheses
SD	Sustainable Development
SDC	Sustainable Development Goals
SLR	Systematic Literature Review
TEV	Total Economic Value
UNEP	United Nations Development Programe
WB	World Bank

1 Introduction

1.1. Backgrounds

Coastal zones, with their thriving communities, diverse ecosystems, and economic significance [1, 2], face increasing challenges due to population growth and the impact of both natural and anthropogenic climate change [3, 4, 5, 6, 7]. With over 30% of the global population residing in these areas, they serve as vital hubs for human activity and development [1, 5]. This underscores the need for sustainable development in coastal zones, aligning with the Sustainable Development Goals (SDGs), especially SDG13.1' Climate Adaptation' which aims to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries, SDG14' Life Below Water', which aims to protect and sustainably manage coastal (14.1) and marine ecosystems (14.2) and their resources (14.5) [8]. Coastal engineers, their employers like Boskalis', and their clients are inherently driven to improve the sustainable aspects of coastal solutions. Nevertheless, to understand and evaluate various coastal engineering solutions on their sustainable aspects, it is necessary to quantify both the impacts and benefits across sustainability's economic, social, and environmental pillars.

This thesis aims to develop a framework that evaluates the economic value of the social and environmental impacts and benefits of coastal solutions. This will be done by monetizing the impacts and benefits and utilizing the well-established frameworks of Life Cycle Assessment (LCA) and Ecosystem Services Assessment (ESA). The following sections will present the thesis's rationale, problem statement, objective, and research questions. It concludes with an outline of the thesis report structure.

1.2. Motivation

1.2.1. Enhancing Sustainability

Sustainability is defined as meeting the present needs without jeopardising the ability of future generations to fulfil their own needs [9]. The 2030 Agenda for Sustainable Development (SD) links sustainable development to sustainability in the economic, social, and environmental dimensions [8], while recent studies also include political [10] and cultural dimensions [11]. However, in practice, economic sustainability has typically taken precedence over environmental sustainability, resulting in the neglect of social sustainability issues and a significant gap in discussions surrounding sustainability [11]. In addition, the 2030 Agenda for SD does not provide explicit guidance on balancing the different sustainability dimensions when trade-offs or conflicts arise [12].

In its international good practice principles for sustainable infrastructures report, UNEP [13] advocates for a comprehensive evaluation of infrastructure sustainability throughout its life cycle, taking into account the cumulative effects on ecosystems and communities over the lifetime of projects. It also emphasises the importance of avoiding environmental impacts by selecting infrastructure that provides primary cost-effective services, delivers co-benefits for both people and the planet, and demonstrates higher resource efficiency and circularity [13].

Globally, there is an increasing trend towards enhancing sustainability in infrastructure projects by making it an important award criterion in tender procurement. The World Bank (WB), as of September 1st, 2023, started using a rated criteria method in their global procurement activities. Rated criteria are combined with price and life cycle cost formulas to provide a more accurate evaluation of worth, emphasising the quality and sustainability of suggested proposals. This rated criteria method is also popular in public procurement processes across Western Europe, North America, Japan, Singapore, Australasia, and other members of the Organization for Economic Co-operation and Development (OECD) [14]. Moreover, many countries collaborating with the WB have integrated rated criteria into their procurement regulations, and other nations are currently updating their procurement laws to include this feature [14].

In the European Union, 62% of public procurements use rated criteria. Some member states, such as France, use these criteria even more extensively, with up to 90% coverage. This has been the policy since 2014, under the Most Economically Advantageous Tender (MEAT) program [15, 14]. In the Netherlands, the Environmental Cost Indicator, MilieuKostenIndicator (MKI), is used to value the environmental impacts of projects throughout their lifetime, but its use is limited to this purpose. [16]

1.2.2. Promoting Nature Based Solutions

In coastal engineering, the coastal protection function can be achieved by various alternatives, from traditional solution (grey) sea dikes to more nature-based solutions (NBS) (green), such as sand nourishment. The choice between traditional and NBS involves a complex consideration of ecosystem services, capital, operational, and environmental costs. Traditionally, grey engineering solutions have been favoured due to their lower initial costs and reduced maintenance requirements compared to NBS alternatives. However, a comprehensive financial analysis incorporating the monetary valuation of ecosystem services (ES) could reveal a different perspective. When the significant ES offered by NBS, such as enhanced biodiversity, improved recreational opportunities, increased tourism, and increased carbon sequestration, are accounted for, the financial attractiveness of these solutions becomes evident [17, 18]. Despite their higher initial costs and increased maintenance, including ES in the financial evaluation may render NBS more economically advantageous than conventional grey engineering solutions.

Valuation of ecosystem services helps make the contributions of the alternative solutions more visible and thereby generates a better understanding of how we assess, negotiate, measure, and use tradeoffs [19]. A more profound comprehension of the ES associated with flood protection and the methods to quantify them has the potential to attract extra funding for flood protection infrastructure [3].

1.2.3. Promoting Informed Decision Making

Incorporating environmental and social impacts into the financial analysis of infrastructure projects is crucial. This approach offers a comprehensive understanding of the project's environmental costs and benefits, reducing the risk of shifting environmental burdens and enhancing the identification of trade-offs and synergies [20, 21]. Environmental and social considerations serve as a shared communication tool, allowing for comprehensive decision-making in various fields, including trade-offs, land-use planning, coordinated management, investments, and the provision of public goods and services [22, 23, 24, 25, 26].

Seyedabdolhossein Mehvar, et al. [27] emphasised the significance of quantifying ecosystem services and environmental impacts to support informed decision-making by policymakers and stakeholders. Valuing the change in coastal ecosystem services through monetary assessment often captures the decision-maker's attention [27]. When considering coastal solution alternatives, changes in existing conditions create trade-offs among ecosystem services. Quantitatively evaluating these trade-offs is essential for making informed decisions. By assessing the costs and benefits of various coastal protection alternatives and their associated ES, it becomes possible to determine the alternatives that will yield the most significant benefits [23].

1.2.4. Monetary Valuation of Social and Environmental Impacts and Benefits

Monetisation allows a company to comprehend, compare, and contrast the magnitude of different solutions and their externalities using a standardised metric [17, 28]. Translating the ES in monetary terms highlights social, ecology and economy links. Moreover, valuing the environmental impact of different alternatives would give insight into which alternative is environmentally attractive in terms of the total environmental cost, reduced raw material use, and better circularity.

1.3. Problem Statement

To promote more sustainable coastal engineering solutions, measuring and assessing the value they bring to the economy, society, and the environment is essential. In international tenders, contractors frequently propose solutions, such as Building with Nature (BwN) approaches, that offer greater value to biodiversity but may be less cost-effective. The challenge lies in quantifying these benefits, often resulting in more sustainable solutions remaining unrealised. Traditional economic analyses of flood protection investments tend to focus solely on primary benefits, such as mitigated damages, while overlooking secondary effects, like increased tourism, enhanced property values, or improvements in well-being [3].

A. Krzemień, et al. [23] emphasised the significant challenges in measuring sustainability, noting that different weighting and aggregation methods have distinct advantages, limitations, and practical applications. Additionally, establishing a unified method for measuring the sustainable aspects of coastal activities remains challenging due to variations in proposed methods, standards, indicators, and criteria [10].

Despite numerous attempts to evaluate projects' social and environmental impacts, a universally accepted tool or standard has yet to emerge [29]. Studies aiming to integrate ES and LCA frameworks tend to exclude coastal ecosystems due to a mismatch between the Ecosystem Services Valuation Database (ESVD)[1] and LCA applications [32]. The ability to accurately assess the numerous impacts, externalities, and interconnections between nature and economic activity is inadequate. It is crucial to prioritise measuring what matters and integrate this knowledge into decision-making processes [33].

In the LCA framework, monetary valuation occurs in the Life Cycle Impact Assessment (LCIA) phase, combining environmental impacts expressed in different units, making them not directly comparable [34]. In addition, traditional LCA does not fully account for the advantages of ES [35]. A. Krzemień, et al. [23] reported that environmental impacts are typically evaluated using indicators with different units and implications, so comparisons among various benefits are challenging. A common methodology to assess the sustainability of coastal solutions that can be used both by contractors and their clients would, therefore, be beneficial.

The knowledge gap in measuring the sustainable aspects of coastal solutions can be stated as follows:

1. Ecosystem services (ES) in coastal engineering interventions and their monetisation are overlooked and limited. Studies available are about the ES related to coastal protection using natural coastal protection such as mangroves or coral reefs. A comprehensive framework for conducting a holistic evaluation of coastal ecosystem services and their overall condition is lacking. Practical applications of natural capital and ecosystem services concepts are hindered by inconsistent approaches in modelling, assessing, and valuing ecosystem services, along with limiting factors such as the expense of applying sophisticated methods and the absence of appropriate institutional frameworks.

2. Monetizing life cycle assessments (LCAs) is challenging due to the absence of uniformity in the current LCA monetization methods. Further research is required to establish monetary valuation coefficients suitable for specific environmental impact categories. There is no standardized way

[1]"ESVD is the largest open-access database of standardised monetary values for all ecosystem services worldwide. It provides a comprehensive insight into the value of nature beyond current GDP scopes, based on over 30 years of extensive research by leading academics and official reports on the monetary valuation of ecosystem services [30, 31]."

of utilizing monetary valuation techniques on an international level.

3. There is a lack of a comprehensive framework that integrates both the monetisation of ecosystem services (beyond provisioning services[2]) and the life cycle assessment of international coastal engineering interventions. Additionally, no comprehensive study has attempted to monetarily value ecosystem services and environmental impacts and incorporate them into the project's cost-benefit analysis.

Therefore, despite the growing recognition of the importance of valuing ecosystem services, a significant research gap exists within the context of coastal engineering projects. The literature lacks a transparent and standardised framework for valuing ecosystem services specific to coastal engineering projects. Additionally, there is a dearth of valuation methods tailored to these projects' unique characteristics and requirements. This research gap hinders decision-makers ability to comprehensively evaluate the impacts and benefits of coastal engineering projects on sustainable aspects.

1.4. Objective, Research Questions and Methodology

The main objective of this master thesis is to develop and test a holistic monetary valuation framework that can be used to measure and compare the benefits and impacts of different coastal solutions, using the concept of ecosystem services, life cycle impact assessment and cost-benefit analysis. This objective gives rise to the main research question of this study:

How can coastal interventions' impacts and benefits (economic, social, and environmental) be monetarily evaluated?

A literature review is conducted to identify which methodologies exist and would be most beneficial in valuing and quantifying the economic, social, and environmental impacts and benefits of international coastal engineering projects. Therefore, the literature covers the monetisation of the project's environmental impacts (LCA) and benefits (ESA). It explores integrating ecosystem services and life cycle assessment to improve sustainability accounting. This gives rise to the first supporting question:

How can we integrate Ecosystem Services (ES) and Life Cycle Assessment (LCA) to enhance the economic valuation of coastal interventions?

As there is no comprehensive framework for monetizing both LCA and ES of coastal engineering projects that can be used internationally, a new framework is developed to provide a comprehensive economic valuation of the projects beyond capital and operational cost. The availability of such a framework will allow contractors and their clients to recognize opportunities and trade-offs of the proposed hydraulic engineering solution, leading to more informed decisions.

The developed framework is applied to a case study in the Netherlands, where hard and soft coastal protection measures are proposed. The feasibility of using the framework globally is also outlined by highlighting the steps to be taken if the case study is in a different country, where Suriname is an example. Validation through a case study will answer the following supporting question:

How to perform a quick economic valuation of coastal interventions?

By addressing this research objective, this thesis will provide insights into the interplay between coastal engineering solutions, their environmental impacts, ecosystem services, and valuation. The developed framework will facilitate informed decision-making, ensuring the inclusion and quantification of the benefits and impacts associated with coastal engineering projects.

[2] Ecosystem services are classified into provisioning, regulating and culture services. Provisioning services could include food, wood, water supply, sand and gravel, salt and minerals, and fisheries, to name a few. Ecosystem services are covered in more detail in section 2.3.3

1.5. Report Structure

The thesis report is structured into seven chapters: Introduction, Literature Review, Monetary Valuation Framework, Framework Application: Case study - Hondsbossche Pettemer Sea Defence, Feasibility of Applying the Framework Internationally: Case Study Suriname, Discussion, and Conclusion & Recommendations. This is visualized in Figure 1.1

Chapter 1 initiates the discussion with an introduction, presenting the motivation, problem statement, and thesis objective, which has already been presented. Chapter 2, the Literature Review, delves into pertinent literature, spotlighting the existing knowledge gap. It examines the research on monetising Ecosystem Services (ES) and Life Cycle Assessment (LCA), specifically focusing on coastal engineering solutions. The chapter also critically reviews existing frameworks that integrate ES and LCA.

Chapter 3 builds upon the insights gleaned from the second chapter, leading to the development of the ES-LCA monetary valuation framework. Chapter 4 applies this proposed framework to a practical case study in the Netherlands. Chapter 5 tests the feasibility of applying the framework in an international context, highlighting how its core components would be applied to a project in a different country, Suriname, as an example.

Chapter 6 delves into the literature and case study's results, interpreting and discussing the findings. Chapter 7 answers the thesis questions driving this study and rounds off the thesis with recommendations for potential framework enhancements.

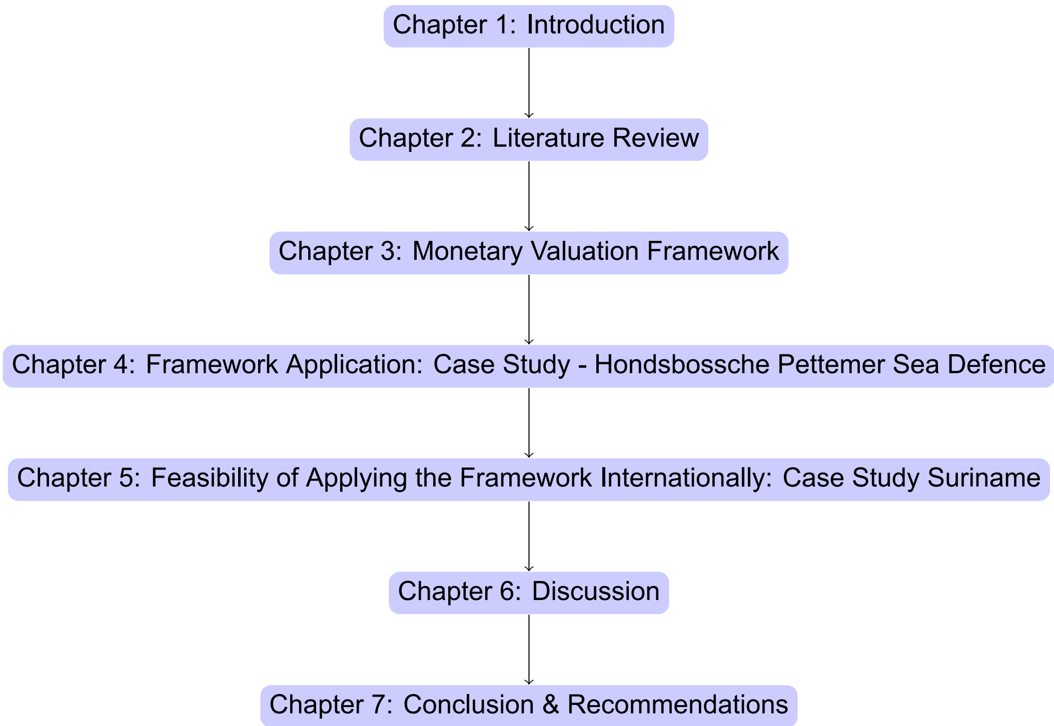

Figure 1.1: Report structure

2
Literature Review

2.1. Introduction

The literature review is divided into five sections. The first section explains the methodology used for the literature review to ensure a comprehensive analysis. The second section is focused on ecosystem services (ES) and their monetary valuation. It identifies relevant coastal ecosystem services (CES) and determines the most appropriate monetary valuation methods. The third section investigates construction work's life cycle assessment (LCA) and its monetisation. It examines the various methods used to assess and monetise the impact of a construction project throughout its life cycle, highlighting the challenges and applications related to LCA monetisation. The fourth section elaborates on existing frameworks integrating ES and LCA and their limitations. It provides insights into how these two approaches can be combined to yield a more comprehensive understanding of the value of coastal engineering interventions. Lastly, the chapter concludes with a summary highlighting the gaps in the literature.

2.2. Methodology

In conducting this literature review, both systematic and narrative analysis methods were used. The purpose of the systematic literature review (SLR) was to provide a comprehensive overview of the monetary valuation methods of ES that were applied to coastal ecosystems in general and those related to coastal engineering projects in particular. The narrative review provided information beyond the scope of the SLR, such as LCA monetisation, non-academic sources, and existing valuation frameworks.

2.2.1. Systematic Literature Review (SLR)

This section describes the systematic literature review (SLR) method that aims to identify all the methods used to value coastal ecosystem services (CES) worldwide monetarily. The study also aimed to identify gaps in knowledge regarding the valuation of ES associated with coastal engineering interventions. The research followed the Reporting Standards for Systematic Evidence Syntheses (ROSES) framework [36]. This framework provided a standardised approach to searching, screening, and critically appraising literature and synthesising relevant information within a specific context [36].

The SLR identified the monetary valuation methods used for CES and the geographic regions where they have been applied. The SLR concluded that despite the availability of numerous ES valuation methods, they have not been utilised to value the benefits generated from coastal engineering interventions.

Search Strategy

In order to gather all relevant peer-reviewed journal articles about the monetisation of CES concerning coastal engineering interventions until August 19, 2023, a search strategy was developed. This strategy consisted of three search strings containing keywords about monetisation methods, CES, and coastal engineering interventions without geographical limitations. A Boolean search strategy was employed in

Scopus, using the combined keywords in the title, abstract, or keywords section. This search strategy is detailed in Appendix A.1. The search yielded 2167 publications, which were exported for screening and analysis.

Screening Strategy

The 2167 articles were screened by title, abstract, and article text analysis, according to set eligibility criteria explained in Appendix A.2.

SLR Finding

The SLR identified the monetary valuation methods used for CES and the geographic regions where they have been applied. The SLR concluded that despite the availability of numerous ES valuation methods, they have not been utilised to value the benefits generated from coastal engineering interventions.

The SLR revealed that studies related to mangroves, wetlands, coral reefs, and coastal ecosystems tend to consider ES monetisation. However, the same does not apply to coastal engineering interventions. Out of the 2167 articles reviewed, only two discussed the inclusion of CES monetisation in the economic analysis of coastal engineering interventions. Even then, the discussion was minimal and focused only on monetary valuation methods.

The monetary valuation of ecosystem services related to the coastal biome is better covered in the non-academic domain. Therefore, a narrative literature search was conducted. Besides the screened SLR articles, this search included reports from various international institutions such as the World Bank, the United Nation's System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA-EA), the World Association for Waterborne Transport Infrastructure (PIANC), the International Association of Dredging Companies (IADC), The Economics of Ecosystems and Biodiversity (TEEB), the World Research Institute (WSI), and the International Institute for Sustainable Development (IISD).

2.3. Coastal Ecosystem Services Monetization

2.3.1. Introduction: Ecosystem Services (ES)

Ecosystem services (ES) refer to the benefits humans receive from nature [25, 37]. There are three categories of ecosystem services: provisioning services (such as food and wood), regulating services (such as air quality and water quality regulation), and cultural services (such as recreation opportunities and cultural heritage). Additionally, biodiversity and supporting services are an underlying group of ecosystem functions (such as nutrient cycling and primary production) that are crucial for delivering the other three categories of services [25]. The ES framework serves as a bridge between ecosystems and human well-being in the sociocultural context. This framework explains how humans depend on ecosystems and how ecosystem services relate to human well-being. Figure 2.1 illustrates the connections between different categories of ecosystem services, aspects of human well-being that are often observed, and the degree to which socioeconomic factors can potentially influence these connections. The strength of these connections and the potential for influence vary across different ecosystems and regions [25].

The concept of ES has gained significant prominence in academia, business and policy sectors for analysis and decision-making purposes [20, 38, 23, 24]. It plays a crucial role in addressing the limitations of traditional economic analysis by providing a comprehensive framework to understand and quantify the benefits that ecosystems provide to society [25, 26]. Traditional neoclassical economics failed to account for the full value of ecosystems, resulting in environmental exploitation and biodiversity loss [26]. The concept of ES bridges this gap by establishing a connection between the benefits and values we receive from nature and the condition of nature itself by linking socioeconomic systems and ecosystems through the flow of ecosystem services [22, 23].

By recognising and quantifying the various ecosystem services, the ES approach enables a more holistic understanding of ecosystems' direct and indirect contributions to human well-being [26]. This understanding is crucial for informed decision-making, policy development, and land-use planning, as it allows for considering the trade-offs involved in resource management and integrating environmental concerns into economic strategies [23, 24, 25, 26]. It helps to examine humans' impacts on ecosystems and the feedback effects these changes have on the ecosystem benefits to humans [20].

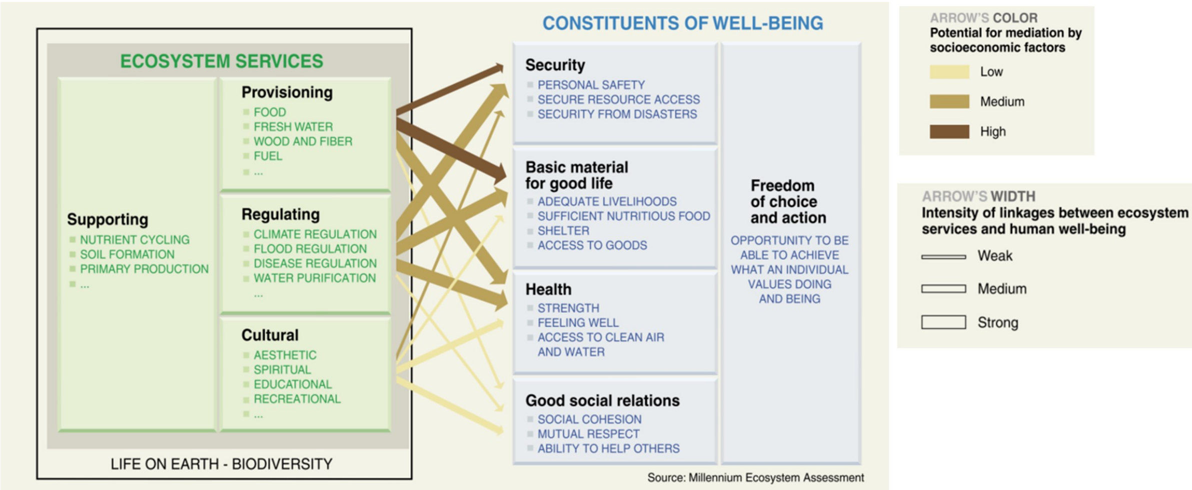

Figure 2.1: Linkage between ES and human well-being. Source: [25]

2.3.2. Total Economic Value (TEV) Framework

The TEV consists of various types of use and non-use values (Figure 2.2). Use value involves some interaction with the resource, either directly, indirectly, or optionally. Non-use value is derived simply from the knowledge that natural resources and aspects of the natural environment are maintained, such as existence, bequest, and altruistic values. Non-use values are not associated with any personal use of a resource and are held by people for unselfish reasons [39, 40].

The sum of use and non-use values is the total economic value (TEV), which refers to the value of a particular ecosystem service over the entire area covered by an ecosystem during a defined period [27]. Figure 2.2 presents the TEV concept and the value types with an example of possible ES.

According to Seyedabdolhossein Mehvar, et al. [27], direct use values pertain to ecosystem services that directly contribute to human well-being and can be utilised tangibly, such as food production or timber extraction. On the other hand, indirect use values encompass services that offer benefits beyond the immediate ecosystem. These services are derived from activities that support and protect the ecosystem but may not have direct, measurable values [27]. Such services include coastal protection, erosion control, or nutrient cycling. Cultural services can be classified under different typologies of ecosystem services. For example, recreational and tourism services offer non-consumptive values such as enjoying recreational and cultural amenities like wildlife observation, bird watching, and water sports. Recreational services can also be considered as a direct use value in the context of this analysis. Non-use or passive-use values represent the value of ES that persist even when they are not actively utilised. These include existence and bequest values, which involve the public's recognition of the existence of ecosystem services that will endure for future generations to appreciate [27].

2.3.3. Coastal Ecosystem Services (CES)

Coastal communities are home to over 30% of the global population, and out of 33 major cities worldwide, 21 are situated on the coast [1, 5]. The economies and resilience of coastal communities highly depend on the coastal ecosystem and its services [27]. Coastal ecosystems provide economic, cultural and ecological benefits, as well as other valuable services that include food, fibre, firewood, access to recreation, habitat/shoreline protection, water filtration, and act as important components of nutrient, carbon, water, and oxygen cycles [42]. They also contribute to economic prosperity through port trading and tourism [2]. CES of natural habitats such as mangroves, seagrass, coral reefs, salt marshes, beaches, and dunes have been extensively researched [43, 44, 45, 46, 47, 39, 48, 49, 27, 50, 51].

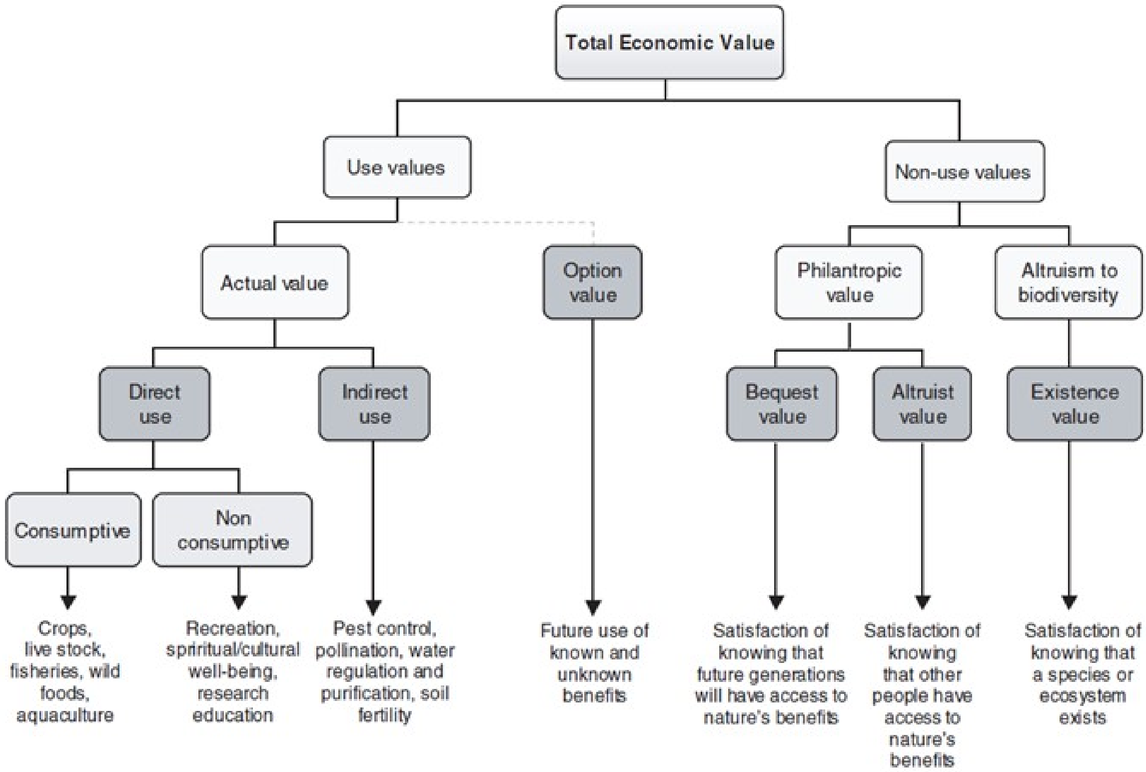

Figure 2.2: Total economic value concept. [41]

Figure 2.3 shows the result of the systematic literature review – Appendix A - showing which coastal ecosystems their ES has been explored in the literature.

The CES includes raw material and food, coastal protection, erosion control, water purification, maintenance of fishes, maintenance of wildlife, carbon sequestration, nutrient cycling, tourism, recreation, education, and research (Table 2.1) [43, 52, 53]. The systematic literature review also showed the countries where CES had been previously explored in the academic literature, Figure 2.4. Table 2.1 classifies CES into the four ecosystem categories and provides an example of their relevance to coastal engineering interventions. These CES are also classified according to the TEV concept based on their use value, Figure 2.5.

ES need to be valued for inclusion in a project's economic valuation. According to TEEB [33], we cannot sustain what we do not measure. Next, the monetary valuation of CES is discussed.

2.3.4. CES Monetary Valuation

Project costs and benefits fluctuate over space and time due to the physical and biological processes of the different services and the spatial distribution of affected stakeholders. Choosing between investment options involves trade-offs among objectives and needs careful consideration of project goals, decision processes, and evaluation criteria before assessment [56]. This section provides an overview of methods to evaluate coastal engineering alternative projects.

Monetary valuation is a methodology that involves converting social and biophysical impacts into monetary units. It allows for determining the economic value of goods that do not have an existing market. This practice aids in quantifying and understanding the value of non-market goods in economic terms. By assigning monetary values to ecosystem service change due to a project, we can effectively assess the cost and benefits of the project and incorporate that into decision-making processes [34, 57].

Coastal ecosystems have been deteriorating over the last century, with high to very high impacts on biodiversity and a rapidly increasing trend of impacts [25]. Coastal engineering interventions induce

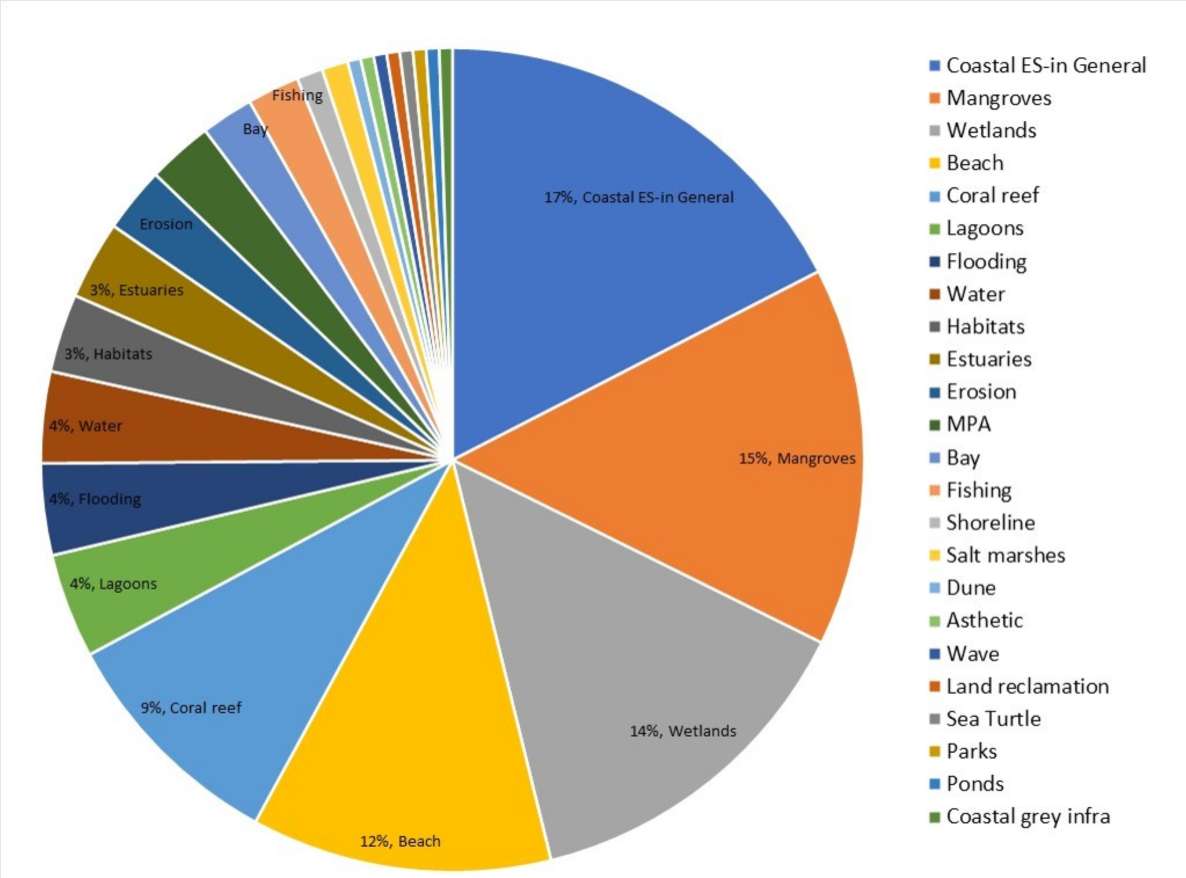

Figure 2.3: Types of coastal ecosystems and their percentages from 95 articles. Source: the result of this study – Appendix A

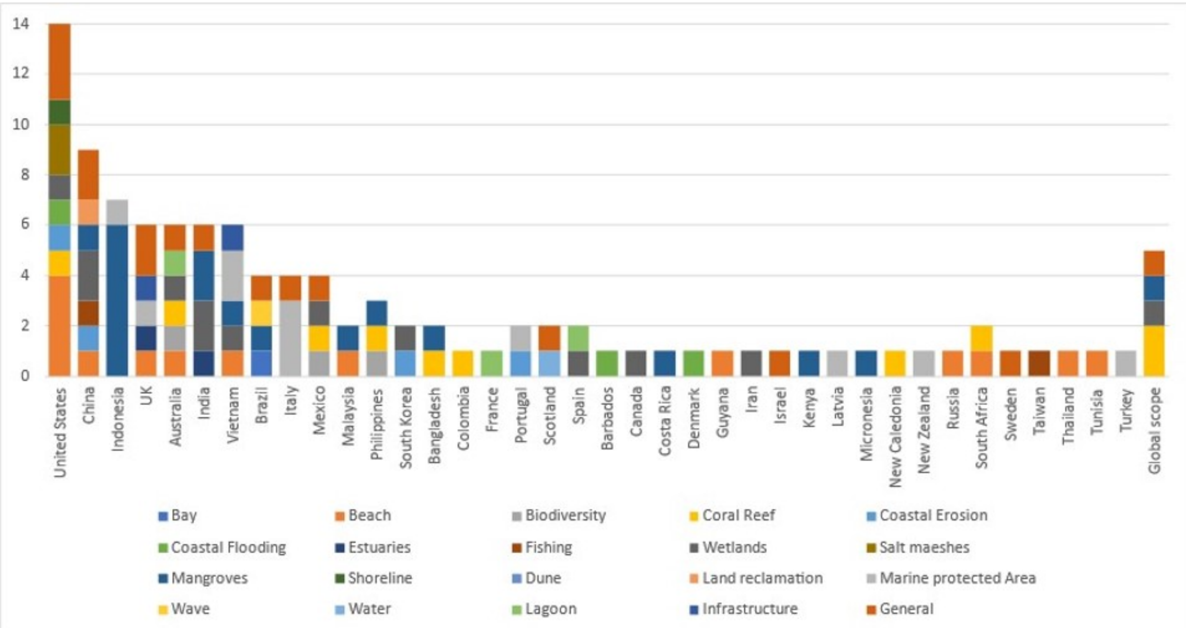

Figure 2.4: Type of ecosystems explored, linked to the countries of the study. Source: the result of this study – Appendix **??**

a change in the coastal ecosystem. Besides providing coastal protection, erosion control, and ecosystem services, they also impact existing CES, Table 2.1. Figure 2.6 illustrates the general assessment flow for ecosystem services change due to human action. Figure 2.7 illustrates TEEB's proposed ap-

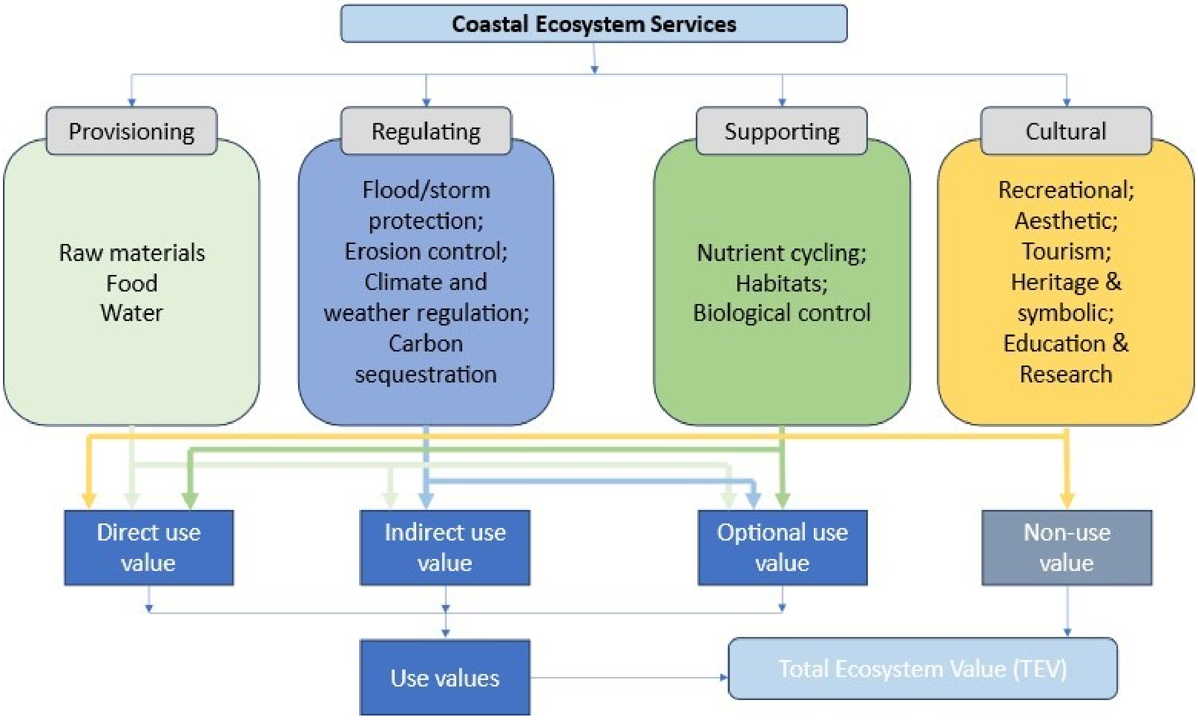

Figure 2.5: Pathway to categorise ecosystem services to understand their economic values. Adopted from [27] and [54].

proach to unravelling the link between ecosystems, biodiversity, and human well-being expressed in the economic valuation of ecosystem benefits [41]. It helps analyse the impacts of human activities on ecosystems and the feedback effects these changes have on the ecosystem's benefits for humans.

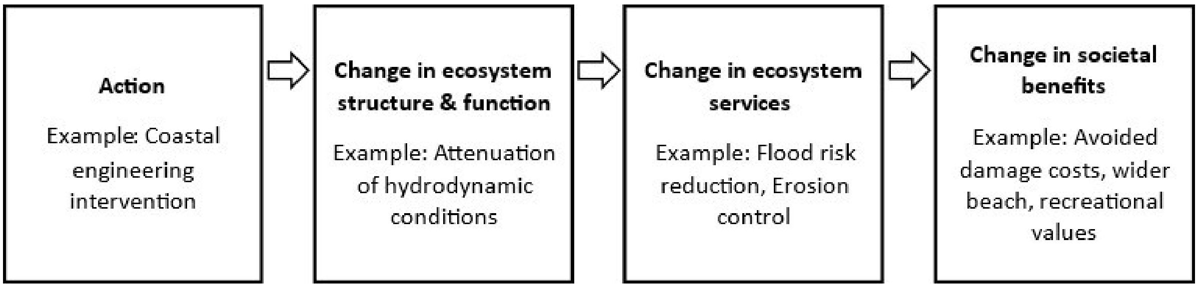

Figure 2.6: General framework for an ecosystem services assessment with an example from the coastal ecosystem. Adopted from [58] and [59]

Table 2.1: ES classification with a broad ES typology, detailed ES categories and examples of possible links with the dredging and marine construction sector. Adapted from Annelies Boerema, et al. [55] and based on the major classifications by TEEB, MEA and CICES.

ES	Categories	Examples of negative impacts from dredging/marine construction projects	Examples of positive impacts on the ES from dredging and marine construction projects
Provisioning	Food	Reduction of available fishing grounds and number of fish.	Creating, maintaining, or restoring nursery areas for fish, incorporating aquaculture facilities, or supporting facilities into the project design.
	Water	Reducing access to water by installing breakwaters or natural habitats.	Improving the access to water for navigation.
	Raw materials	Destruction of mangrove forests that are used for wood.	Dredged material as a resource.
Regulating and maintenance	Water purification	Destruction of natural habitats	Dredging and maintenance; projects impact contaminant dynamics; design can optimise this function.
	Air quality regulation	Destruction of natural habitats	Creating, maintaining, or restoring forests (terrestrial or kelp).
	Erosion control	-	Maintain the beach width and protect coastal communities
	Coastal flood/storm protection	Destruction of natural habitats, changes to hydrodynamics and sediment balance	Coastal development using both hard and soft engineering solutions design and maintenance.
	Climate and weather regulation	Destruction of natural habitats.	Enhancing carbon storage through nature restoration (e.g., mangroves, marshes).
	Ocean nourishment	Destruction of natural habitats.	Creating, maintaining, or restoring natural habitats.
	Carbon sequestration	-	-
	Natural physical structures and processes (air, water, substrate)	Destruction of natural habitats, changes to hydrodynamics and sediment balance.	Navigation; design and infrastructure of waterways/ports; sediment management (incl. handling of dredged material); nature-based solutions.
Cultural	Symbolic, aesthetic, and Heritage values	Alteration of historically or culturally valuable landscape or infrastructure.	Design and infrastructure of waterways/ports with symbolic and aesthetic values.
	Recreation and Tourism	Alteration of recreational landscape or its environment.	Incorporating infrastructure with recreational value into the design of e.g., coastal protection projects.
	Cognitive effects	Loss or damage of stratigraphic or archaeological records.	Sharing of information on the impact of the project through media, information panels, etc.
	Education & research	-	Information derived from ecosystems used for intellectual development, culture, art, design, and innovation
Supporting	Nutrient cycling	-	The flow of nutrients (e.g., nitrogen, sulfur, phosphorus, carbon) through ecosystems
	Water cycling	-	Flow of water through ecosystems in its solid, liquid, or gaseous forms
	Biological control	Destruction of natural habitats.	Creating, maintaining, or restoring marine ecosystems.
	Habitat & Biodiversity	Destruction of natural habitats	Dredging and maintenance; Project impact contaminant dynamics; design can optimise this function.

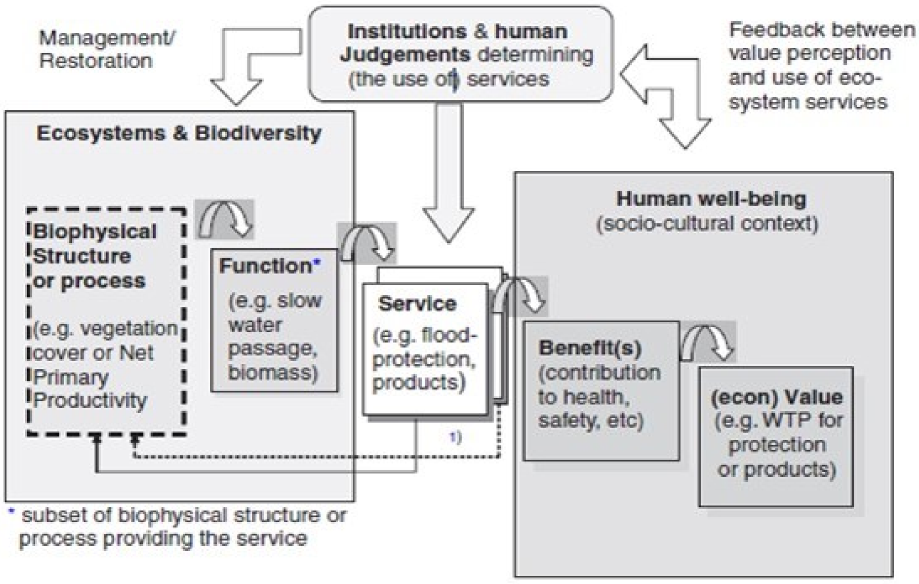

Figure 2.7: General ES assessment flow with an example from CES. Adopted from [58] and [59]

2.3.5. CES Monetary Valuation: Methods

Based on the systematic literature review findings, there are three main groups of valuation techniques: market-based, revealed preference, and stated preference. Other methods include value transfer and expenditure measures. Table 2.2 summarises these methods.

Table 2.2: Monetary valuation methods* for coastal ecosystem services. Sources: [27] [57]

Valuation Method		Description	Coastal Ecosystem Services
Revealed preference	Production-based (net factor income)	Often used to value the ecosystem services that contribute to the production of commercially marketed goods	Regulating services such as oxygen production, CO2 absorption, nitrogen fixation and carbon storage, providing fish nurseries, water purification, coastal protection
	Hedonic pricing	Commonly used to value the environmental services contributing to amenities. Property's price often represents the amenity value of ecosystems.	Tourism and recreation, aesthetic, improving air quality
	Travel cost	Considers the travel costs paid by tourists and visitors to the environmental value of a recreation site	Tourism and recreation, recreational fishery, and water sports
	Damage avoided cost, replacement cost	Based on either the cost that people are willing to pay to avoid damages or lost services, the cost of replacing services or the cost paid for substitute services providing the same functions and benefits	Buffering CC impacts such as wave attenuation, providing coastal protection against storms and erosion, flood impact reduction, water purification, carbon storage

Continued on the next page

Table 2.2: Monetary valuation methods* for coastal ecosystem services (continued)

Valuation Method		Description	Coastal Ecosystem Services
Stated preference	Contingent valuation (CVM)	The most applied method for both uses and non-use values, based on surveys asking people their willingness to pay (WTP) to obtain an ecosystem service	Tourism and recreation, recreational fishery and water sports, aesthetic value, cultural and spiritual value, art value, Contingent choice educational value
	Contingent choice (CCM)	WTP is stated based on choices between different hypothetical scenarios of ecosystem conditions	
Market price	Market price	Often used for the ecosystem products that are explicitly traded in the market	Fiber, wood and seafood provision, raw material for building, and aquarium
Benefit transfer	It transfers available data from previous valuation studies for a similar application		Applied for all environmental impact and ecosystem services
Expenditure measures	Makes use of the employment indicator to provide valuable and relevant information to decision-makers who are interested in local or regional economic impacts of changes in ecosystem services		Employment

* For a detailed explanation of each method, refer to UNEP-WCMC [57], ISO 14008 [60], Mehdi Zandebasiri, et al. [61], [62], and Boris van Zanten, et al. [56].

Table 2.3 summarises the applicability of some of the most common valuations to the most valued ES in the study of Boris van Zanten, et al. [56].

Table 2.3: Links from ecosystem services to valuation methods. Source: [56]

Ecosystem Services	Valuation method						
	Market prices	Net factor income	Avoided damage	Replacement cost	Stated preference	Travel Cost	Value transfer
Food and raw material	Yes	Yes					Yes
Tourism and recreation		Yes			Yes	Yes	Yes
Climate regulation	Yes		Yes				Yes
Biodiversity	Yes				Yes		Yes
Water quality			Yes	Yes			Yes
Health					Yes		Yes

Benefit Transfer

Benefits transfer, called 'value transfer', is used for a wide range of ecosystem services and environmental impacts [62]. It involves utilising valuation evidence from previous studies to inform decision-making in a new context. This approach is favoured for its efficiency and cost-effectiveness compared to conducting a new primary valuation study. However, the value transfer process carries inherent uncertainties and the possibility of errors. These uncertainties stem from the need to rely on expert judgment to identify and apply relevant valuation evidence in different contexts and the potential lack of suitable studies as a source of evidence [63, 64].

According to [65, 64, 19], there are two fundamental categories for value transfer: unit value transfer and value function transfer. Each category has its own subcategories, and they vary in terms of complexity, data needs, and reliability of results.

Unit value transfer has three forms. The first is an unadjusted unit value transfer from a single study where the mean value estimate and confidence interval are transferred. This ideally comes from a study on the same good and location but at a different time, although more commonly, studies from similar locations and times are used. The second form is an unadjusted unit value transfer from multiple studies. Here, mean value estimates and confidence intervals from two or more studies are used to define a range of values or calculate an average value for the change in the provision of the policy good. This could include using mean values from a meta-analysis study, which compiles economic value estimates from several studies. The third form is an adjusted unit value transfer where the mean value estimate is adjusted to account for differences between the study and policy goods in relation to one or more factors expected to influence economic value. The most commonly adjusted factor is income due to its expected influence on values and ease of data accessibility [65, 64, 19].

Value function transfer, the second category, allows the analyst to account for various factors that explain variations in economic values. These factors could include the socio-economic characteristics of the affected population, the good's characteristics, the change in its provision, and the availability of substitutes. There are two forms of this transfer. The first is a value function transfer from the study good context to predict a mean value for the policy good. Adjusted value function approaches are also possible here, where function coefficients can be based on multiple data sources. The second form is a meta-analysis function, which is estimated based on results from multiple valuation studies. This approach allows for a broader base of evidence in predicting the value of the change in the provision of the policy good [65, 64, 19].

Overall, the best practice recommendation is to use the unit value approach when transferring across similar goods and sites. When transferring across similar goods but dissimilar sites, the value function transfer is more appropriate, and the functions should only include generic variables with prior economic expectations [65, 64, 19].

2.3.6. CES Monetary Valuation: Challenges

Based on the finding of the systematic literature review conducted – Appendix A, ES of coastal engineering interventions are overlooked and limited in the economic valuation of the project. An assessment for the ES of these measures is rarely conducted and monetary valued. This is because the monetary valuation of ES is generally complicated to do [66, 19]. The valuation of ES benefits is subjective, as individuals may prioritise income over cultural identity (such as social ties) and may be willing to sacrifice one aspect of their well-being (cultural identity) in favour of another (material wealth) [41]. Consequently, specific benefits can carry varying degrees of importance to different people [41].

There is a lack of a comprehensive framework for conducting a holistic evaluation of ecosystem services and their overall condition [67, 68]. While natural capital and ecosystem services concepts have been widely accepted and acknowledged for their potential to improve environmental management [38], their practical applications have been limited due to inconsistent approaches in modelling, assessing, and valuing ecosystem services [1]. The expense of applying sophisticated methods, the absence of appropriate institutional frameworks, and mistrust or misunderstanding of the science are also limiting factors.

While only two academic articles were found by the systematic literature review that included a monetary valuation of CES of coastal engineering interventions, a few more studies by research institutes like the International Association of Dredging Companies (IADC) [20, 55], the International Institute for Sustainable Development (IISD) [17], and The World Association for Waterborne Transport Infrastructure (PIANC) [69] briefly discussed the monetisation of CES of some coastal engineering interventions. In these studies, the challenges of CES monetisation mentioned above were also highlighted.

2.4. Life Cycle Assessment Monetization

2.4.1. Introduction: Life Cycle Assessment (LCA)

The LCA is a comprehensive, structured method conforming to international standards ISO 14040 and ISO 14044 [70]. Its objective is to estimate the potential environmental impacts attributable to the life cycle of a product from cradle to grave, including resource extraction, production, usage, recycling, and waste disposal [71, 72]. It allows for quantifying emissions, resource consumption, and potential health and environmental impacts related to goods or services [70, 73, 74]. It is instrumental in identifying critical environmental performance points across a project life cycle, informing decision-makers towards sustainable practices, and selecting performance indicators [75]. The LCA study has four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase, which are illustrated in Figure 2.8. Figure 2.9 illustrates the life cycle phases in construction work, highlighting what to consider for LCI input. LCA is instrumental in identifying critical environmental performance points across a project life cycle, informing decision-makers towards sustainable practices, and selecting performance indicators [75].

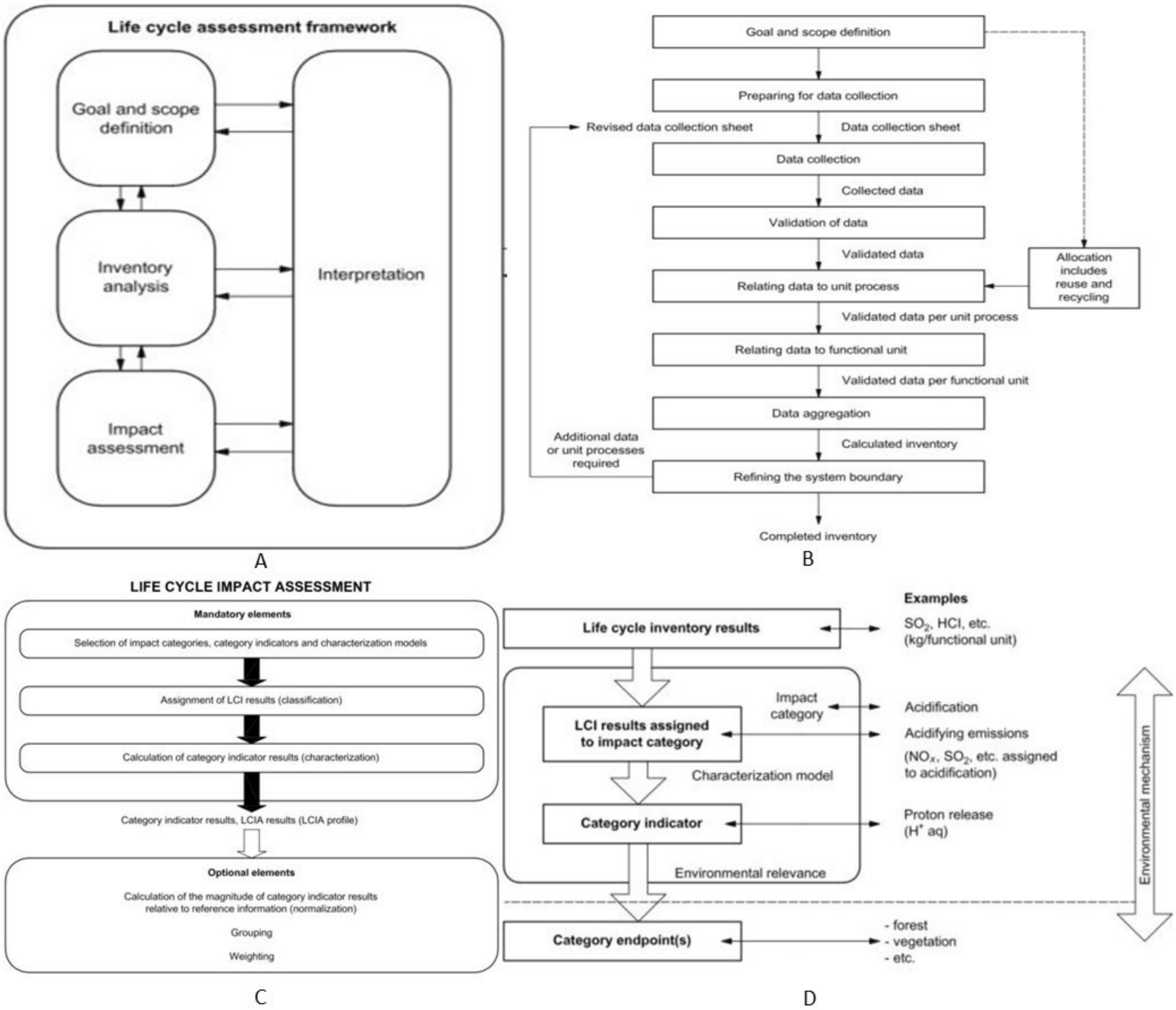

Figure 2.8: Life Cycle Assessment framework - LCA (A), steps of Life Cycle Inventory Phase – LCI (B), steps of Life Cycle Impact Assessment - LCIA (C), and the process of quantifying the life cycle environmental impact through impact categories from the LCI data (D). Source: [70, 73]

2.4.2. LCA's Phases

The LCA method, standardised by ISO 14040 and ISO 14044, includes four main stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle

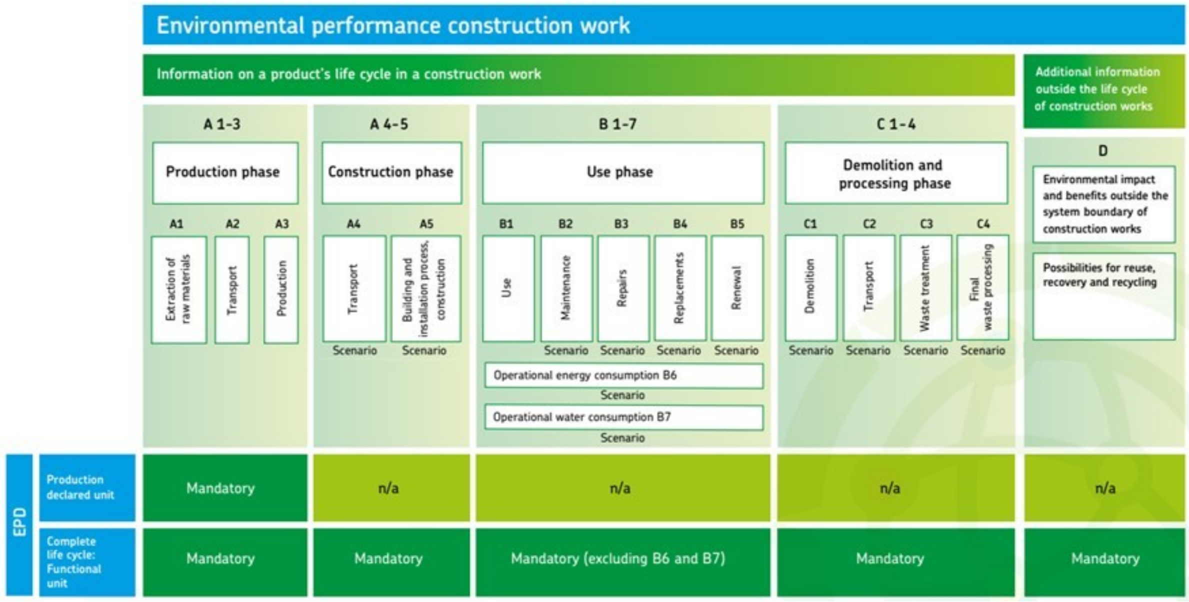

Figure 2.9: LCA phases in building construction work [71]. It is based on the EN 15804, which is in turn based on several international LCA standards: ISO 14025:2010, Environmental labels and declarations – Type III environmental declarations – principles and procedures (ISO 14025:2006); ISO 14044:2006 Environmental management – Life cycle assessment – requirements and guidelines (ISO 14044:2006), and EN 15978 and - Sustainability of structures – Assessment of the Environmental performance of buildings – Calculation method. EPD = Environmental Product Declaration.

interpretation. While some LCAs only perform the first two stages of an LCI study, a comprehensive LCA evaluates environmental impacts linked to system inputs and outputs (LCIA) and interprets the inventory and evaluation results [70, 73].

The European standard EN 15804+A2 describes the LCA trajectory [71]. In the goal and scope stage, the product, functional unit, and system boundary are decided, among other things. LCI gathers data on natural resource use and emissions for each process in a product's life cycle. This data is inventoried. It is followed by the LCIA, in which the product's environmental impact is calculated. Finally, recommendations are made based on the findings.

Within each impact category - Table 2.4, all contributing emissions and resource consumptions are converted to a common unit to be aggregated. LCIA compromises characterisation, classification, and optionally normalisation, grouping and weighting steps. The characterisation and classification steps include a selection of the environmental impact categories of interest, assigning the elementary flows from LCI into these environmental impact categories, and calculating impact category indicators based on inventory data using characterisation factors. Normalisation involves calculating the impact category indicator results relative to reference values but is not needed for the scope of this thesis. Lastly, the results are grouped and weighed based on value choices and data quality analysis [76, 73, 77]. The weighting step enables the monetisation of environmental impacts by attributing an economic value to the equivalent unit of the characterisation result of each impact category [34, 75]. Table 2.4 states all the environmental impact categories and their indicators [71]. Figure 2.10 presents a simplified life-cycle assessment of impact pathways and planetary boundaries situated in the drivers–pressure–state–impact–response (DPSIR) framework.

Table 2.4: Environmental Impact Categories and Indicators

Environmental Impact Category	Indicator	Unit
Climate change - total	Global Warming Potential total (GWP total)	kg CO_2 -eq.

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Table 2.4: Environmental Impact Categories and Indicators (continued)

Environmental Impact Category	**Indicator**	**Unit**
Climate change - fossil	Global Warming Potential fossil fuels (GWP fossil)	kg CO_2-eq.
Climate change - biogenic	Global Warming Potential biogenic (GWP biogenic)	kg CO_2 -eq.
Climate change - land use and land use change	Global Warming Potential land use and land use change (GWP – luluc)	kg CO_2 -eq.
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC11-eq.
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H^+-eq.
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP freshwater)	Kg P-eq.
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching marine end compartment (EP marine)	kg N-eq.
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP terrestrial)	mol N-eq.
Photochemical Ozone Formation	Formation Potential of Tropospheric Ozone (POCP)	kg NMVOC-eq.
Depletion of abiotic resources - minerals and metals	Abiotic depletion potential for non-fossil resources (ADP minerals & metals)	kg Sb-eq.
Depletion of abiotic resources – fossil fuels	Abiotic depletion for fossil resources potential (ADP fossil)	MJ, net cal. val.
Water use	Water (user) deprivation potential, deprivation weighted water consumption (WDP)	m^3 world eq. deprived
Particulate Matter emissions	Potential incidence of disease due to PM emissions	Health problems - incidence
Ionising radiation, human health	Potential human exposure efficiency relative to U235 (IRP)	kBq U235-eq.
Eco-toxicity (freshwater)	Potential Comparative Toxic Unit for ecosystems (ETP fw)	CTUe
Human toxicity, cancer effects	Potential Comparative Toxic Unit for Humans (HTP-c)	CTUh
Human Toxicity, non-cancer Effects	Potential Comparative Toxic Unit for Humans (HTP-NC)	CTUh
Land use-related impacts / Soil quality	Potential soil quality index (SQP)	Dimensionless

2.4.3. Weighting in LCIA

In the context of this thesis, the weighting step – in the LCIA – is mandatory prior to the monetary valuation of LCA [34]. Assigning weight in LCA (weighting factor -WF) is a complex process as it is considered more subjective, making it a potentially contentious issue [74]. Andrea Martino Amadei, et al. [34] reported that weights in LCIA are determined through various factors, including the specific preferences of different stakeholders, such as experts and citizens, variations in impacts across geography and time, and the urgency or political relevance of specific actions. Stakeholders, including experts, industry representatives, and citizens, may prioritise different environmental impacts differently. For instance, experts may prioritise specific environmental impacts, such as carbon emissions or water

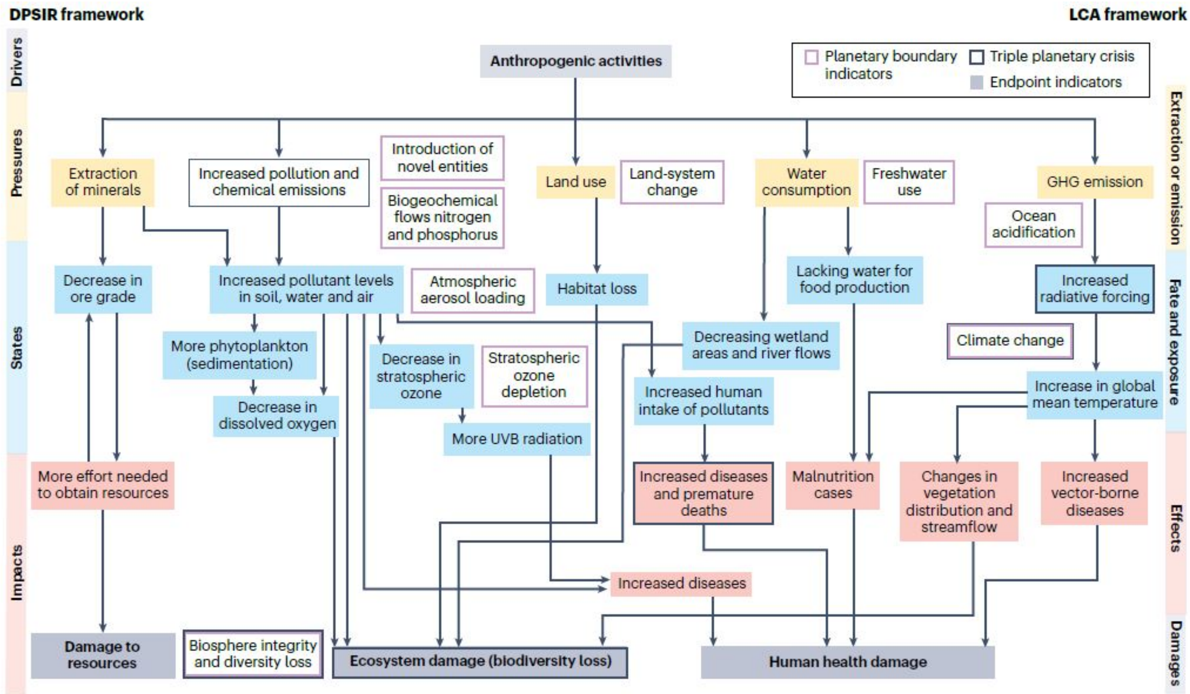

Figure 2.10: Simplified life-cycle assessment impact pathways and planetary boundaries situated in the drivers–pressure–state–impact–response framework [76]. "The triple planetary crisis (solid black boxes) aspects of climate change, biodiversity loss, and human health impacts from pollution are situated in terms of placement along the DPSIR framework and in relation to LCA impact pathways. Endpoint indicators (dark grey boxes) include damage to human health or marine, terrestrial or freshwater ecosystems. Responses from the drivers–pressure–state–impact–response (DPSIR) framework are not shown because the outcomes of life-cycle assessments (LCAs) support the development of responses (such as policies). However, responses as such are not included in the LCA framework [76]". Midpoint indicators are not shown explicitly. They are listed in Table 2.4

consumption, based on scientific evidence and consensus within the field. In contrast, industry representatives may emphasise economic factors, while citizens might prioritise factors that directly affect their daily lives, such as air quality or waste generation.

Moreover, geographical variations can significantly influence the weighting of specific activities, as the environmental impact may differ based on the location where it occurs. For example, the impact of deforestation in a biodiverse rainforest might be weighted more heavily than in a less ecologically sensitive area. Additionally, the weight of water consumption may vary in water-scarce regions compared to areas with abundant water resources [72].

Furthermore, the urgency and relevance of specific impacts, such as air pollution in densely populated urban areas, may change their weights over different periods. The political relevance of specific actions can also play a role in deciding weights. For instance, in the context of climate change, reducing carbon emissions might be assigned a higher weight due to its global significance and time-sensitive nature [78]. Weights are crucial in assigning importance to different aspects and help make well-informed decisions considering all relevant factors [34, 77]. Xing Wu et al. [74] discussed some weighting approaches, which are presented in Table 2.5.

Table 2.5: The weighting approaches of the environmental impacts. Source: [79, 74]

Weighting Approach	Description	Examples
Proxy	Uses several quantitative measures to represent the total environmental impact	The Ecological Footprint estimates the biologically productive area required to support current consumption patterns.
Technology	Estimates the ecologically productive area required to support current consumption patterns	
Panel	Involves judgments about the seriousness of impacts across various categories using questionnaires or face-to-face communication	The Delphi or Analytic Hierarchy Process, as used in the studies
Distance-to-Target	Defines an administrative or "sustainable" target for each category and considers the distance from the current level to the target	The EDIP and Eco-Indicator-95 methods
Monetisation	Measures the seriousness of impact across categories using monetary values. It uses willingness-to-pay (WTP) to restore the impacts of each category as the weighting factor, and in cases where market prices are unavailable, indirect methods are employed	The EPS system uses WTP, while Tellus system uses data on emission taxes

2.4.4. Monetization of LCA

Monetary valuation is a valuable tool used in Life Cycle Assessment (LCA) that helps aggregate environmental impacts, often expressed with different units of measure. This allows for easier comparison and understanding of the LCA results, enabling effective communication and informed decision-making processes [34, 75]. This section discusses the development in this field, the knowledge gap and challenges, and the monetary valuation methods applicable to LCA. Based on the findings, the section concludes with a suggestion for practitioners when the aim is to do a quick monetary valuation on an international project.

LCA Monetary Valuation: Methods and Applications

The monetary valuation was first explored in LCA in 1999 by Göran Finnveden [80], who reviewed various methods such as the EPS system, the Ecoscarcity method, and economic valuations based on impact analysis approaches [34]. According to Andrea Martino Amadei, et al. [34], Finnveden's 1999 study found the implementation of those methods limited by inconsistencies, data gaps, and assumptions. Subsequently, Göran Finnveden, et al. [79] introduced the Ecotax method based on taxes and fees on emissions and resources used in Sweden, providing a unique solution for using different monetary valuation approaches in LCA impact categories. Afterwards, several authors - Göran Finnveden, et al. [81], Sofia Ahlroth, et al. [82], and Sofia Ahlroth [83] - discussed the benefits of using monetary valuation in the weighting phase of LCA such as e.g., enabling a cross-comparison between different impacts and/or with other economic costs and benefits, but concluded that practical implementation remained challenging [34, 84].

The monetary valuation methods reported for the LCA are similar to that of ESA - Section 2.3.5. The monetary valuation methods for LCA and their suitability per impact categories are presented in Figure 2.11, [34, 84]. Massimo Pizzol, et al. [84] classified these methods based on a scoring system, identifying the most suitable monetary valuation methods in the context of LCA and highlighting the need for different approaches at the "endpoint" and "midpoint" levels[1]. Table 2.6 lists all existing LCA applications and their suitable monetary valuation methods. V. Durão, et al. [75] critically analysed these methods in the construction sector context. While agreeing with the former authors on the advantage of monetising LCA in the weighting step, they concluded that LCA's monetary valuation is still challenging. The study found that Eco-costs, Ecovalue 2008, Ecotax 2002 and Social Cost of Carbon are the most suitable methods because they are based on CML (Centre for Environmental Sciences - Leiden University) baseline midpoint impact categories, declared in EPDs but are limited by the geographic representability.

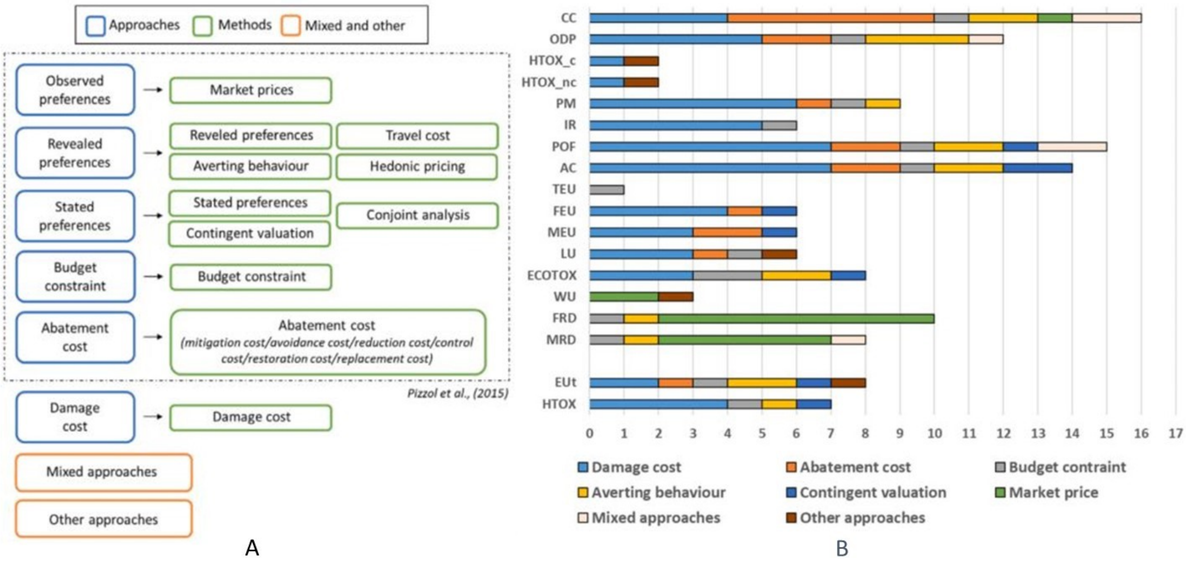

Figure 2.11: The monetary valuation methods used in LCA and their suitability per impact category. Source: [34, 84] Figure A: Overview of the monetary valuation method reported for LCA. Figure B: Number of monetary valuation methods and type of approaches per Environmental Footprint Impact Category (EF IC). EF ICs: CC = climate change; ODP = ozone depletion; HTOX-nc = human toxicity noncancer; HTOX-c = human toxicity, cancer; PM = particulate matter; IR = ionising radiations; POF = photochemical ozone formation; AC = acidification; TEU = eutrophication, terrestrial; FEU = eutrophication, freshwater; MEU = eutrophication, marine; LU = land use; ECOTOX = ecotoxicity freshwater; WU = water use; FRD = resource use, fossils; MRD = resource use, minerals and metals. Other ICs included: HTOX = human toxicity; EUt = eutrophication (some studies did not provide MVC at the same level of aggregation of the EF).

Rosalie Arendt, et al. [85] analysed nine different monetisation methods and found various methods and values across different monetisation applications, often leading to non-standard results. They emphasised the need for careful attention to the wide variety of available monetary valuation approaches, as the choice of approach can significantly impact the monetary damage values obtained in LCA studies [85]. The authors also noted that the potential advantages of using monetary valuation in LCA are limited by the underdeveloped Monetary Valuation Coefficient (MVC), particularly for specific impact categories [85]. Monetary valuation gets rejected for the Environmental Footprint weighting approach due to its immaturity [34]. Table 2.7 presents the range of the monetary valuation coefficients for each impact category and the valuation method used to obtain them.

[1]The definition of midpoint and endpoint indicators are presented in Appendix B.4

Table 2.6: Overview of the general LCA monetary application presented by [84], [75], and [85]

Monetary Application	Description of its Use in LCA	Suitable valuation method	Geographical scope	AoPs	Equity Weighting	Suitable for
ECOVALUE 08/ECOVALUE 12	Applies a comprehensive cost-based approach to monetise environmental burdens. Specific to the Swedish geographical context. Focus on environmental concerns such as mineral resources, climate change, eutrophication, and acidification.	Damage costs/stated preference and market price	Sweden	Divers for different impact categories, partially no documentation	Not clearly documented	Endpoint
STEPWISE2006	Uses a distance-to-target method coupled with an economic valuation based on WTP. Developed in Denmark and specific to Danish contexts.	Damage costs/Ability to pay	Global	Human health biodiversity resources	Yes	Midpoint & End-point
LIME 1-3	Calculates the environmental damage cost per substance level to assess environmental impacts in a life cycle assessment study. Developed in Japan and is predominantly used in an Asian context.	Damage costs / stated preference	Global with country resolution (G20 countries)	Human health social assets (natural resources), terrestrial ecosystems, NPP 1	No	Midpoint & End-point
ECOTAX (2002/2006)	Uses the actual taxes as proxies for the marginal external costs. Designed to be utilised as shadow price data within environmental LCA, including resource, pollution, and waste management taxes.	Societies' willingness to pay	Sweden	Not applicable	Not applicable as it is not connected to an AoP	Midpoint & End-point
RCA (Reduction Cost Approach)	Utilises abatement cost method to evaluate environmental costs associated with product development.	-	-	-	-	-
EPS (Environmental Priorities Strategies in product design)	Environmental impacts are monetised using damage cost estimates based on willingness-to-pay (WTP) studies. Originally developed in Sweden.	Damage costs / mostly market price and revealed preference	Global	Human health, bio productivity, biodiversity, abiotic resources, water, labour productivity	Yes, every human welfare loss is treated as if they were an OECD citizen	Endpoint

Overview of the general LCA monetary application (continued)

Monetary Application	**Description of its Use in LCA**	**Suitable valuation method**	**Geographical scope**	**AoPs**	**Equity Weighting**	**Suitable for**
EVR Method	Based on prevention costs, assign cost to all environmental impacts measured in € per eco-indicator point. Applied across EU contexts.	Abatement costs	Europe / Netherlands	No applicable	Yes, but only applicable for human toxicity	Midpoint
Eco-costs	Used to translate environmental impacts into economic costs by measuring the cost of preventing a specific amount of environmental impact. Used in environmental performance assessment for building designs in different climate zones and in assessing costs relating to energy generation.	Revealed willingness to pay - Market prices (prevention prices)	-	-	-	Midpoint
Environmental Prices	Based on a broad combination of techniques such as abatement costs, market prices, and stated and revealed preferences. Specific to a European geographical context.	Damage costs and abatement costs	Europe	Human health, ecosystems, buildings and materials, resource availability, well-being	No	Midpoint
External Costs of Energy (ExternE)	A project developed to monetise socio-environmental damages caused by distinct energy carriers and used in approximations of the economy of fusion energy and comparisons of main external cost components for electric vehicles.	Damage cost	-	-	-	Endpoint
Social Cost of Carbon	A pure weighting method that integrates LCA results with an economic model to derive environmental damage. Globally applied.	-	Global	-	-	Midpoint & End-point

Overview of the general LCA monetary application (continued)

Monetary Application	**Description of its Use in LCA**	**Suitable valuation method**	**Geographical scope**	**AoPs**	**Equity Weighting**	**Suitable for**
Trucost	A pure weighting method that integrates LCA results with an economic model to derive environmental damage. Globally applied.	WTP through ecosystem services (market price) or stated preference	Global	Human health, ecosystem services, abiotic resources	Yes, DALYS for all people are weighted equally	Midpoint & End-point
MMG-Method	Compared monetisation methods quantitively and qualitatively generate results for eighteen impact categories. Specific to the European context.	Damage, abatement, and restoration costs	Europe, Flanders, global	Human health-, biodiversity, agricultural production, resources	Not explicitly treated	Midpoint
ECI (MKI in the Netherlands)	Based on the shadow cost, weighting factors for each environmental impact category determined by NMD	-	Netherlands	-	-	Midpoint

Abbreviations are DALY: disability-adjusted life year, AoP: area of protection, POCP: photochemical ozone creation, LCA: Life Cycle Assessment, WTP: willingness to pay, NPP: net-primary production

Table 2.7: Range of the monetary valuation coefficients for each impact obtained. Adopted from [34] and [71]

Environmental Impact Categories (EF IC)	Unit	MVCs - Global [34]			MVCs-NL[71]
		Min	Max	Average	
Global warming potential (GWP)	€/kg CO_2 eq.	2.11E-02	6.85E-01	2.11E-02	5.00E-02
Ozone depletion Potential (ODP)*	€/kg CFC-11 eq.	3.20E+01	1.15E+02	5.55E+01	3.00E+01
Human toxicity (HTP)	€/kg 1–4 DB eq.	2.43E-02	3.21E-01	1.23E-01	9.00E-02
Human toxicity (HTP)	€/CTUh	8.57E+05	1.09E+06	9.71E+05	
Particulate matter (PM)*	€/kg PM10 eq.	1.62E+01	6.07E+01	3.73E+01	
Particulate matter (PM)	€/disease inc.	7.98E+05	7.98E+05	7.98E+05	
Ionising radiation (IR)*	€/kBq U235 eq.	1.03E-03	1.01E+00	2.12E-01	
Photochemical oxidant formation (POCP)	€/kg C_2H_4 eq.	2.95E-01	1.06E+01	4.36E+00	2.00E+00
Photochemical oxidant formation (POCP)*	€/kg NMVOC eq.	2.30E-03	1.39E+01	3.51E+00	
Acidification*	€/kg SO_2 eq.	2.15E-01	1.59E+01	4.07E+00	4.00E+00
Acidification	€/mol H+ eq.	3.50E-01	3.50E-01	3.50E-01	
Eutrophication (Freshwater)	€/kg PO_4 eq.	1.88E+00	2.79E+01	1.15E+01	9.00E+00
Eutrophication (Marine)	€/kg N eq.	1.94E+00	1.28E+01	6.64E+00	
Eutrophication (Freshwater)	€/kg P eq.	2.15E-01	7.66E+01	2.02E+01	
Ecotoxicity freshwater	€/kg 1–4 DB eq.	1.34E-03	5.70E+01	1.74E+01	3.00E-02
Ecotoxicity freshwater	€/CTUe	3.89E-05	3.92E-05	3.91E-05	
Resource use, minerals Metal	€/kg Sb eq.	1.65E+00	1.92E+04	4.81E+03	1.60E-01
Resource use, Fossils	€/kg Sb eq**	6.35E-07	8.47E-06	4.85E-06	1.60E-01
Resource use, Fossils***	€/MJ**	1.32E-03	1.76E-02	1.01E-02	3.33E+02
Water use	€/m^3 water eq.	7.09E-02	2.15E-01	1.43E-01	
Water use	€/m^3 eq.****	5.08E-03	5.08E-03	5.08E-03	
Land use	€/pt	1.78E-04	1.78E-04	1.78E-04	
Land use	€/m^2 arable	1.61E-01	1.61E-01	1.61E-01	
Land use	€/m^2a	8.91E-02	7.21E-01	4.05E-01	
Land use	€/kg C deficit	1.59E-06	1.59E-06	1.59E-06	

***** The values of Amadie are adopted from Table 4 of the article. The remaining ICs with no * are extracted from Table 2 of the article. ****** If 'depletion of fossil energy carriers' is available in the MJ unit, the conversion factor 4.81E-4 kg antimony/MJ can be used [71]. ******* €/m3 eq. Deprived water.

LCA Monetary Valuation Challenges

The literature highlighted some reasons why the implementation of monetary valuation remains challenging. One difficulty is that the impacts assessed in LCA are highly abstract. On the one hand, LCA assesses potential impacts which do not refer to specific situations but are generalisable and aggregated over space and time [84]. The monetary valuation of potential impacts should be broadly applicable through general MVCs, which are not straightforward. There is a notable difference in the availability of MVC across impact categories. Some categories, such as climate change, are frequently analysed, while others, like terrestrial eutrophication, have very limited available information [34].

On the other hand, LCA considers both midpoint and endpoint impacts. Midpoint impacts like climate change and ozone depletion typically represent clear cause-effect relationships. In contrast, endpoint impacts, such as damage to human well-being and ecosystem quality, involve complex processes affecting specific targets in human health, the natural environment, and natural resources known as 'Areas of Protection (AoP)'. As a result, assessing midpoint impacts is usually done from the bottom-up, focusing on the quantitative relationship between the elementary flows from the life cycle inventory (e.g. resource consumption, emissions into the air, etc.) and its midpoint impact, while endpoint assessment takes a top-down approach, emphasising the relationship between an AoP and its endpoints. Applying monetary valuation at the midpoint or endpoint may require different approaches. These approaches allow us to focus on specific emissions and their impacts or to deal with the complexity of an endpoint by breaking it down into different features or attributes [84].

LCA monetary Valuation: Existing Implementation Method

For practitioners in the construction industry, LCAs are used increasingly in public procurement tenders and are considered an important criterion to determine the winning bid [16]. In the Netherlands, LCA is the building block for the Environmental Cost Indicator (ECI) - Milieu Kosten Indicator (MKI) in Dutch. ECI is a monetary measure that combines all relevant environmental impacts into a single score. The weighting factors assigned to each environmental impact are based on a 'shadow price' that indicates the cost to the government of neutralising the environmental impact of the construction work or construction product in question [71]. The shadow price is the highest permissible cost level for the government (prevention cost) per unit of emission control [86].

The ECI, therefore, represents the environmental shadow price[2] of a product or project. Most environmental impacts associated with a product occur along the supply chain rather than at the production facility. An LCA is conducted to measure these emissions. However, due to the use of data from various sources, the environmental impacts measured can vary significantly and be categorised differently. This makes it challenging to compare the numbers effectively. This is where the ECI proves its value. Providing a single-score indicator simplifies and harmonises diverse environmental data points into a monetary value. Consequently, it offers a consistent measure that can be easily compared across different industries.

The ECI result ensures that the environmental performance of different contractors can be compared objectively. Contractors with the lowest ECI for a project are eligible for the highest discount on their offer. Figure 2.12 shows (A) the calculation steps of ECI and (B) how it is used to evaluate tenders.

Similar practices are being encouraged and applied worldwide. For instance, the World Bank and its clients started—as of September 1st, 2023—applying the rated criteria in procurement (World Bank, 2023). Instead of relying solely on the lowest evaluated price, rated criteria ensure the inclusion of crucial quality and sustainability factors. This approach prioritises and evaluates bids based on a broader range of important considerations beyond low prices.

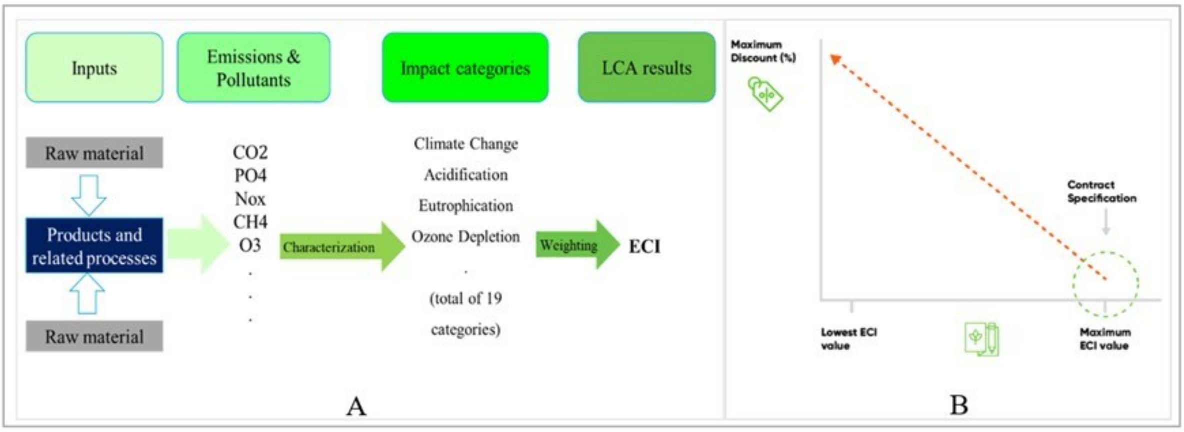

Figure 2.12: Environmental Cost Indicator (ECI) - (A) calculation steps and (B) Discounts process in Tenders. Adopted from [16]

2.5. Economic Appraisal Method

Economic appraisal methods seek to gather evidence on the overall value of a project's impacts. This is an essential step in integrating individual service changes to create a comprehensive assessment of the overall effects [57]. As this thesis aims to consider both the costs and benefits in the economic evaluation of each coastal engineering alternative, Cost-Benefit Analysis (CBA) is the most suitable appraisal method in this context.

[2]More details on the shadow price methodology can be found in [86]

2.5.1. Cost-Benefit Analysis

According to Boris van Zanten, et al. [56], CBA is a widely used method for evaluating and comparing investments, projects, and policies. It involves assessing a project's monetary costs and benefits compared to a baseline scenario. However, conducting a CBA can be complex when dealing with coastal engineering alternatives that offer multiple benefits to various stakeholders. It requires careful consideration in defining and modelling the spatial extent of impacts while avoiding double counting or mis-categorizing costs and benefits. To make costs and benefits comparable, those occurring at different times are converted to "present values" using a relevant discount rate, reflecting society's time preference and the opportunity cost of capital. CBA can express the economic performance of projects through three main statistics: net present value (NPV), benefit-cost ratio (BCR), and internal rate of return (IRR). A positive NPV suggests that a project will enhance social welfare; a BCR greater than one indicates its benefits exceed its costs. An IRR exceeding the discount rate implies that the project generates returns surpassing other economic investments. The OECD [87] offers guidance on conducting CBA for environmental investments.

2.6. Integrating ES into LCA

Integrating Ecosystem Services Assessment (ESA) into Life Cycle Assessment (LCA) has been a topic of increasing interest in recent years. However, the current literature suggests that there are still significant gaps and challenges to be addressed in this area [88, 21, 32].

The integration of ESA into LCA methods has been limited [21, 32]. This limitation is primarily attributed to inherent differences in data, modelling approaches, and interpretation methods [32]. The lack of alignment between the system boundaries in LCA and ESA, as well as their inventory, impact indicators, and taxonomy, has hindered the development of a comprehensive ES impact modelling within the context of Life Cycle Impact Assessment (LCIA) [21]. As a result, LCA studies primarily focus on the environmental impacts of product systems throughout their life cycle (e.g., impacts on resource availability and ecosystem quality) without explicitly considering ES [88].

To achieve a more comprehensive understanding of sustainability and account for all benefits and burdens of a product, a framework that integrates ESA into LCA is needed. In this regard, several frameworks have been proposed. For instance, Sue Ellen Taelman, et al. [32] proposed a sustainability framework accounting for ES in LCA at the endpoint impact by performing the LCA and ESA separately and combining the results or complementing driving forces. Similarly, K. Alshehri, et al. [35] and B. Rugani, et al. [21] proposed a framework integrating ESA and LCA. Their frameworks are theoretically the same and comprise five steps: goal and scope, inventory, impact, and valuation steps. What these frameworks have in common is that the ES integrated into the LCA mostly provisioning ES that can be measured and accounted for using ES accounting models such as the Integrated Evaluation of Ecosystem Services and Trade-off (InVEST[3]) model. Their application to a broader ES type is still limited, as highlighted by [89].

Existing frameworks tend to focus on the provisioning type of ES (linked to land cover and land use—like vegetation cover) due to the availability of modelling tools to quantify them, most often urban land use, e.g., InVEST. However, even for ES types covered by ecosystem accounting models, the literature highlights the need for a consistent conceptual framework that can facilitate the integration of such ecological models into the LCIA methodology [90].

2.7. Literature Review Summary

At the end of the literature review chapter, it can be concluded that:

- The monetary valuation studies of ecosystem services are abundant, but that related to coastal engineering interventions are very scarce, especially in the academic section,

[3]The objective of InVEST is to allow ecosystem services to be evaluated, mapped, and compared to other scenarios. It is an open-source system with GIS capabilities to evaluate land quality with several possible valuation parameters. It includes terrestrial and freshwater systems and does not include marine or coastal systems.

- The monetary valuation of LCA is less established compared to ecosystem services related to human-wellbeing,
- Monetary valuation methods of both ES and LCA lack consistency from one study to another, as well as geographically; for instance, the difference in the monetary value for the same services or same monetary valuation coefficients of the LCA that are derived from the same valuation method is reported to be large,
- While some studies propose frameworks integrating ES into the LCA, these frameworks have not been tried on a construction project such as coastal intervention infrastructures.
- As shown in Table 2.8, no coastal engineering study has performed both LCA and ESA, as part of the project assessment.

Table 2.8: Summary of key articles related to ES and LCA

		Life Cycle Assessment (LCA) Phases for Construction Sector						
		No LCA	Product Stage	Construction stage	Use stage	End of life stage	All stages	General*
Ecosystem Services (ES)	No ES						[91]	[75], [34], [85], [74]
	Provisioning							
	Supporting							
	Cultural							
	Regulating	[92]						
	Mixed ES	[93], [94], **[95]**, [96], [48], **[97]**						
	General*	[38]						[98], [88], [21], [99], [35], [32]

Red: the article contain a case study. Green: About coastal Ecosystem services. *: Article has general knowledge - not a project based but about research, policy or framework.

3
Monetary Valuation Framework

3.1. Introduction to the Framework

This chapter introduces a comprehensive framework for the monetary valuation of coastal engineering interventions. This framework is designed to incorporate key characteristics identified through the literature review performed in Chapter 2, thereby serving as a tool for selecting and evaluating various alternatives. It builds upon existing frameworks such as the Millennium Ecosystem Assessment [25], the Environmental and Social Impact Assessment (ESIA) [100], and the traditional Life Cycle Assessment (LCA) [60, 70, 73]. Furthermore, it addresses the limitations identified in the frameworks of Sue Ellen Taelman, et al. [32], B. Rugani, et al. [21], Xinyu Liu, et al. [101], and K. Alshehri, et al. [35] by incorporating both regulating and cultural ecosystem services, as opposed to focusing solely on provisioning services.

Coastal engineering interventions have the potential to significantly enhance human well-being and yield a range of socio-economic benefits. However, the impacts and benefits of these interventions can vary considerably across different alternatives. The primary objective of this framework is to facilitate a comprehensive evaluation of the sustainability of coastal engineering interventions by integrating Ecosystem Service Assessment (ESA) and Life Cycle Assessment (LCA) methodologies. Considering the framework's focus on coastal regions, known for their complexity and dynamic nature, it tackles the difficulty of finding a common functional unit for both LCA and ES indicators by expressing them in monetary value. As a result, this framework carries out LCA and ESA simultaneously, merging them in the final monetary valuation result.

This approach is particularly suitable for coastal engineering interventions for several reasons. The framework is specifically designed for coastal ecosystem services, which is the first attempt in terms of scope and context. It applies to all Ecosystem Services (ES), including supporting, provisioning, regulatory, and cultural, unlike previous frameworks, which primarily focus on provisioning services only due to the lack of characterisation factors for other ES [35]. The framework is user-friendly for practitioners as it employs the well-known LCA and ESIA standards with a mandatory monetary valuation step and a combined interpretation step. The framework overcomes the difficulties of identifying common functional units by comparing the alternatives directly in the economic valuation phase.

The framework comprises four main components (Figure 3.1): LCA monetary valuation (Section 3.2), ESA monetary valuation (Section 3.3), financial analysis (Section 3.4), and interpretation of results (Section 3.5). Subsequent sections describe each component in greater detail.

In summary, this framework attempts to monetary value the sustainability of coastal engineering interventions, considering their potential adverse and beneficial impacts. Integrating ES and LCA offers a comprehensive tool for assessing different alternatives' sustainability impacts and benefits.

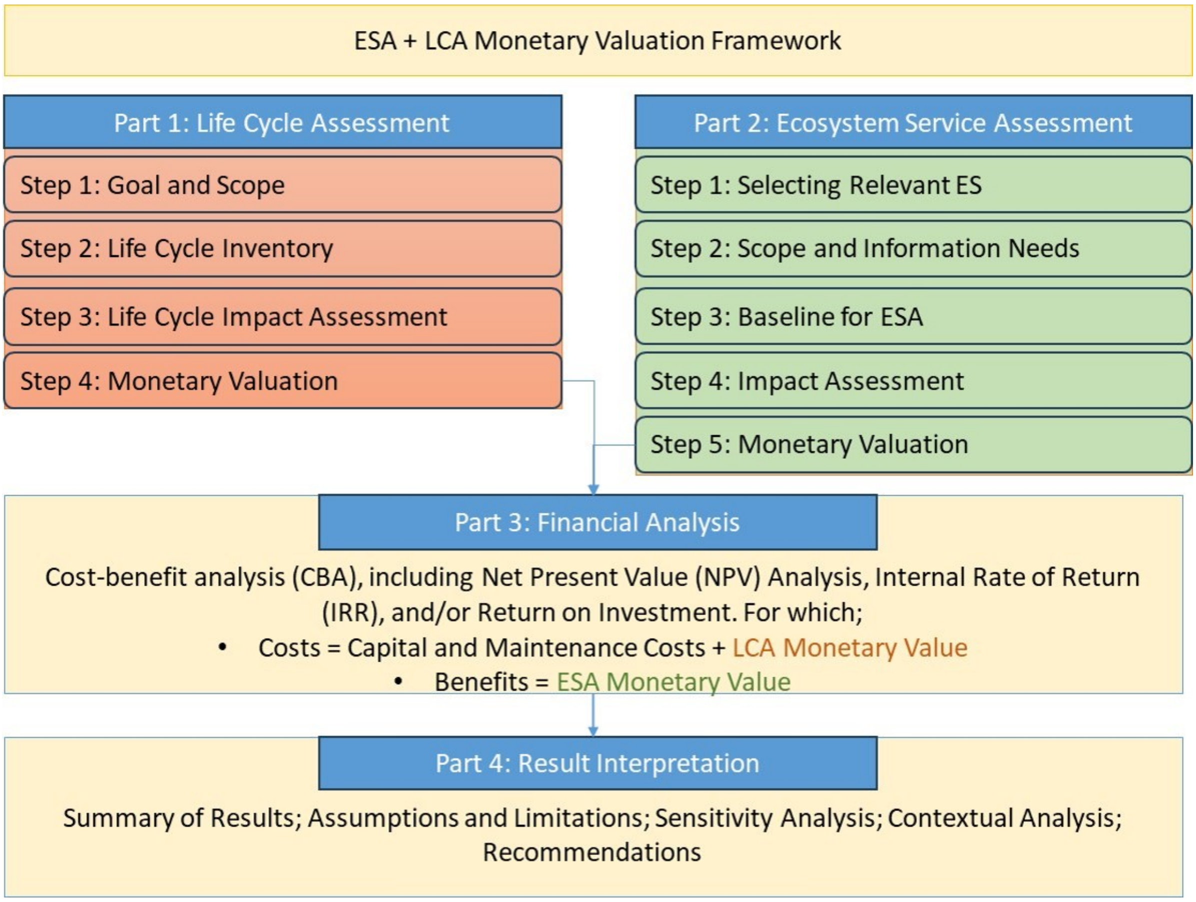

Figure 3.1: ESA + LCA monetary valuation framework for coastal engineering interventions.

3.2. Life Cycle Assessment (LCA) Monetary Valuation

This part follows the standard LCA framework [70, 73]. Other primary references for this part of the framework are Rosalie Arendt, et al. [85], ISO 14008 [60] and Andrea Martino Amadei, et al. [34]. The following sections discuss the different phases of LCA in the context of coastal engineering interventions: the goal and scope definition, the Life Cycle Inventory (LCI), the Life Cycle Impact Assessment (LCIA) and the monetary valuation.

3.2.1. Goal and Scope Definition

In this framework, the goal of conducting a Life Cycle Assessment (LCA) is to compare the environmental impact of different coastal protection alternatives. The extent of the LCA, including the system boundary and level of detail, depends on the subject and purpose of the study [70]. The depth and breadth of the analysis can vary based on specific objectives, such as a comprehensive or quick assessment. First, it is essential to identify the different coastal alternatives to be assessed and determine the assessment's context.

According to Zhichao Wang and Fang Liu [102], the study's scope must be tailored to align with its intended goal. This includes considering system functions, functional units, system products, boundaries, allocation procedures, and environmental impacts. Furthermore, the scope should outline data requirements, assumptions, limitations, the type of critical review to be undertaken, and the report requirements. The interpretation of study results significantly depends on how the goal and scope are defined. These definitions involve making decisions that influence data collection, system modelling, and assessment methods. Therefore, it is essential to establish clear and well-defined goals and scope to ensure the accurate interpretation of study findings [102]. The following points elaborate more on some of these crucial elements:

Defining the Function Unit (FU)

FU is crucial for comparing the impact of different alternatives. For coastal engineering interventions, this could be a specific length of coastline protected (e.g., one kilometre) for a certain period (e.g., the project's design lifetime).

Defining the System Boundaries

The term "system boundaries" refers to the various stages involved in the life cycle of coastal engineering alternatives. This includes the production phase (A1-3) to the demolition and processing phase (C1-4), which covers all processes from the extraction of raw materials (such as sand or dike material) to the maintenance, restoration, or eventual removal of the protection measures.

Defining the Temporal Boundary

The temporal scale is assumed to be the design life of the coastal engineering alternatives.

Selecting the Environmental Impacts Categories

Here, the number and type of environmental impact categories are selected. For instance, Until the end of 2020, the environmental performance of LCA consisted of 11 environmental impact categories following the guidelines of EN 15804 [77]. However, due to the amendment of EN15804 in 2019 and the subsequent alignment of its methodology with the LCA methodology from the Product Environmental Footprint (PEF), the profile now encompasses 19 environmental impact categories as of January 1, 2021, per EN15804+A2 (NL) [71]. The relevant environmental impact categories are selected based on the information and data available and the study's objective.

Selecting the LCA's Application

In this step, the LCA's calculation model is selected. Some established LCA calculation models are R<THiNK, SimaPro, OpenLCA, and Product Environmental Footprint (PEF). These models provide a structured framework for quantifying and assessing the environmental impacts across the life cycle of the coastal solutions.

Stating the Assumptions and Limitations of the Study

This step explicitly states all the assumptions required for its implementation. For instance, one assumption may be that different coastal interventions provide equal protection. In addition, it is important to acknowledge the limitations of the framework application. For instance, it should be stated that the LCA's application assesses the midpoint impact and does not consider the endpoint impact, which can be seen as a limitation [77].

3.2.2. Life Cycle Inventory (LCI)

The LCI follows the methodology stated in ISO 14040 [70], as explained in [73]. It adheres to the goals and scope for data collection, verification, and aggregation. It also links the data to the specific unit process and functional unit defined in the goal and scope description. It thoroughly identifies and measures the flows between the coastal engineering project and the environment, including emissions and resources.

The life cycle inventory (LCI) data for the coastal engineering alternatives should be gathered from primary sources such as project documents or secondary sources such as literature and similar projects from previous years. The type of information required includes data based on the project description and working methods. The LCI data should encompass various aspects such as raw materials (e.g., rocks, sands, concrete, etc., sourced from material suppliers or project specifications), transportation (e.g., estimated distance travelled and mode of transportation for materials and equipment to the construction site), equipment usage (e.g., duration and type of equipment), energy consumption (e.g., electricity, fuel, etc., during different phases of the project based on energy estimates and equipment specifications), water consumption, emissions (types and quantities of emissions generated during the project phases obtained from emission factors and equipment specifications), waste generation (e.g., amount and types of waste generated during construction), maintenance (e.g., estimated maintenance activities and associated resources required over the project's lifespan), and end-of-life (e.g., potential or planned scenarios for the disposal or reuse of the project materials). By collecting comprehensive data on these aspects, the LCI provides a holistic understanding of the environmental impact of the coastal engineering alternatives.

3.2.3. Life Cycle Impact Assessment (LCIA)

During the impact assessment phase of LCA, the findings from the inventory analysis (emissions and resource consumption) are linked to environmental impact categories and indicators using LCIA methods. These methods involve two mandatory steps: categorising emissions and resource consumption into impact categories (such as climate change or particulate matter) and converting them into a standardised unit (such as kilograms of CO2 equivalent). This allows for easier comparison within the same impact category [34, 73, 77]. The environmental impact categories and indicators are calculated using an established LCA calculation model, as indicated in 3.2.1.

3.2.4. LCIA Monetary Valuation

Monetisation assigns relative monetary values to the impact categories indicators results using monetary valuation coefficients [34]. It allows for integrating economic considerations into the assessment, enabling decision-makers to prioritise and make informed choices based on the overall environmental and economic impacts [34].

The choice of monetisation methods – and their monetary valuation coefficients - depends on the context, objective, and scope of the study and the availability of information for the site-specific project. The different available monetary valuation methods are discussed in section 2.4.4 and extensively explained in [60].

The output of this stage is a single-score monetary value aggregated from all monetised indicator results. These values compare the environmental burden of the different coastal engineering considered. By performing LCIA and incorporating monetisation, the framework aims to offer valuable insights into the environmental impacts of different coastal solutions, facilitating informed decision-making processes.

3.3. Ecosystem Services Assessment (ESA) Monetary Valuation

3.3.1. Introduction

Coastal engineering interventions can significantly enhance ecosystem services, providing various socio-economic benefits. The ESA aims to measure the sustainable value different coastal engineering interventions create for the economy, society, and the environment, which is often not accounted for. The impact of these interventions on selected ES is measured and monetary valued. The following sections present a step-by-step approach for conducting a monetary valuation of the impact of coastal engineering interventions on ecosystem services. The primary references for this part of the framework are TEEB [41], WRI [100], Seyedabdolhossein Mehvar, et al. [27], B Gregg, et al. [103] and MEA [104].

3.3.2. Scoping Benefits

The first step is identifying the key ES the coastal engineering alternatives will impact. For different alternatives, there can be substantial variation in the generated or impacted ES. The project could directly or indirectly impact these services. Not all ecosystem services will be equally relevant. An ecosystem service is considered relevant if (1) an ecosystem is potentially impacted, (2) this impacted ecosystem could provide a service, and (3) there are beneficiaries of the impacted service. Consideration should be given to the services' contribution to local livelihoods, health, safety, or culture and their importance to the local community. Some coastal ES are presented in section 2.3.3.

Methods to Identify Relevant ES

The process of identifying relevant ecosystem services (ES) depends on the objective of the assessments along with the available data and resources. This can be achieved through various methods, such as expert elicitation, literature reviews, and stakeholder engagement. To identify significant ES, one should consider which ecosystems and their services could be impacted by the project and who the potential beneficiaries are. Figure 3.2 presents an approach for selecting relevant ecosystem services.

3.3.3. Scope and Information Needs

This step establishes the spatial and temporal boundaries of the ESA and identifies indicators of impacts.

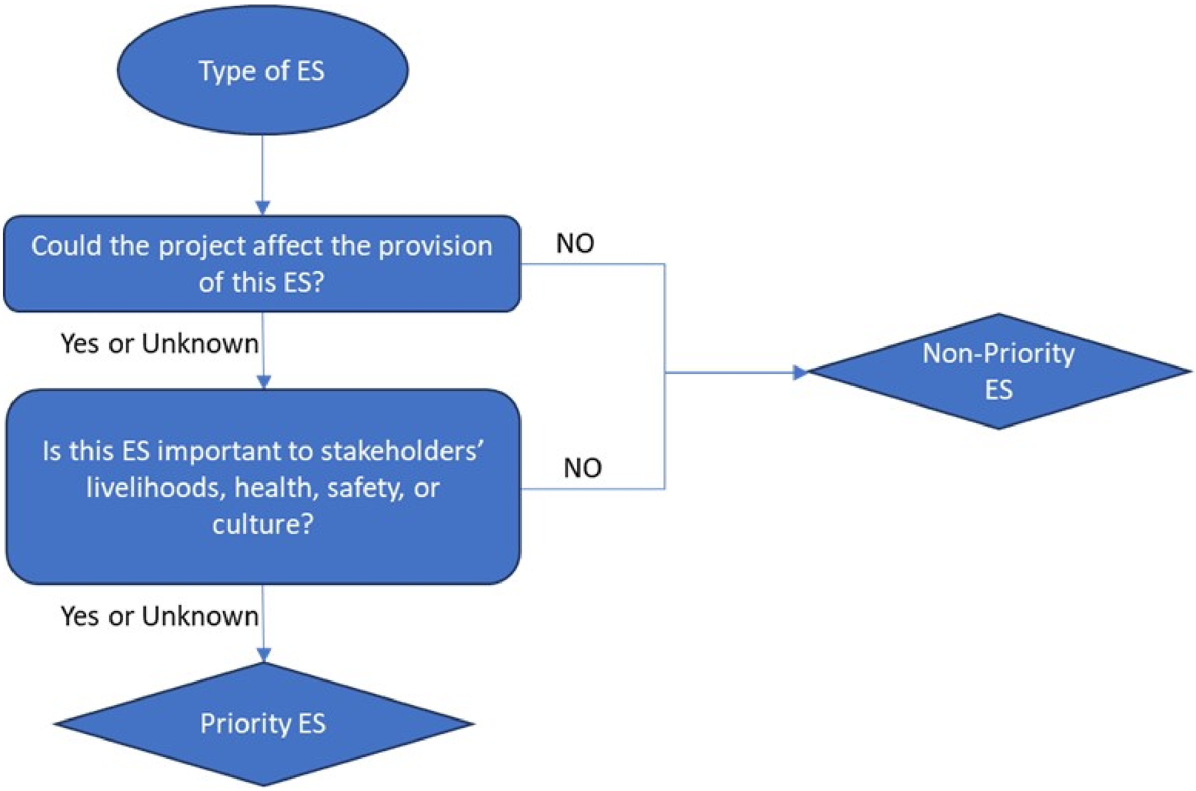

Figure 3.2: Approach for selecting relevant ES. Adopted from [69]

Delineating the Ecosystem Service Impact Assessment Area

The spatial boundary for the ESA is that area that includes the ecosystems affected by the project and the locations where stakeholders access or benefit from the selected ES. This encompasses coastal habitats like beaches, dunes, estuaries, coral reefs, seagrass beds, mangrove forests, and areas further inland that directly or indirectly benefit from the project [100].

Delineating the Ecosystem Service Impact Assessment Time Scale

Like the LCA, the temporal boundary refers to the timeframe for evaluating ecosystem services (ES), ideally matching the project's intended lifespan. However, depending on the study's objectives and scope and the type of ES, the project's influence on the ES could also be considered during various phases of the project's life. Thomas Koellner, et al. [90] discussed various assumptions around the change in ES quality due to changes in land use.

Identifying Indicators of Project Impact on Ecosystem Services

Indicators of ecosystem service benefits show how changes in the supply of ecosystem services can affect their contributions to human well-being [105, 100]. These socio-economic indicators provide information about the potential value changes of ecosystem services to society. Examples include tourism (revenue or visitors), property value, fisheries productivity, coastal livelihoods, flood damage reduction, coastal erosion mitigation, biodiversity conservation, and carbon sequestration. C Brown, et al. [105] discussed the methodology for selecting ES indicators and presented some.

Method to Define the Scope and Information Needed

In this step, the project area and surrounding environment are mapped, and key indicators are identified to measure changes in ecosystem services. The method used for this step depends on the assessment's scope, data availability, and resources. Suppose the necessary information is not provided in the project documents. In that case, it can be obtained through expert elicitation or consulting various stakeholders, including local communities, regulatory agencies, and other affected parties. Surveys, interviews, public meetings, and participatory methods may be employed to gather information and understand stakeholders' perspectives and their reliance on ecosystem services. Modelling tools, such as the Integrated Evaluation of Ecosystem Services and Trade-off (InVEST) model, can also be used to define areas of interest. For instance, the InVEST model offers the Coastal Vulnerability Index, which assesses the exposure of coastal landscapes to erosion and flooding during severe weather based on geophysical and natural habitat characteristics.

3.3.4. Baseline for ESA

In this step, the condition of the selected ES is determined, along with the current levels of use and benefit for each identified indicator within the specified scope. Assessing how these ecosystem services contribute to affected stakeholders' livelihoods, health, safety, or culture is essential. Understanding the interconnection between ecosystem services and benefits will aid in predicting the project's impact on the supply and benefits of ecosystem services.

Methods to Establish the Baseline Scenario

Depending on the ESA scope and data availability, the baseline study can be conducted through expert elicitation or active engagement with local communities, regulatory agencies, and other stakeholders. This engagement aims to gather information about their utilisation and reliance on the selected ecosystem services. Methods such as surveys, interviews, and public meetings may facilitate this data collection process.
The expected outcome of this step is an assessment of the existing and projected conditions, utilisation, and benefits associated with each indicator of ecosystem services. This baseline would serve as a reference point for assessing the project's impacts on ecosystem services and their benefits to human well-being.

3.3.5. Impact Assessment

This step assesses the impact of the different coastal engineering interventions on ES. Building upon the baseline step's finding, the project's impact on the supply and benefits of the ES through their indicators is determined. This step also involves evaluating the consequences of these changes on the well-being of the affected stakeholders.

Method To Predict Project Impact on Selected ES

This step involves utilising expert estimates, scientific and socio-economic data, literature, and other tools to predict changes in ecosystem conditions and functions. These resources are used to make informed predictions and assessments regarding the potential alterations that may occur.

3.3.6. ESA Monetary Valuation

In this step, the impact of the coastal solution is measured in monetary value. The impact on each ES is monetised separately, and then all values are aggregated into a single monetary value according to the total ecosystem service value framework.

Selecting the Monetary Valuation Method

In this step, the most suitable methods for valuing the changes in each ES are identified. The selection of these methods depends on the assessment's goal, scope, and availability of data and resources, as well as on the ES and its indicators type. The valuation methods and their suitability for different ES are illustrated in Tables 2.2 and 2.3. Based on the monetary valuation method and impact magnitude, a monetary value is assigned to each ES indicator.

Calculating the Total Ecosystem Value

In this step, the monetary values of all key ecosystem services affected by the project, directly and indirectly, are combined into a single value using the total ecosystem service value framework. This step involves aggregating the individual monetary values to provide an overall measure of the project's economic impact on ecosystem services.

3.4. Financial Analysis

In this phase, the outcomes of the monetary valuation are contextualised within the framework of the project's goals and articulated in a functional unit that is compatible with subsequent economic evaluations, such as Cost-Benefit Analysis (CBA), Net Present Value (NPV), and Internal Rate of Return (IRR)

[87]. These evaluations incorporate the monetary value derived from the Ecosystem Services Assessment (ESA) as a benefit. Conversely, the cost derived from the Life Cycle Assessment (LCA) is added to the capital and maintenance costs of the project, thereby providing a comprehensive view of the project's financial implications. The assignment of monetary values to ecosystem services and the environmental impact of various coastal engineering alternatives underscores their economic importance, promoting the adoption of sustainable alternatives.

3.5. Results Interpretation

The interpretation of results is a crucial part of the monetary valuation framework. This section is meant to give a thorough understanding of the outcomes from the earlier parts of the framework (LCA monetary valuation, ESA monetary valuation, and economic valuation). It includes a summary of the monetary values, highlighting key findings and comparisons between the coastal engineering alternatives. The interpretation also addresses the assumptions and limitations of the valuation process, their potential impact on the results, and the implications of any changes in these assumptions through a sensitivity analysis. The results are put into the context of the specific coastal engineering project, considering local environmental, social, and economic conditions, as well as relevant policy or regulatory factors. Based on the interpretation, recommendations are provided for decision-making, which could suggest the most cost-effective and environmentally friendly alternative or identify areas for further research. Finally, the interpretation discusses the implications of the findings for future research, including potential refinements to the monetary valuation framework and new research questions prompted by the study.

3.6. Framework Overview

This section outlines the framework's analytical methods, specifically customised to fulfil the study's objectives within practical limitations such as time, data, and funding availability, as outlined in Table 3.1. The framework offers a versatile approach, accommodating either a rapid or comprehensive monetary valuation of the coastal engineering alternatives, depending on the study's goals and existing constraints.

The rapid assessment utilises expert elicitation for identifying benefits and employs value transfer, global data analysis, and index-based valuation approaches for cost and benefits valuation (Table 2.3). In contrast, comprehensive assessment necessitates local data collection, such as interviews and field observations, to ensure higher accuracy. This involves participatory approaches for identifying benefits and solutions, local economic impact modelling of coastal engineering alternatives, benefit valuation using local primary data (e.g., stated and revealed preference methods and local market price analysis), and estimation of opportunity costs using primary local data [56].

Table 3.1: Framework overview with method and data collection suggestions for quick and comprehensive assessment.

Analytical step		Analytical methods and data collection suggestions	
		Quick Assessment	Comprehensive Assessment
LCA	Goal and scope	Study Objectives scope	Study Objectives scope
	Functional Unit	Expert elicitation, 1 km of coastal length protected	
	System Boundary	Expert elicitation, usually in the construction and maintenance phase	All project life cycles
	Temporal boundary	-	-
	LCA Application	Expert elicitation	LCA Applications: RThink, SimaPro, GaBi, OpenLCA, ReCiPe2016

Table 3.1: Framework overview with method and data collection suggestions for quick and comprehensive assessment. (Continued)

Analytical step		Analytical methods and data collection suggestions: Quick Assessment	Comprehensive Assessment
	Life Cycle Inventory	Estimate based on project documents, equipment specifications, material supplier, literature, and previous projects	Project documents, equipment specifications, material suppliers, literature, and previous projects
	Life Cycle Impact Assessment	Expert calculation for selected impact categories covering selected products in the project, e.g., using Excel	LCA Applications: RThink, SimaPro, GaBi, OpenLCA, ReCiPe2016
	LCA monetary Valuation	Expert elicitation, Value transfer [34] - Table 2.7	LCA monetary valuation Application - Table 2.6
ESA	Scoping Benefits	Expert elicitation, literature, Global Database of NBS benefits [106]	Stakeholder interview, Stakeholder/community, participatory mapping
ESA	Scope and Information Needs	Expert elicitation, literature	Stakeholder interview, Stakeholder/community, participatory mapping
ESA	Establishing Baseline reference	Expert elicitation, Literature	Stakeholder interview, Stakeholder/community, participatory mapping, spatial and economic Modelling
ESA	Impact Assessment	Expert elicitation, Literature	Stakeholder interview, Stakeholder/community, participatory mapping, spatial and economic Modelling
ESA	ESA Monetary Valuation	Value/Benefit transfer - Appendix C, literature e.g.,[1, 107, 108, 48, 97, 95], Mapping Ocean Wealth Explorer [109], NBS Benefits Explorer [106] - Global (geospatial) risk reduction value datasets	High-resolution ecosystem extent and condition datasets (and complete natural capital account if available), local market prices of benefits/ecosystem services (agricultural output, nature-based tourism, fish, property value), and stated preference surveys
Economic Valuation	Assumptions	Discount rate, growth (inflation rate), terminal value	
Economic Valuation	Costs	Investment, maintenance, their resulted environmental costs (LCA), ES negative monetary Value	
Economic Valuation	Benefits	ES positive monetary value	
Economic Valuation	Cost Benefit Analysis	Net Present Value (NPV), Internal Rate of Return (IRR) and Return on Investment (ROI), according to [87]	
Result Interpretation		Discuss the result and perform sensitivity analysis (e.g., different discount rates)	

4 Framework Application: Case Study

4.1. Introduction

This chapter presents an application of the monetary valuation framework proposed in Chapter 3. The framework is applied to a hypothetical case study comparing two coastal solutions - sea dike and dune nourishment, for a seven-kilometre coastal stretch in the Netherlands. Table 4.1 presents the input parameters and assumptions used for both alternatives.

Table 4.1: Input parameters and assumptions used for both alternatives.

Category	Material	Unit	Sand Nourishment	Sea Dike	Ratio*
Spatial length		km	7	7	-
Lifetime		Year	50	50	-
Resources	Sand	m^3	28650000	2839788	10.1
	Clay	ton	-	567958	-
	Asphalt	ton	-	70694	-
	Steel	ton	-	25312	-
	Gravel	ton	-	1671384	-
Fuels	Marine Gas Oil	ton	20094	3968	5.1
	Diesel	Litre	876789	966972	0.91
Assumption					
Fuel Consumption Rate	Marine Gas Oil [110]	l/m^3	0.5	0.5	1
	Marine Gas Oil [110]	l/m^3	1.05	1.05	1
	Diesel	l/h	280	280	1
Density	Marine Gas Oil	kg/l	0.845	0.845	1
	Gravel/Rock	ton/m^3	1.8	1.8	1
	Asphalt	ton/m^3	2.35	2.35	1

***** Ratio of the quantities of the sand nourishment (column 4) to that of the sea dike (column 5), Marine Gas Oil's consumption rate = 1.05 l/m^3 for pumped materials and 0.5 l/m^3 for dumped materials.

4.2. Analytical Approach

The analytical approach used in this case study is the monetary valuation framework for coastal engineering interventions, as established in Chapter 3. For each alternative, a quick Life Cycle Assessment (LCA) and Ecosystem Services Assessment (ESA) are conducted and monetary valued. Then, a cost-benefit Analysis is performed to compare the net cost and benefit of each alternative. The flow of this analytical framework is presented in Figure 4.1.

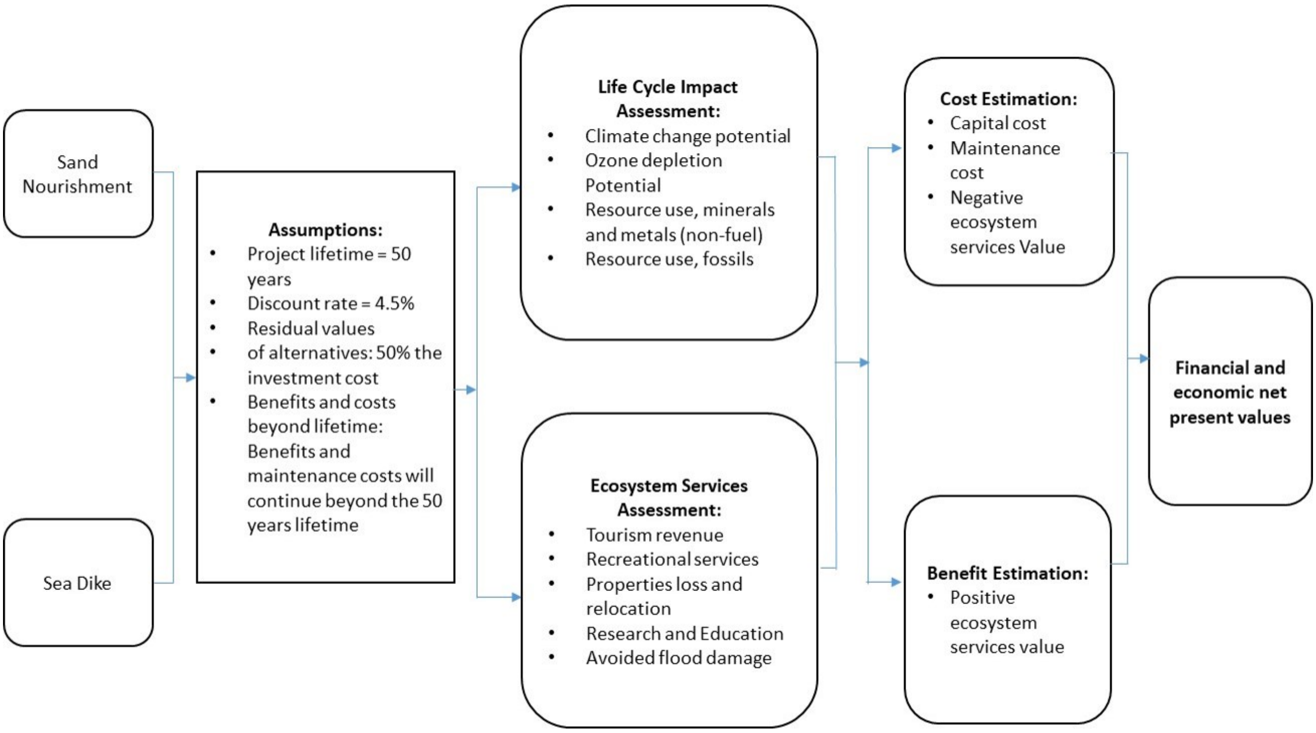

Figure 4.1: The analytical approach for the case study.

The following sections discuss the two alternatives following the quick assessment part of the ES-LCA monetary valuation framework.

4.3. Part 1: Life Cycle Assessment

4.3.1. Goal and Scope

LCA analysis of the two coastal alternatives aims to determine which has a lower ecological impact over the 50-year life cycle expressed in monetary cost. The scope is limited to the environmental impact categories: climate change - total, ozone depletion, depletion of abiotic resources - minerals and metals, and depletion of abiotic resources - fossil fuels. Other impact categories were excluded as they were unavailable for all products, and others were reported with different units for different products. Therefore, only impact categories reported for all products with the same unit are selected to ensure comparability between sand nourishment and sea dike alternatives.

Appendix C briefly explains these impact categories. The impacts and their monetary valuation coefficients (MVCs) for all products compromising both alternatives are obtained from the literature, expert opinion, and a quick estimation using R<THiNK LCA web application for the products with no environmental performance profile available in the literature.

4.3.2. Life Cycle Inventory (LCI)

The LCI data for the coastal engineering dune and sea dike alternatives are obtained from the literature. The materials required for the project are listed in Table 4.1. The resources and material quantities were assumed based on similar projects reported in the literature such as [17]. Similarly, the fuel quantities were estimated based on similar previous projects, using an expert opinion and accounting for all phases of LCA.

A. Sand Nourishment Alternative

Sand Nourishment only material is sand that is assumed to come from the sea about eight nautical miles from the project location. Sand is transported using medium Trailing Suction Hopper Dredgers (TSHDs) for shore replenishment and larger TSHD hopper dredgers for beach and dune replenishment. It is also assumed that 40% of the sand was dumped and 60% was pumped. Land equipment was also needed for the beach and dunes phase: bulldozers, excavators, and wheel loaders.

This study assumes that there is no environmental impact on the sand material itself, as it is a natural material that will also end up in nature. The environmental impact of the sand nourishment alternative is calculated solely based on fuel consumption: marine gas oil for vessels and diesel for land equipment, per EN 15804+A2 standards. The fuel consumption for the realisation of the project is taken as 0.5 litter Marine Gas Oil (MGO) per cubic meter of sand dumped foreshore (0.5 L MGO/m^3) and 1.05 L MGO per cubic meter of sand pumped ashore (1.05 L MGO/m^3) [110]. For shore–land -operation, the fuel consumption was estimated to be 0.074-litre diesel per cubic meter of sand pumped ashore (0.074 L/m^3). The construction is assumed to take a year.

B. The Sea Dike Alternative
The materials needed for constructing the sea dike that provides the same coastal protection as the sand nourishment are listed in 4.1. Similarly, sand is assumed to come from the sea about eight nautical miles from the project location. Clay is sourced from land and assumed to be transported by barges (~150 km distance) and land transport (~12 km). The environmental impacts considered for sand and clay are that resulted from the fuel consumption during transporting and installing them.

The hydraulic asphalt environmental profile reported by Ieke Bak, et al. [111] was used to obtain the life cycle environmental impact from the extraction phase (A1) to the end-of-life phase (D). The life cycle ecological profile for steel and gravel products was calculated using the R<THiNK LCA web application. The ecological profile of both sand and clay were calculated from the fuel consumption during their transportation and construction – Vessel MGO and land equipment diesel, from the same tables used for sand nourishment alternatives TNO [112] and NMD [113]. The fuel consumption for the sand and clay per cubic meter is the same value estimated for the sand nourishments: 0.5 L MGO/m^3 dumped, 1.05 L MGO/m^3 pumped ashore, and 0.074L diesel/m^3 pumped ashore. The construction is assumed to take two years. The environmental impact tables of all products involved are presented in the Appendix B.3.

4.3.3. Life Cycle Impact Assessment

A. Environmental Footprint Impact Categories
The environmental profile for products involved in each alternative over the project lifecycle was obtained from the literature, and the relevant tables are presented in Appendix B, section B.3. The Life cycle impact for the two alternatives was calculated by summing up the impact of all their products, presented in Table 4.1. The total environmental impact per category over the project's life cycle for the sand nourishment and sea dike alternatives is presented in Table 4.2.

The indicators used for global warming, ozone depletion, depletion of abiotic resources (minerals and metals, and fossil fuels) are the global warming potential (GWP), ozone depletion potential (ODP), resource use - minerals & metal (ADP) and resource use - fossils (ADP), respectively.

Table 4.2: Environmental impacts of the sand nourishment and sea dike alternatives over their 50-year lifetime. A = Construction, B = Maintenance.

EF - ICs	Units	Nourishment [1]		Dike [2]		Ratio - [1] : [2]	
		A	B*	A	B**	A	B
GWP	kg CO_2 eq.	7.87E+09	2.36E+08	2.5E+09	1E+08	315%	236%
ODP	kg CFC11 eq.	1.79E+03	5.38E+01	5.90E+02	2.36E+01	304%	228%
ADP - non-fossils	kg Sb eq.	5.23E+03	1.57E+02	9.56E+03	3.82E+02	55%	41%
ADP - fossils	kg Sb eq.	5.37E+07	1.61E+06	2.78E+07	1.11E+06	193%	145%

EF - ICs: Environmental Footprint Impact Categories, **GWP:** Global Warming Potential indicator for global warming, **ODP:** Ozone depletion potential indicator for ozone depletion, **ADP - non-fossils :** resource use, minerals & Metal indicators for the depletion of abiotic resources - minerals and metals, **ADP - fossils:** resource use, fossils indicator for the depletion of abiotic resources – fossil fuels. * Sand nourishment maintenance is assumed to account for 3% of the project resources and environmental impact. ** Sea dike maintenance is assumed to account for 4% of the project resources and environmental impact.

4.3.4. Monetary Valuation of Environmental Impacts

The cost associated with the environmental impact of project construction and maintenance was calculated by multiplying their total environmental impact presented in Table 4.2 with their monetary valuation coefficients (MVCs) presented in Table 4.3. This resulted in the environmental cost reported in Table 4.4.

Table 4.3: The Monetary Valuation Coefficient (MVCs) for the impact categories considered for both alternatives. Source: NMD [71] and Amadei, et al. [34]

Environmental Impact Categories Indicators	Unit	MVCs - Global [34]			MVCs-NL[71]
		Min	Max	Average	
Global warming potential (GWP)	€/kg CO_2 eq.	2.07E-02	6.71E-01	2.07E-02	5.00E-02
Ozone depletion potential (ODP)*	€/kg CFC-11 eq.	3.14E+01	1.13E+02	5.44E+01	3.00E+01
Resource use, minerals & Metal (ADP)	€/kg Sb eq.	1.62E+00	1.88E+04	4.71E+03	1.60E-01
Resource use, Fossils (ADP)	€/kg Sb eq.**	6.22E-07	8.30E-06	4.75E-06	1.60E-01

***** These values are as reported in Table 4 of Amadei, et al. [34] 's article; for other IC, the MVCs are extracted from their Table 2.
****** Converted from MJ unit using the conversion factor 4.81E-4 kg antimony/MJ [71].

Table 4.4: Environmental Lifecycle cost in millions due to the sand nourishment and sea dike alternatives and their maintenance work. All values are in Euros over the project lifecycle (50 years)

Reference	Sand Nourishment		Sea Dike	
	Construction	Maintenance	Construction	Maintenance
Globally Estimated Value (Min)	162.86	4.88	51.78	2.07
Globally Estimated Value (Max)	5383.52	161.47	1859.77	74.39
Globally Estimated Value (Avg)	187.51	5.62	96.81	3.87
NL's NMD value	402.20	12.06	131.28	5.25

4.4. Part 2: Ecosystem Services Assessment

The ecosystem service concept is used to monetarily value and compare the positive and negative impacts of sand nourishment and sea dike alternatives, following the quick assessment framework in Chapter 3, and Table 2.1. The ecosystem services considered for the monetary valuation were based on Arcadis's report [114] and the availability of economic value of the ecosystem service in the literature.

4.4.1. Step 1: Scoping Benefits

Based on similar projects, the coastal solutions' objective includes flood protection and spatial quality, focusing on elements such as nature, landscape, cultural heritage, leisure and tourism, access, and residential environment [115, 17]. Accordingly, the key ecosystem services selected for this assessment are tourism, recreation, research and education, avoided property and relocation damage, avoided pollution damage, and avoided flood damage. Both alternatives provide the same safety protection. The environmental impact/temporary negative ecosystem services resulting from the disturbance to marine life during the movement of sand are ignored due to a lack of monetary valuation data.

4.4.2. Steps 2-5: Impact Assessment and Monetization

Arcadis [115] has qualitatively evaluated the impact of the several coastal alternatives on the selected ecosystem services using a 7-point scale compared to an existing situation: very positive (++), positive (+), slightly positive (0/+), no effect (0), somewhat negative (0/-), negative (-), and very negative. This 7-point scale is converted to a percentage scale to provide a weighting factor of impact for the sand nourishment and sea dike alternatives, e.g., ++, +, 0/+, and 0, are assumed equivalent to 100%, 50%, 25%, and 0%, respectively.

The monetary values for selected services are obtained from the literature such as Arcadis [114], Ronja Bechauf et al. [17], and others as referenced in Table 4.5. The ratio between sand nourishment and sea dike values is assigned following Arcadis's [115] 7-point scale. The weighting scale ensured the ability to assign a monetary value to both alternatives. Table 4.5 shows the selected ecosystem services and their monetary value.

Table 4.5: Coastal ecosystem services and their monetary value.

Coastal Ecosystem Services	Unit	Sand Nourishment	Sea Dike	References
Tourism	€/year	6293000	1573250	[17]
Recreational	€/year	1712593	366722	[116]
Properties loss and relocation	€/year	160000	(8000000)*	[117]
Avoided pollution damage	€/year	31472	31472	[17]
Avoided flood damage	€/year	2222780	2222780	[17]
Research and education	€/year	1233433	308358	[27]

***** Property loss and relocation due to sea dike only occur in the project's first year.

According to the data presented in Table 4.5, the economic value of tourism, research, and education associated with sand nourishment is four times higher than that of the sea dike. Similarly, the recreational value generated from sand nourishment is 4.7 times greater than that of the sea dike. The sea dike and sand nourishment alternatives provide the same level of protection services and are given equal weight. However, some residential houses are assumed to be removed to construct the sea dike. The cost of the removed houses is assumed to be 8 million euros. This damage cost is considered a negative aspect for the sea dike in the first year of construction and is added as a positive value for the sand nourishment alternatives over the project's lifetime.

These benefits and impacts sand nourishment and sea dike were determined through a combination of recognised economic valuation techniques, such as benefit transfer, and expert elicitation methods. According to Ronja Bechauf, et al. [17], these methodologies were chosen based on their suitability to assign monetary values to each ecosystem service and benefit. In line with the classification of ES [25], the services under the avoided pollution damage and carbon storage categories can be seen as the benefits derived from the natural system's ability to regulate environmental aspects and, hence, are considered 'Regulatory'. Tourism and recreation fall under the cultural category because it relates to recreation and human interaction with the ecosystem.

4.5. Part 3: Financial Analysis & Result Discussion

The primary objective of the financial analysis is to evaluate the financial performance of two alternatives, taking into account their environmental, social, and economic costs and benefits. This comprehensive approach allows decision-makers to make informed judgments about their overall value to society throughout their lifecycle. The financial analysis integrates the monetary values of environmental impact and ecosystem services with the construction and maintenance costs of the two coastal protection alternatives in the cost-benefit analysis, specifically through the Net Present Value (NPV). All monetary values have been adjusted to their 2015 equivalents. The discount and growth rates for public physical investments/infrastructure in 2015 were 4.5% and 1.64%, respectively [118, 17].

Moreover, it is assumed that the maintenance cost, environmental cost due to maintenance, and ecosystem benefits will continue beyond the 50-year time horizon of the financial analysis. The terminal values - the value of flows beyond the forecast period - are calculated using the same discount and growth rate.

4.5.1. Cost-Benefit Analysis

This section puts together the main components of the comprehensive financial analysis:

1. Investment (CAPEX) and maintenance (OPEX) costs
2. LCA - Environmental impact monetary values (Costs)

3. ESA - Ecosystem services monetary values (Benefits)

A. Sand Nourishment Alternative
The construction (CAPEX) and maintenance (OPEX) costs for the sand nourishment were estimated at € 181,450,000 and € 36,260,000. The maintenance work is assumed to be performed every consecutive year, alternating between foreshore and beach nourishment, for € 1,510,810 per maintenance cycle over the project's lifetime (~€755,405 per year).

B. Sea Dike Alternative
The sea dike alternative is estimated to incur construction costs of € 214,108,135 and maintenance costs of € 8,311,709. The maintenance work is expected to be carried out annually, with an estimated cost of € 173,161 throughout the project's lifetime.

The LCA - environmental impact monetary values (Costs) and ESA - ecosystem services monetary values (Benefits) have been presented in sections 4.3.4 and 4.4.2. Table 4.6 summarise the overall costs and benefits of the two coastal protection alternatives. These values represent the input for the NPV analysis.

Table 4.6: Summary of the costs and benefits of the sand nourishment and sea dike alternatives, with all values reported in 2015 euros. Without brackets = Benefits, between brackets = Costs

Category		Unit	Sand Nourishment	Sea Dike
CAPEX	Construction cost	€	(181,450,000)	(214,108,135)
OPEX	Maintenance cost	€/year	(755,405)	(173,161)
Ecosystem Services*	Tourism	€/year	6,293,000	1,573,250
	Recreation	€/year	1,712,593	366,722
	Research and education	€/year	1,233,433	308,358
	Properties loss and relocation	€/year	160,000	(8,000,000)*
	Avoided flood damage	€/year	2,222,780	2,222,780
Environmental cost - Netherlands [71]	Due to project construction	€/year	(8,043,925)	(2,625,665)
	Due to project maintenance**	€/year	(6,031,768)	(109,403)
Environmental cost - Global [34]	Due to project construction	€/year	(5,623,852)	(1,936,134)
	Due to project maintenance**	€/year	(2,811,926)	(80,672)

* Tourism, recreation, and research and education services are assumed to start after the construction (1 year for sand nourishment and two years for the sea dike). The others are assumed to start immediately. Properties loss and relocation for sea dike occur only once - in the first year. ** The environmental cost of construction is divided by the 50-year project's lifetime. The environmental cost due to maintenance work starts after construction and is allocated to the years the maintenance takes place.

4.5.2. Net Present Value (NPV) & Return on Investment (ROI)Analysis

To effectively evaluate the two alternatives' financial performance while considering their environmental, social, and economic costs and benefits, the financial analysis is performed in four scenarios (S1-S4), starting with only the capital investment and maintenance costs (S1), then adding the ecosystem services' costs and benefits only (S2), then adding the environmental costs only (S3). Then, in the fourth scenario, both the ecosystem services' costs and benefits and the environmental costs are added to the CAPEX and OPEX.

S1: Capital (CAPEX) and maintenance costs (OPEX) only
S2: S1 + the ecosystem services' costs and benefits
S3: S1 + the environmental costs
S4: S2 + the environmental costs

The NPV and ROI analysis results for the two coastal alternatives for the four scenarios are presented in Figures 4.2 and 4.3, respectively. These results are discussed in the following sections.

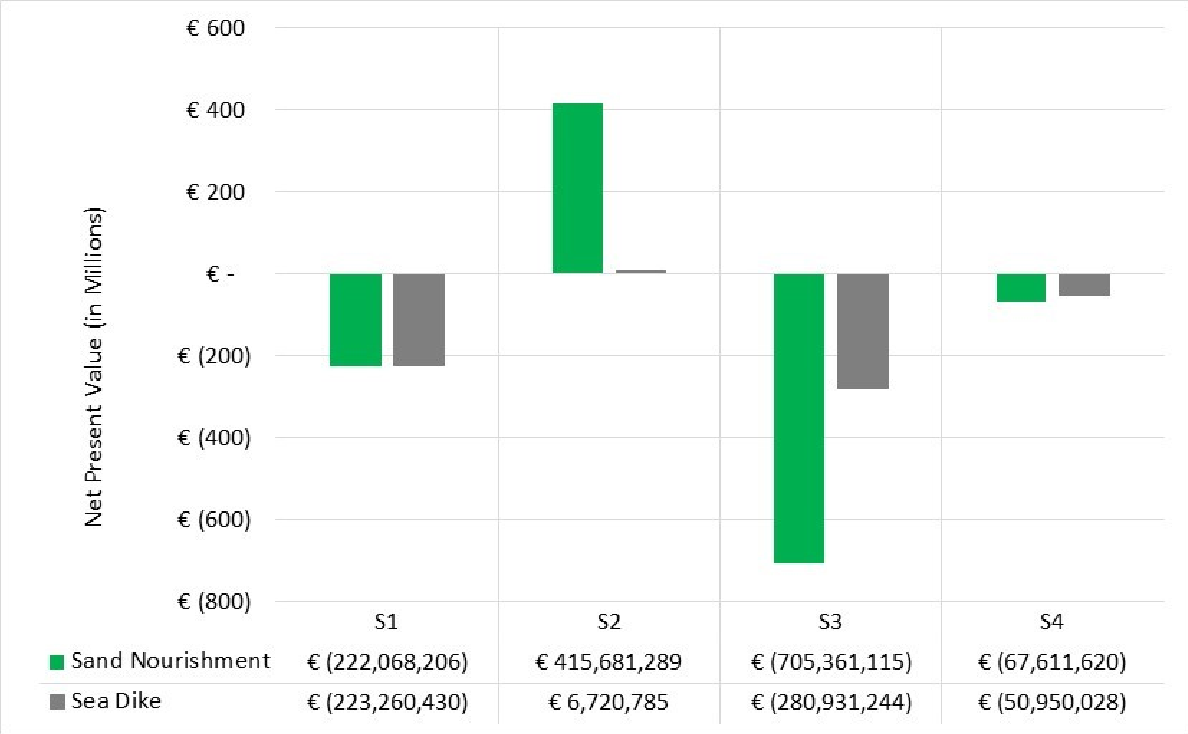

Figure 4.2: Net Present Value (NPV) of the two coastal protection alternatives with four scenarios (S1 - S4) at 4.5% discount rate and 1.64% growth rate

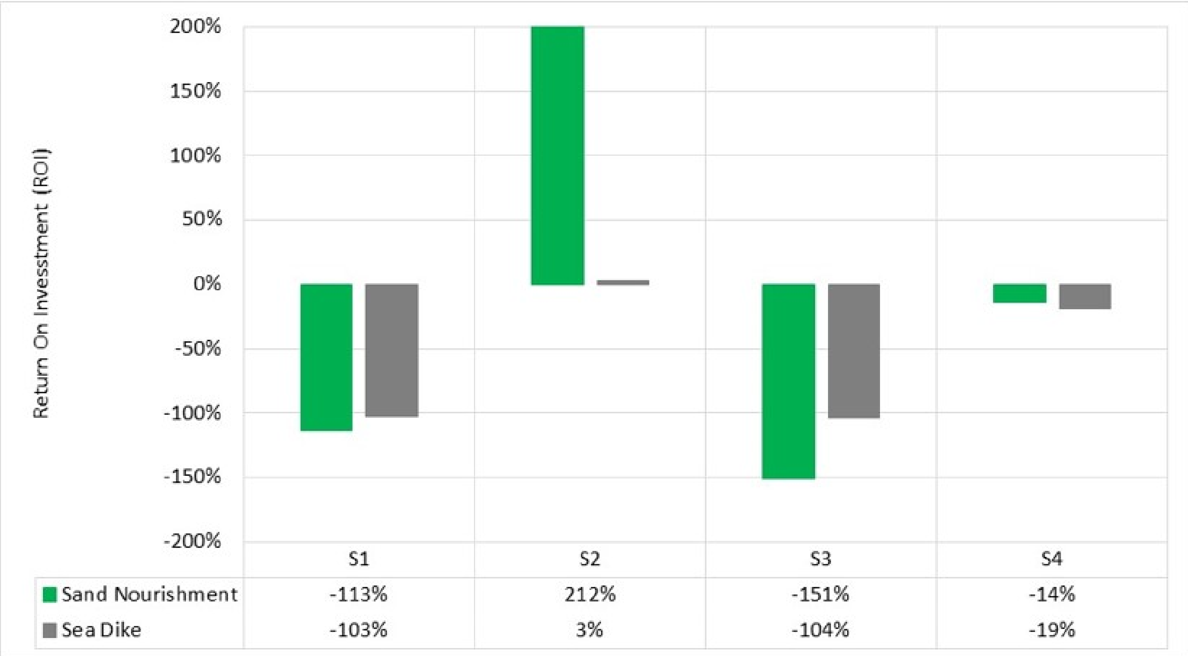

Figure 4.3: Return on investment (ROI) of the two coastal protection alternatives with four scenarios (S1 - S4) at 4.5% discount rate and 1.64% growth rate

S1: **Financial Analysis for Scenario 1**

In this scenario (S1), the two coastal protection alternatives are analysed solely on their investment and maintenance costs. This is a useful base scenario as the ecosystem services' costs and benefits and the environmental costs do not generate monetary flow. The results shown in

Figures 4.2 and 4.3 show that both alternatives yield negative NPV and ROI. The results indicate that considering only coastal engineering projects' capital and maintenance costs renders them unprofitable. This is an expected result simply because no cash inflow is generated from the project. In addition, the higher maintenance cost for the sand nourishment leads to almost the same NPV as the sea dike even though it is ~35 million less in investment cost than the sea dike.

The ROI metrics for both alternatives in this scenario are also negative, with Sand Nourishment and Sea Dike returning -113% and -103%, respectively. These results indicate significant financial inefficiency, where each euro invested results in a considerable loss. The Sea Dike's slightly less negative ROI suggests a marginally better performance in minimizing losses.

S2: **Financial Analysis for Scenario 2**

In scenario 2 (S2), the financial analysis considers the investment and maintenance costs and the costs and benefits of ecosystem services. It presents a stark contrast between the two coastal protection alternatives. Sand nourishment emerges as a highly favourable option with a substantial positive NPV of €415.68 million, signalling a significant economic benefit. Conversely, the sea dike, while yielding a positive NPV of €6.72 million, falls short of the economic returns associated with Sand Nourishment. This considerable disparity underscores the potential profitability of Sand Nourishment based on the considered ecosystem services.

The ROI for Sand Nourishment in this scenario is notably high at 212%, indicating that the investment more than doubles in value. On the other hand, the Sea Dike's ROI is a modest 2%, suggesting it merely breaks even. These figures highlight sand nourishment as a far more lucrative investment in Scenario S2, while the sea dike appears to offer a limited economic return. This is because the ecosystem services provided by sand nourishment are valued higher than those offered by the sea dike, as shown in Table 4.6. Furthermore, these benefits continue beyond the project's lifetime.

S3: **Financial Analysis for Scenario 3**

In scenario S3, the financial analysis considers the investment and maintenance costs and their associated environmental costs (as shown in Table 4.6). Scenario S3 is characterized by negative NPVs for both alternatives, with sand nourishment experiencing a severe negative NPV at €(705) million. The Sea Dike, although also negative, exhibits a comparatively less severe NPV of €(281) million. This scenario indicates that both options are economically disadvantageous, but sand nourishment is particularly vulnerable under these conditions. This is due to the higher MGO used for the construction of sand nourishment and its associated environmental impact.

In this scenario, sand nourishment and sea dike have a return on investment (ROI) of -151% and -104%, respectively. This suggests that the sea dike is financially preferable to sand nourishment. One reason for this is that the environmental cost of sand nourishment is much higher than that of the sea dike alternative, as shown in Table 4.6. Additionally, maintenance-related environmental costs are expected to continue beyond the project's lifetime.

S4: **Financial Analysis for Scenario 4**

Scenario 4 considers all the project's direct and indirect costs and benefits mentioned in Table 4.6. This approach provides a comprehensive view of which alternative is more financially attractive when considering both ecosystem services and life cycle environmental impact. Surprisingly, as shown in Figures 4.2 and 4.3, both sand nourishment and sea dike alternatives approach break even but still remain negative. Sand Nourishment records an NPV of (€68) million, while the Sea Dike is slightly better at (€51) million.

The ROI figures in Scenario S4 indicate near break-even outcomes for both alternatives, with Sand Nourishment at -14% and the Sea Dike at -12%. While both options result in a minor loss, the relatively small negative ROI indicates that both alternatives are closer to financial viability in this scenario than in the others.

Summary
To help understand the relative performance of each alternative under varying conditions, the net present values (NPV) of sand nourishment and sea dike coastal protection alternatives across different scenarios are compared against the base scenario (S1). The percentage difference of each alternative in S2, S3, and S4 compared to S1 is calculated and presented in Table 4.7.

Table 4.7: The percentage difference of each alternative compared to the base scenario (S1)

Scenario	Percentage Difference from S1	
	Sand Nourishment	**Sea Dike**
S2: CAPEX, OPEX, ES Benefits	-287%	-103%
S3: CAPEX, OPEX, Environmental Costs	218%	26%
S4: CAPEX, OPEX, ES Benefits, Environmental Costs	-70%	-77%

In sand nourishment, Scenario S2 presents a dramatic improvement over the base scenario (S1), with a percentage difference of -287%, shifting from a negative NPV in S1 to a highly positive one. This substantial improvement indicates that sand nourishment becomes a significantly more attractive option under the conditions of Scenario S2. Conversely, Scenario S3 shows a severe deterioration, with a 218% increase in the negative NPV compared to S1, making this option much less financially viable. In Scenario S4, while the NPV remains negative, the project shows a 70% reduction in financial burden compared to S1, suggesting a moderate improvement. Overall, sand nourishment exhibits high sensitivity to the different scenarios, with outcomes ranging from highly profitable to significantly unviable.

For the sea dike, Scenario S2 also shows a marked improvement over the base scenario (S1), with a percentage difference of -103%, reflecting a shift towards a positive NPV and enhancing the project's financial attractiveness. Scenario S3, on the other hand, sees a 26% increase in the negative NPV, indicating a deterioration in financial viability, though less severe compared to sand nourishment. Scenario S4 offers a 77% improvement over S1, reducing the financial burden, though the NPV remains negative. Overall, the sea dike shows greater stability across scenarios, with Scenario S2 particularly enhancing its financial feasibility, while Scenarios S3 and S4 show more moderate changes in viability.

The choice between sand nourishment and sea dike is scenario-dependent, with no alternative consistently outperforming the other across all scenarios. This highlights the importance of tailored solutions based on specific environmental and economic conditions. Moreover, the result is sensitive to factors such as the monetary value chosen for each ES, the monetary valuation coefficients used to monetise the life cycle environmental impacts, and the discount rate used. The influence of these factors is explored in the following sensitivity analysis.

4.6. Sensitivity Analysis

This section explores the sensitivity analysis of the results to changes in input parameters. It's crucial to comprehend the link between inputs and outputs and identify the most influential variable on the outcome. The parameters expected to influence the result if varied and that are considered for the sensitivity analysis are:

- The discount rate
- The monetary value used to monetise the ecosystem services
- The monetary valuation coefficient used to monetise the environmental impacts
- Material used: volumes and delivery method
- Terminal Value

4.6.1. Change in Discount Rate

Discounting is a technique for comparing costs and benefits occurring at different times by converting future values into their present-value equivalents. Selecting low, moderate, and high discount rates in project financial analysis provides a comprehensive view of the project's financial viability under varying risk scenarios. It also supports informed decision-making, comparative analysis, and strategic planning by considering various market conditions.

The influence of different discount rates (DR) on the Net Present Value (NPV) analysis for the sand nourishment and sea dike coastal engineering alternatives under the four different scenarios (S1, S2, S3, and S4) presents a complex picture that is pivotal for decision-making in coastal management. This analysis is crucial as it helps understand these options' financial viability and long-term sustainability under varying economic conditions.

The NPV results for sand nourishment and sea dike vary significantly across the four scenarios and the three different discount rates (2%, 4.5%, and 10%), as illustrated in Table 4.8 and Figure 4.4. These variations indicate how sensitive the financial attractiveness of coastal engineering projects is to the chosen discount rate and the specific scenario considered.

Table 4.8: The influence of different discount rates on the NPV of the sand nourishment and sea dike coastal solutions - All values in millions of Euros, rounded to the nearest million.

Alternatives	Sand Nourishment			Sea Dike		
Discount Rate	2%	4.5%	10%	2%	4.5%	10%
scenario 1	€ (414)	€ (222)	€ (197)	€ (267)	€ (223)	€ (218)
scenario 2	€ 3,189	€ 416	€ 58	€ 1,108	€ 7	€ (135)
scenario 3	€ (2,526)	€ (705)	€ (404)	€ (383)	€ (281)	€ (246)
scenario 4	€ 1,077	€ (68)	€ (149)	€ 992	€ (51)	€ (163)

Both alternatives appear to have a wide range of NPV outcomes depending on the scenario and discount rate:

Sand Nourishment

S1: The NPV is negative across all discount rates. The NPV slightly improves as the discount rate increases, but it remains negative.

S2: At a 2% discount rate, sand nourishment shows a highly positive NPV, suggesting strong financial viability. However, as the discount rate increases, the NPV sharply decreases, remaining positive at 4.5% but becoming marginally positive at 10%.

S3: The NPV remains negative across all discount rates, reinforcing that sand nourishment may not be feasible in Scenario 3.

S4: The NPV is positive at a 2% discount rate but turns negative as the discount rate increases to 4.5% and 10%. The NPV worsens as the discount rate increases, highlighting its sensitivity to discount rate changes.

Sea Dike

S1: The NPV is negative at all discount rates. The NPV slightly improves as the discount rate increases, but it remains negative. However, it is less negative than sand nourishment at 2% discount rate but more negative at 4.5% and 10% discount rates, suggesting relatively less financial viability under these conditions.

S2: The NPV for the sea dike is positive at the 2% discount rate, indicating strong financial viability. However, as the discount rate increases to 4.5%, the NPV drastically decreases to €7 million, and at 10%, it turns negative to (€135 million). This suggests that the sea dike is only financially viable at lower discount rates in Scenario 2.

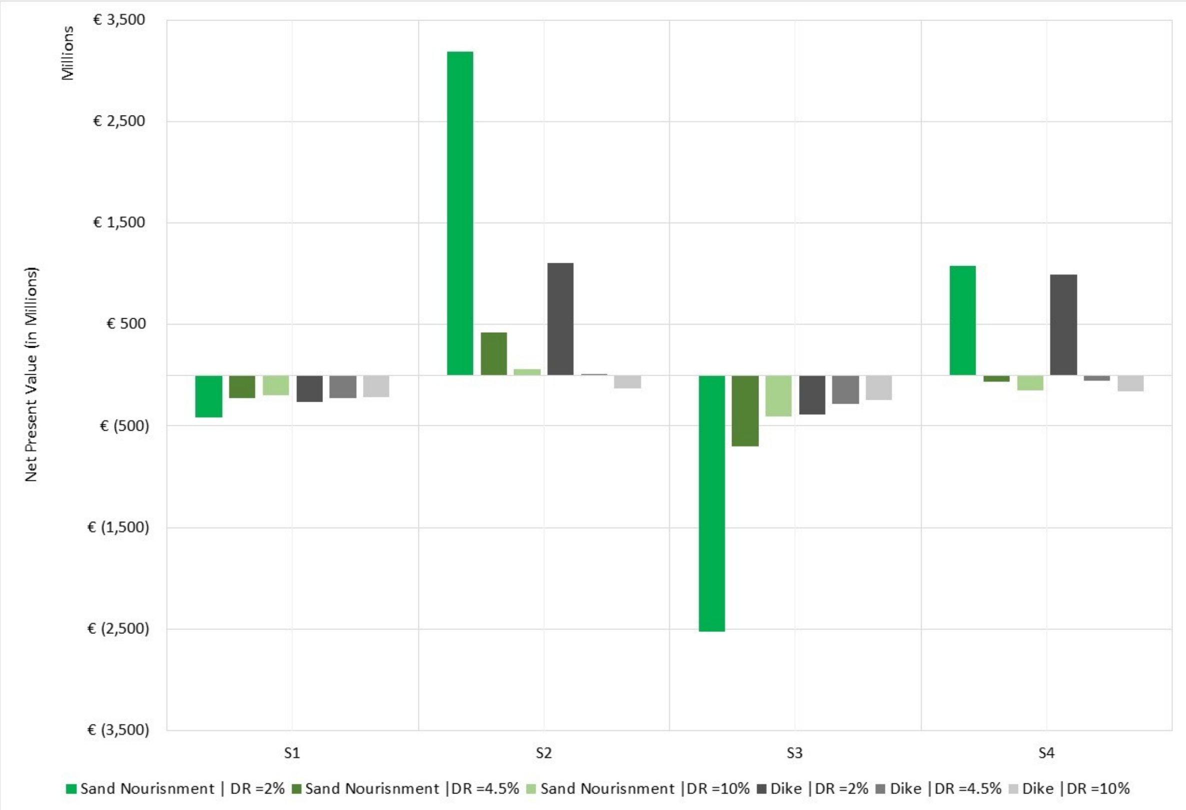

Figure 4.4: The influence of different discount rates (2%, 4.5%, and 10%) on the NPV of the sand nourishment and sea dike coastal solutions.

S3: The NPV is negative across all discount rates, indicating that the sea dike is not a financially viable option under these conditions. The NPV slightly improves as the discount rate increases, but it remains negative.

S4: The NPV is positive at a 2% discount rate but turns negative with higher discount rates, similar to the trend observed in sand nourishment.

Summary

The results underscore the critical impact of the discount rate on the financial analysis of coastal engineering projects. A lower discount rate generally favours projects with long-term benefits, such as sand nourishment and sea dikes, as it reduces the present value of future costs and increases the present value of future benefits. Conversely, a higher discount rate diminishes long-term investments' attractiveness by increasing future costs' present value.

Moreover, the variability in NPV across different scenarios for sand nourishment and sea dike options emphasises the importance of scenario planning in coastal engineering projects. It highlights how external factors and uncertainties can significantly impact the financial viability of these projects.

The analysis illustrates the nuanced and complex financial considerations that must be considered when evaluating coastal engineering alternatives. It highlights the importance of selecting an appropriate discount rate and carefully considering various scenarios to make informed, sustainable coastal management and protection decisions.

4.6.2. Change of Ecosystem Service's Monetary Value

This analysis focuses on the sensitivity of NPV to changes in the value of ecosystem services (ES) for the two alternatives: Sand Nourishment and Sea Dike. This sensitivity analysis is pivotal for understanding how the financial attractiveness of these alternatives is influenced by the incorporation of ecosystem services values, transitioning from low to medium and then to high-value ranges. Scenarios

1 (S1) and 3 (S3) serve as references since they do not account for ecosystem services, allowing for a focused analysis of Scenarios 2 (S2) and 4 (S4), which do incorporate these values. Table 4.9 and Figure 4.5 illustrate the sensitivity of the financial analysis of the two coastal alternatives to change in ecosystem service monetary value.

Table 4.9: Influence of different ecosystem service value on NPV analysis of the two coastal engineering alternatives (All values in millions of Euros, rounded to the nearest million)*

	High ES Value Range		**Mid ES Value Range**		**Low ES Value Range**	
	Dune	**Dike**	**Dune**	**Dike**	**Dune**	**Dike**
S1	€ (222)	€ (223)	€ (222)	€ (223)	€ (222)	€ (223)
S2	€ 2,127	€ 1,209	€ 416	€ 7	€ 31	€ (168)
S3	€ (705)	€ (281)	€ (705)	€ (281)	€ (705)	€ (281)
S4	€ 1,644	€ 1,151	€ (68)	€ (51)	€ (453)	€ (226)

*Negative values expressed in brackets, Dune = Sand Nourishment and Dike = Sea Dike, ES = Ecosystem Services

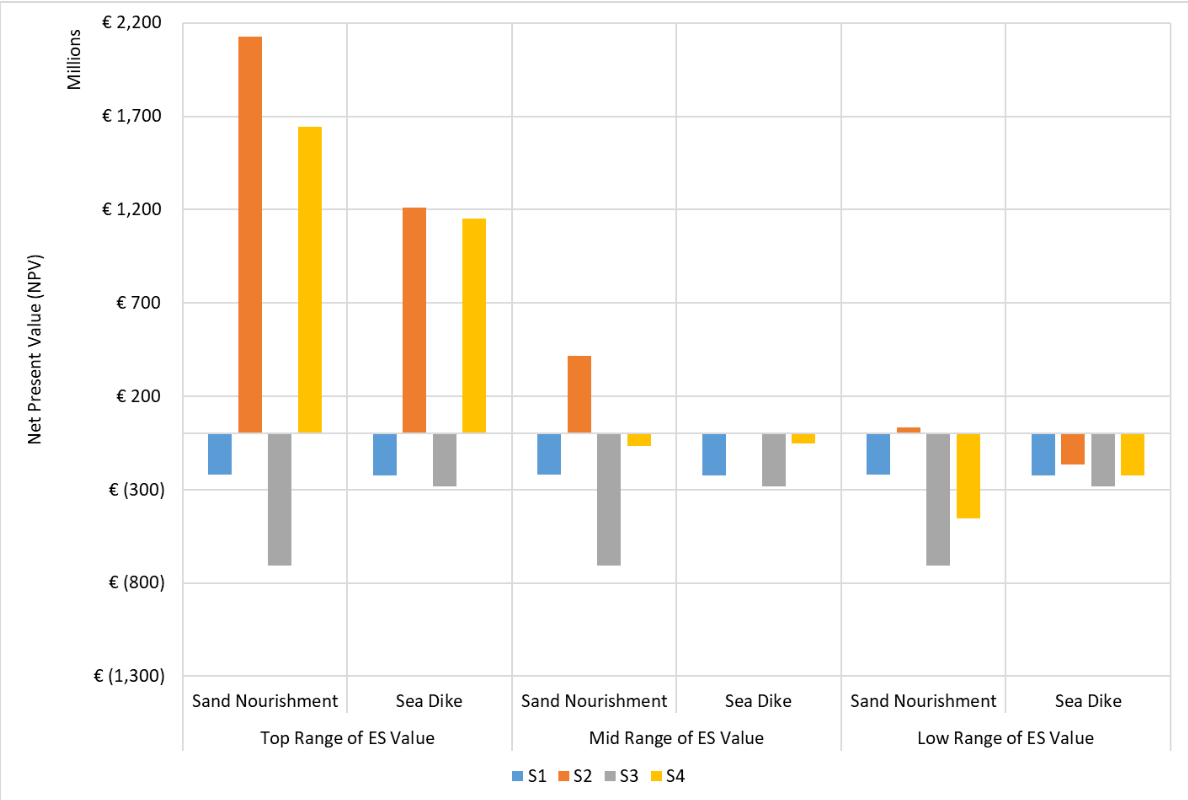

Figure 4.5: Influence of different ecosystem services value on NPV analysis of the two coastal engineering alternatives.

Sand Nourishment
When evaluating the NPV under S2, which considers capital, maintenance, and ecosystem services benefits, the sensitivity of sand nourishment to the valuation of ecosystem services is significant. As the value of ecosystem services estimate increases from low to medium and then to high, the NPV exhibits a substantial positive shift from €31, €416, and €2,127 million, respectively. This dramatic increase underscores the crucial role that ecosystem services valuation plays in enhancing the financial attractiveness of sand nourishment.

In S4, which further incorporates life cycle environmental impacts alongside the factors considered in S2, the sensitivity of sand nourishment's NPV to ecosystem services valuation remains pronounced but follows a nuanced trajectory. From a low value leading to an NPV of €(453) million, moving to a medium range results in a significant improvement to €(68) million, and eventually, a high valuation escalates the NPV to €1,644 million. This progression highlights the sensitivity and illustrates the mitigating effect of high ecosystem services valuation against environmental impact costs.

Sea Dike
For sea dike projects, S2 analysis reveals a sensitivity pattern where the Net Present Value (NPV) transitions from negative at a low ecosystem services value of €(168) million to marginally positive at a medium value of €7 million, and significantly positive at a high valuation of €1,209 million. This transition from negative to positive NPV underscores the substantial impact that the valuation of ecosystem services has on the financial feasibility of sea dike alternatives.

Incorporating life cycle environmental impacts in S4, the NPV of the sea dike shows marked sensitivity to ecosystem services valuation. The NPV shifts from a negative value of €226 million at low valuation to a less negative value of €51 million at medium valuation, and ultimately to a substantially positive value of €1,151 million at high valuation. This pattern highlights not only the sensitivity of NPV to ecosystem services valuation but also the potential for high ecosystem services valuation to offset environmental costs, thereby enhancing the overall NPV.

Summary
The sensitivity analysis of NPV to ecosystem services valuation reveals critical insights into the financial analysis of coastal engineering alternatives. For both sand nourishment and sea dike, the NPV is highly sensitive to the valuation of ecosystem services, with a clear trend: as the value of ecosystem services increases, so does the NPV, moving from negative or marginally positive figures to significantly positive ones. This trend underscores the importance of accurately valuing ecosystem services in the financial evaluation of coastal engineering projects. It highlights how a higher valuation of ecosystem services can significantly enhance the financial attractiveness of such projects, especially when environmental impacts are considered.

4.6.3. Change of Environmental Impact's Monetary Valuation Coefficients

The exploration of the sensitivity of the Net Present Value (NPV) to changes in Monetary Valuation Coefficients (MVCs) for two coastal protection measures—sand nourishment and sea dikes—reveals profound insights into the financial and environmental implications of incorporating environmental impacts into project valuations, as shown in Table 4.10 and Figure 4.6.

Table 4.10: Influence of different monetary valuation coefficients (MVCs) on NPV analysis of the two coastal engineering alternatives. (All values in millions of Euros, rounded to the nearest million)*

MVCs Used	NL's NMD		Global (Min)		Global (Avg)		Global (Max)	
Alternatives	Dune	Dike	Dune	Dike	Dune	Dike	Dune	Dike
S1	(222)	(223)	(222)	(223)	(222)	(223)	(222)	(223)
S2	416	7	416	7	416	7	416	7
S3	(705)	(281)	(450)	(246)	(484)	(266)	(7754)	(1040)
S4	(68)	(51)	188	(16)	153	(36)	(7117)	(810)

*Negative values expressed in brackets, Dune = Sand Nourishment and Dike = Sea Dike, ES = Ecosystem Services

Scenarios S1 and S2 serve as baselines, showing the NPVs of both alternatives without considering environmental impacts, thus unaffected by MVCs. Introducing environmental impacts into the NPV calculation in S3 and S4 brings the influence of MVCs into sharp focus. The sensitivity of the NPV to changes in MVCs across different scales—national (NL) and global (min, avg, max)—illuminates the substantial variance in financial viability, contingent on the valuation of environmental impacts. This section discusses the impacts of these MVC changes on the NPVs of sand nourishment and sea dikes, offering a comparative perspective on their financial viability and sensitivity to environmental impact valuation.

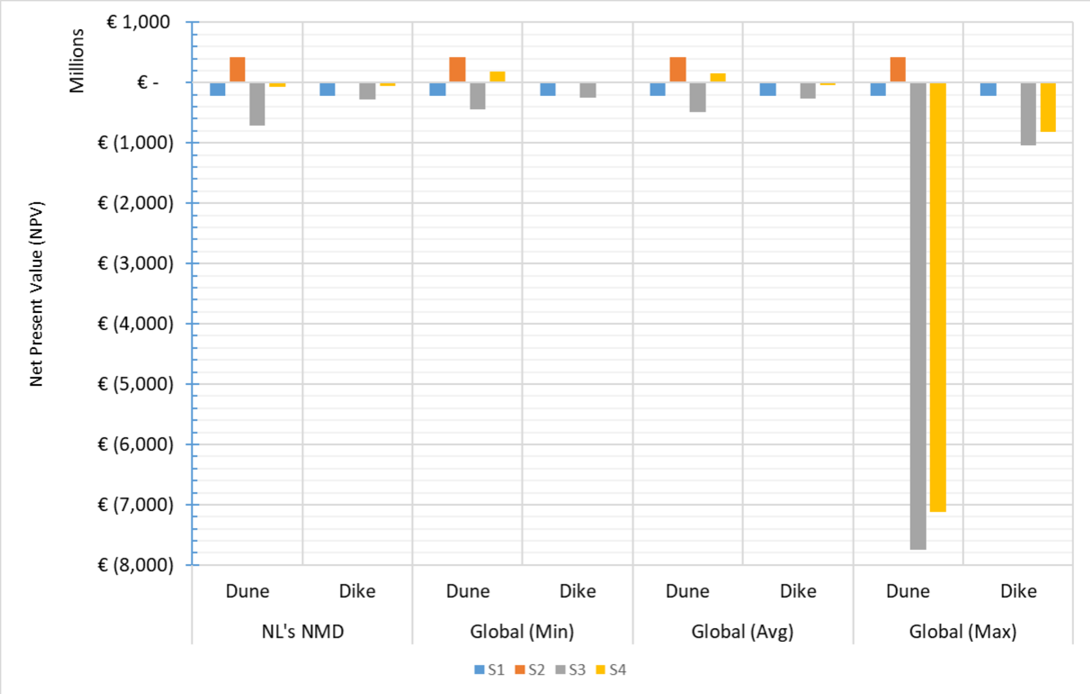

Figure 4.6: Influence of different MVCs on NPV analysis of the two coastal engineering alternatives.

Both alternatives demonstrate marked sensitivity to changes in MVCs, albeit to varying degrees and with distinct implications for their financial viability:

Sand Nourishment
In S3, the NPV for sand nourishment exhibits extreme sensitivity to changes in MVCs, with a dramatic decrease (become less negative) when moving from Global Max, NL, Global Average, and Global Minimum MVCs. This underscores the significant financial burden imposed by high environmental impact costs, making the project increasingly unfeasible at a higher estimate of the environmental cost. However, S4 presents a more complex scenario where, under specific MVC conditions (Global Min and Avg), the NPV become positive (€188 and €153 million, respectively). This suggests that sand nourishment can emerge as a financially viable option when environmental impacts are valued moderately.

Sea Dike
The sea dike alternative demonstrates a similar sensitivity to MVC changes. In S3, the NPV decreases substantially (becomes less negative) as the MVCs transition from Global Maximum, NL, global average, and global minimum, though the reduction scale is less pronounced than in sand nourishment. This indicates that while the sea dike is also adversely impacted by higher environmental costs, it may be somewhat more resilient to these changes due to potentially lower inherent environmental impacts. In S4, the sea dike's NPV remains negative across under all MVCs used but exhibits less variance than sand nourishment. This relative stability suggests that while the sea dike's financial viability is compromised by high environmental costs, it might offer a more predictable investment under fluctuating MVCs.

National NL MVCs vs Global Average MVCs
The analysis shows that sand nourishment is financially more viable under global minimum and average Monetary Valuation Coefficients (MVCs). The Net Present Value (NPV) of sand nourishment becomes positive under these conditions in scenario S4, while the NPV of sea dikes remains negative but slightly improves (i.e., becomes less negative) under global minimum and average MVCs. Overall, sand nourishment showed higher sensitivity to the value of MVCs than sea dike alternative.

Summary
The NPV's sensitivity to changes in MVCs has profound implications for decision-making in coastal

protection projects. It highlights the critical importance of accurately valuing environmental impacts, as these can significantly alter the financial attractiveness of alternatives. The comparative analysis also suggests that neither alternative offers a one-size-fits-all solution. Instead, their selection should be contingent upon a nuanced understanding of ecosystem services and environmental impacts, financial constraints, and long-term sustainability goals.

4.6.4. Material Used: Volumes and Delivery Method

The sand nourishment and sea dike alternatives differ significantly in their material composition, which consequently influences their delivery methods, from transportation to construction. As shown in Table 4.1, sand nourishment consists solely of sand in large quantities, whereas sea dikes are composed of a variety of materials, including sand (in smaller volumes), clay, asphalt, steel sheet piles, and rock and gravel. Changes in the quantities of these materials have a substantial impact on the financial analysis of both sand nourishment and sea dike alternatives, as illustrated in Table D.3 - Appendix D.2.

This analysis examines the sensitivity of the Net Present Value (NPV) for both sand nourishment and sea dike alternatives to variations in the materials used, their volumes, and the methods of delivery. In this context, ”R” refers to the reference case as stated in Table 4.1, while ”0.5R” and ”1.5R” represent half and 1.5 times the reference case, respectively. The financial impact of these variations is detailed in Table 4.11 and illustrated in Figure 4.7.

Table 4.11: Net Present Value (NPV) sensitivity analysis for sand nourishment and sea dike alternatives based on material volumes and delivery methods. All values in millions of Euros, rounded to the nearest million, and R = The reference case.

	Sand Nourishment			**Sea Dike**		
	0.5R	R	1.5R	0.5R	R	1.5R
S1	€ (111)	€ (222)	€ (333)	€ (112)	€ (223)	€ (335)
S2	€ 527	€ 416	€ 305	€ 118	€ 7	€ (105)
S3	€ (353)	€ (705)	€ (1,058)	€ (141)	€ (281)	€ (421)
S4	€ 285	€ (68)	€ (420)	€ 89	€ (51)	€ (191)

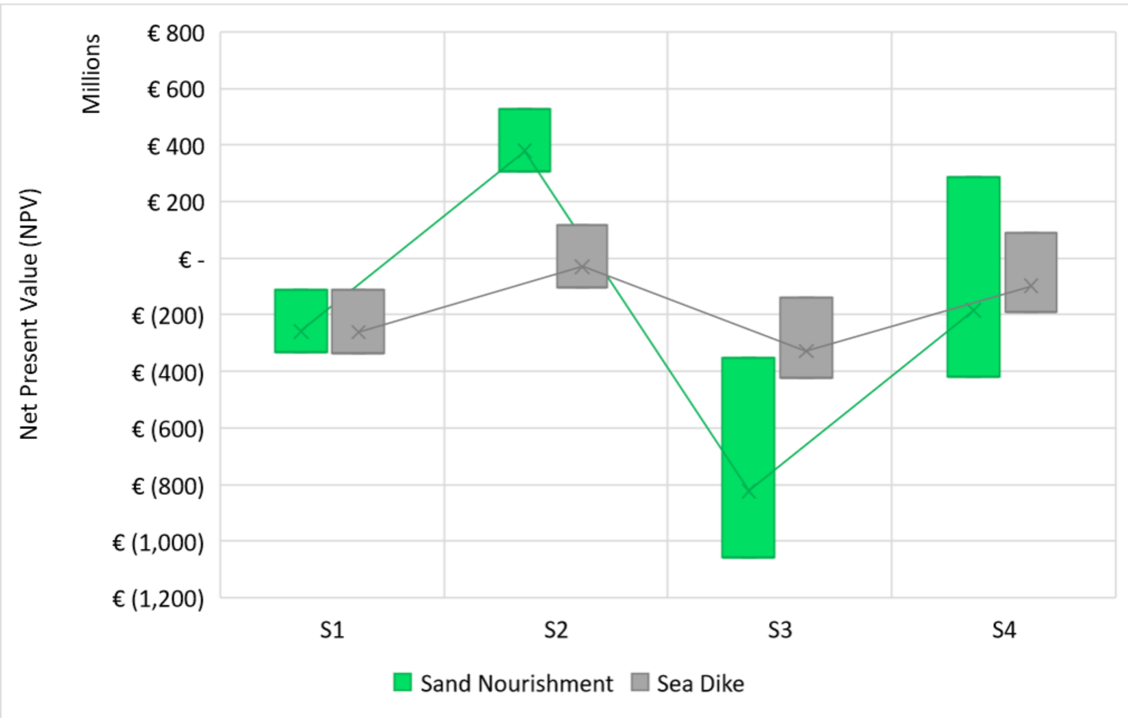

Figure 4.7: Impact of material volume and delivery method on the Net Present Value (NPV) of sand nourishment and sea dike alternatives.

Sand Nourishment

S1: In Scenario S1, the NPV shows a notable decrease as the volume of material increases, with values ranging from €(111) million at 0.5R to €(333) million at 1.5R. This indicates that the financial viability of the project decreases as material volumes increase.

S2: Scenario S2, which includes the benefits of ecosystem services, maintains a positive NPV across all volumes, although the value declines from €527 million at 0.5R to €305 million at 1.5R. This suggests that while ecosystem services bolster the project's financials, the increasing material volume still exerts a downward pressure on NPV.

S3: Scenario S3, accounting for environmental costs, results in a steep decline in NPV, turning increasingly negative from €(353) million at 0.5R to €(1,058) million at 1.5R. This highlights the significant financial burden posed by environmental impacts associated with larger material volumes.

S4: In Scenario S4, which includes both ecosystem services and environmental costs, the NPV is positive at €285 million for 0.5R but turns negative at higher volumes, with a value of €(420) million at 1.5R. This indicates that while the inclusion of ecosystem services provides some financial benefit, it is outweighed by the increased environmental costs at higher material volumes.

Sea Dike

S1: For the sea dike alternative, Scenario S1 exhibits a similar trend to sand nourishment, with the NPV decreasing as material volumes increase, ranging from €(112) million at 0.5R to €(335) million at 1.5R.

S2: In Scenario S2, the sea dike alternative shows positive but decreasing NPV values as material volumes increase, from €118 million at 0.5R to €(105) million at 1.5R, indicating lower sensitivity compared to the sand nourishment alternative.

S3: Scenario S3, which considers environmental costs, shows negative NPV values, with figures ranging from €(141) million at 0.5R to €(421) million at 1.5R. However, the impact of material volume on NPV is less severe than that observed in the sand nourishment alternative, reflecting a relatively lower financial burden from environmental impacts.

S4: In Scenario S4, the NPV is positive at €89 million for 0.5R, but it turns negative as material volumes increase, with a value of €(278) million at 1.5R. Similar to the sand nourishment case, the financial viability of the sea dike is highly sensitive to material volume, especially when both ecosystem services and environmental costs are considered, but not to the same extent as sand nourishment.

Summary

The results presented in Table 4.11 and Figure 4.7 highlight the critical importance of optimizing material volumes in coastal engineering projects. Both sand nourishment and sea dike alternatives exhibit significant sensitivity to changes in material volumes, with financial outcomes deteriorating as volumes increase.

It is important to note that while sand nourishment involves only one type of material—sand—the sheer volume required for the project significantly contributes to higher environmental costs compared to the materials used for the sea dike. This elevated cost is directly linked to the substantial fuel consumption needed for transporting and constructing the sand nourishment, which primarily relies on Marine Gas Oil (MGO) for marine operations. The large volume of MGO required is the primary driver behind the high environmental costs associated with sand nourishment. Consequently, when the volume of sand—and thereby the MGO consumption—is reduced, the Net Present Value (NPV) for sand nourishment shows a marked improvement.

Conversely, the sea dike alternative, although also sensitive to material volumes, does not experience the same degree of financial impact from environmental costs. This is due to the relatively lower material volumes and associated fuel consumption. Therefore, while both alternatives are affected by changes in material volumes, sand nourishment is more adversely impacted, particularly due to its dependence on large volumes of MGO.

4.6.5. Terminal Value

When evaluating project alternatives, the terminal value's inclusion or exclusion significantly impacts the Net Present Value (NPV) calculation. This calculation is critical in selecting the best investment. The terminal value represents the future cash flows beyond a typical forecast period, converted into a single present value figure. It is especially relevant in projects with long-term impacts, such as coastal engineering solutions. Table 4.12 and Figure 4.8 show the impact of including the terminal value versus not including it on the NPV of the two alternatives (Sand Nourishment and Sea Dike) under four different scenarios (S1, S2, S3, and S4).

Table 4.12: Influence of including/excluding terminal value (TV) on NPV analysis of coastal engineering alternatives. (All values in millions of Euros, rounded to the nearest million)*

	Sand Nourishment		**Sea Dike**	
	with TV	**without TV**	**with TV**	**without TV**
S1	€ (222)	€ (196)	€ (223)	€ (217)
S2	€ 416	€ 35	€ 7	€ (145)
S3	€ (705)	€ (468)	€ (281)	€ (271)
S4	€ (68)	€ (238)	€ (51)	€ (199)

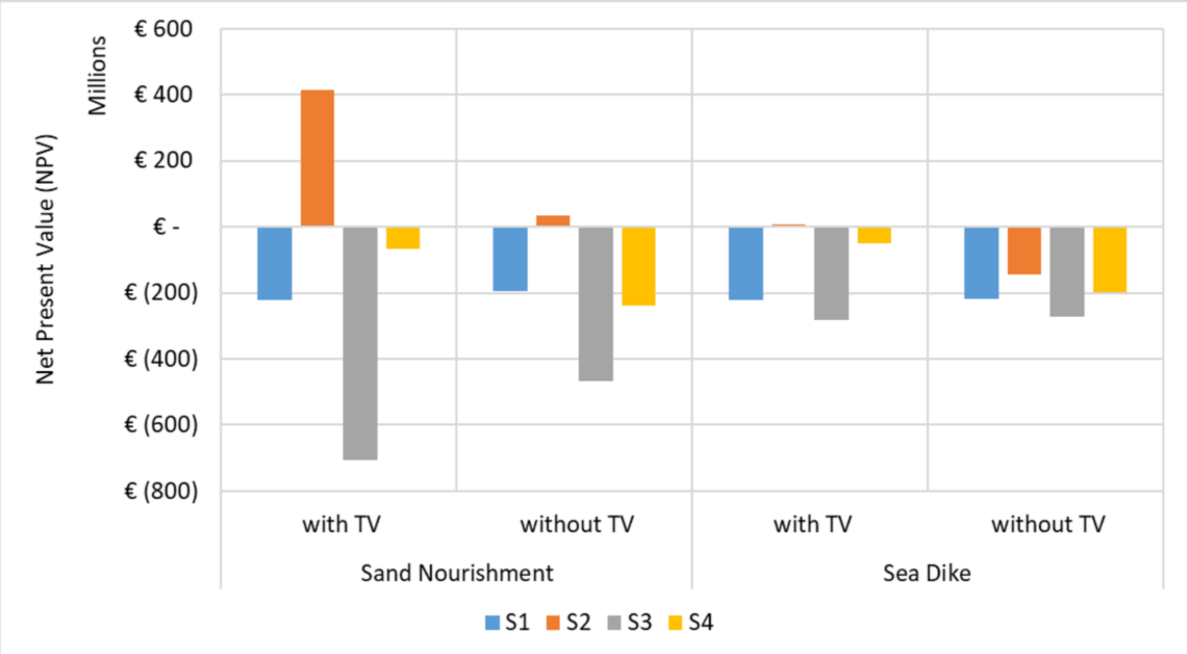

Figure 4.8: Influence of including/excluding terminal value (TV) on NPV analysis of coastal engineering alternatives.

Sand Nourishment

S1: Considering only the capital and maintenance cost, including the terminal value results in a decrease in the NPV €(222) million compared to excluding it €(196) million. This indicates that the anticipated future costs substantially reduce the present value of the project when the terminal value is considered.

S2: When ecosystem services benefits are included, including the terminal value increases the NPV from €35 million to €416 million. This demonstrates the substantial positive impact of long-term benefits, due to ecosystem services' value, on the project's financial viability.

S3: When the value of environmental impacts is considered, including the terminal value significantly increases the NPV from €(468) million to €(705) million. This demonstrates the substantial negative impact of long-term cost, due to environmental impact, on the project's financial viability.

S4: Considering both ecosystem services benefits and life cycle environmental impacts, including the terminal value improves the NPV from a negative value €(238) million to a less negative value €(68) million. This suggests that the long-term costs or reduced benefits when considering terminal value negatively impact the project's NPV.

Sea Dike

S1: Similar to sand nourishment, including the terminal value results in a slight increase in the NPV from €(217) million to €(223) million. This indicates that future costs, due to maintenance, negatively impact the present value.

S2: When ecosystem services benefits are considered, including the terminal value increases the NPV from €(245) million to €7 million. This demonstrates the substantial positive impact of long-term benefits, due to ecosystem services' value, on the project's financial viability.

S3: When the value of environmental impacts is considered, including the terminal value results in a more negative NPV €(281) million compared to excluding it €(199) million. This shows an increase in long-term costs when terminal value is considered.

S4: With both ecosystem services and environmental impacts considered, including the terminal value results in a significantly less negative NPV €(51) million compared to excluding it €(199) million. This suggests that the long-term benefits outweigh the costs when terminal value is considered.

Summary

The sensitivity analysis of including versus not including the terminal value (TV) in the financial analysis reveals that the terminal value can substantially impact the Net Present Value (NPV) of coastal engineering solutions. Including the terminal value often leads to a more accurate representation of long-term projects by capturing future cash flows, both positive and negative. For projects with significant long-term benefits or costs, excluding the terminal value might lead to underestimating or overestimating the project's financial viability.

For both alternatives, the inclusion of the terminal value has a pronounced impact, especially in scenarios S2/ S3, where long-term benefits/costs significantly improve/worsen the NPV. In scenario S1, the NPV becomes more negative, indicating higher long-term costs, while in scenario S4, it becomes less negative, suggesting some benefits.

In all cases, the terminal value has a considerable impact on the overall NPV, underscoring its importance in the long-term financial assessment of projects, particularly those with far-reaching environmental and economic impacts. Decision-makers should carefully evaluate the assumptions and estimations used to calculate the terminal value due to its substantial impact on the project's financial viability.

5

Feasibility of Applying the Framework Internationally: Case Study Suriname

5.1. Introduction

This chapter aims to demonstrate the applicability of the ES-LCA monetary valuation framework developed in Chapter 3, focusing on the quick assessment section, to international coastal engineering projects, with Suriname's 'Weg naar Zee' area as a case study. The Weg naar Zee area has experienced significant coastal erosion, leading the Government of Suriname to consider two alternative projects as a mitigation strategy: mangrove restoration or sea dike. Table 5.1 outlines how to adapt and implement the ES-LCA monetary valuation framework to Suriname, highlighting the specific socio-economic, cultural, and ecological differences. The following sections elaborate more on each step and point to the point of attention.

Table 5.1: Applying the quick assessment framework on Weg Naar Zee coastal protection project, Suriname.

Analytical step		**Analytical methods and data collection suggestions**
		Framework Quick Assessment Application to the Weg Naar Zee Mangrove Restoration, Suriname
Step 1		
LCA	Goal and scope	Study Objectives scope
	Functional Unit	Expert elicitation e.g., 1 m^2
	System Boundary	Construction and maintenance phase
	Temporal boundary	-
	LCA Application	Expert elicitation, Literature, manual calculation
	Life Cycle Inventory	Estimate based on project documents, equipment specifications, material supplier, literature, and/or previous projects
	Life Cycle Impact Assessment	This thesis literature finding (Appendix B.3)
	LCA Monetary Valuation	Using the global monetary valuation coefficient reported in this thesis (Table 2.7)
Step 2		
ESA	Scoping Benefits	Expert elicitation, literature, Global Database of NBS Benefits
	Scope and Information Needs	Expert elicitation, Open-source literature

Continued on next page

Table 5.1 – continued from previous page

Analytical step		**Analytical methods and data collection suggestions**
		Framework Quick Assessment Application to the Weg Naar Zee Mangrove Restoration, Suriname
	Establishing Baseline reference	Expert elicitation, Global Database of NBS Benefits
	Impact Assessment	Expert elicitation Open-source literature, Global Database of NBS Benefits
	ESA Monetary Valuation	Value/Benefit transfer (Appendix C), literature, Mapping Ocean Wealth Explorer - Global (geospatial) risk reduction value datasets
Step 3		
Economic Valuation		Cost: Capital Investment, Maintenance, and Negative Ecosystem services values
		Benefits: Positive Ecosystem Service Values, and Avoided damage
		Cost-Benefit Analysis: Net Present Value
Step 4		
Result Interpretation & Sensitivity Analysis		

5.2. Guideline for the Suriname Case Study

5.2.1. Framework Preparation and Data Collection

Adapting the framework to Suriname's context requires preliminary groundwork, including collecting necessary data such as demographic data, land use, existing policies, regulations, and valuation studies. Engaging with local communities, government authorities, NGOs, academia, and other relevant stakeholders is crucial for adequately contextualising the analysis. This engagement ensures the inclusion of valuable local knowledge and insights often overlooked in broader-scale studies. Some readily available data sources are [119, 120, 121, 122].

5.2.2. Life Cycle Assessment

The implementation of LCA in Suriname follows the same structure as in the Netherlands. The steps include identifying and characterising alternative coastal protection measures, compiling resource usage and emissions for their life cycles, and quantifying these resources and emissions into impact categories. Due to the limited availability of Suriname-specific life-cycle inventory databases, generic databases such as Ecoinvent may be used, with regionalisation attempted where possible, or by using the environmental profile for products that is reported in Appendix B.3. Environmental impacts can then be monetised using monetary valuation coefficients, Table 2.7, allowing for a quick assessment of the project's environmental costs.

5.2.3. Ecosystem Service Assessment

ES assessment in Suriname requires identifying and characterising the relevant ES provided by mangrove ecosystems, including timber, climate regulation, coastal protection, and cultural values. The process involves scoping relevant benefits, delineating system boundaries, establishing a baseline reference, and conducting an impact assessment (Sections 3.3.2 - 3.3.5). Literature can provide valuable information for this step, such as the study by Lauretta Burke and Helen Ding [122]. The identification of indicators should consider data availability and local stakeholder consultations. Due to the lack of local monetary valuation studies, the transfer of values from similar contexts may be utilised for monetary valuation; potential input values are presented in Appendix C.

5.2.4. Financial Analysis

The financial analysis compares the net present values, benefit-cost ratio, or other financial metrics of all identified costs and benefits. This analysis is crucial for evaluating the financial feasibility and sustainability of the proposed mangrove restoration projects in Suriname. In this step, input about the discount and growth rate are needed and can be obtained from the country's central bank website or the World Bank open data [123].

5.3. Attention Points

When adapting the framework to Suriname, several criticalities and sensitivities must be considered, including:

- **Data Availability**: Limited local data may pose challenges for LCA and ES assessment. Efforts should be made to cautiously regionalise generic data and utilise value transfer methods.
- **Stakeholder/Expert Engagement**: Involvement of local stakeholders or an expert is essential for capturing the full range of ES values important to local communities and ensuring the project's social acceptability.
- **Ecological Differences**: The unique ecological characteristics of mangrove ecosystems in Suriname require careful consideration in both LCA and ES assessment to accurately evaluate their contributions and impacts.
- **Cultural and Socio-economic Context**: The valuation of ES must consider the specific cultural and socio-economic context of Suriname, potentially requiring adjustments to monetary valuation methods and coefficients.

5.4. Data Inputs Crucial for implementation

For a successful adaptation and implementation of the framework in Suriname, crucial data inputs include:

- **Detailed project documents**: Outlining the proposed coastal protection measures, their expected impacts, and benefits, as well as the material used, their sources and quantities, and construction method.
- **Local ecological and socio-economic data**: Providing insight into the specific conditions and values of the local community and ecosystems.
- **Existing policies and regulations**: Informing the legal framework within which the project will operate. Valuation studies and traditional knowledge: Offering a basis for monetary valuation and understanding traditional coastal management practices.

5.5. Conclusion

This chapter demonstrates the adaptability of the ES-LCA monetary valuation framework to international contexts, using Suriname as a case study. By carefully considering local ecological, cultural, and socio-economic differences and engaging with a wide range of stakeholders, the framework can provide valuable insights into the sustainability of coastal engineering solutions beyond its original Dutch context.

6 Discussion

6.1. Introduction

This chapter discusses the key findings from the literature review, evaluates the strengths and weaknesses of the ES-LCA monetary valuation framework, and analyses the methods and results of the case study, including a detailed sensitivity analysis. Furthermore, it explores the potential for applying the framework globally, highlighting the necessary considerations for its successful implementation across different geographical and socio-economic contexts.

6.2. Key Literature Review Findings

The literature review conducted in this study reveals several critical insights and gaps in the existing body of knowledge regarding the monetary valuation of ecosystem services (ES) and life cycle assessment (LCA) in the context of coastal engineering interventions.

Firstly, the literature underscores the fragmented nature of ES and LCA valuation methodologies. Various approaches to monetising ecosystem services, such as market-based methods, revealed preferences, and stated preferences, exhibit significant variability in their application and outcomes. This variability challenges achieving consistent and comparable results across different studies and geographical locations. Additionally, the valuation of ecosystem services and environmental impacts is complex and subjective. For instance, individuals may prioritize aspects like material wealth over cultural identity, leading to different values being assigned to various benefits. Some may prioritize economic gains while others emphasize social ties or cultural identity, resulting in diverse weights for different ecosystem services. This divergence means that the valuation of these services can vary significantly based on the evaluator's perspective and context. Similarly, the selection of LCA's monetary valuation coefficients reflects the preferences of different stakeholders, including experts, citizens, and industry representatives, each of whom may prioritize various environmental impacts differently. Industry representatives might emphasize economic factors, whereas citizens may focus on aspects directly affecting their daily lives, such as air quality or waste generation. This variation in priorities leads to diverse outcomes in environmental impact assessments, making it challenging to achieve standardization across different contexts and perspectives.

Secondly, the integration of ES and LCA within a unified framework remains underexplored. Most existing studies either focus on the ecosystem services provided by natural coastal defences or the environmental impacts of engineered solutions, but rarely both comprehensively for green or grey coastal solutions. This gap underscores the necessity for a holistic framework to bridge this divide and provide a balanced assessment of ecological, social, economic and engineering considerations.

Finally, the literature review identifies the benefit/value transfer method as a pragmatic approach for conducting quick assessments. This method, however, requires careful calibration and validation to ensure its applicability across diverse contexts. The need for robust, localised data remains a recurring theme, highlighting the challenges and opportunities in enhancing the accuracy and reliability of such valuation methods.

6.3. ES-LCA Monetary Valuation Framework

6.3.1. Strengths

The primary strength of the ES-LCA framework lies in its comprehensive and integrative approach. The framework enables a holistic evaluation of coastal interventions by combining the ecosystem services assessment (ESA) with the life cycle assessment (LCA). This integration facilitates the simultaneous consideration of ecosystem services and environmental impacts, providing a more balanced and nuanced understanding of the net effects of various coastal engineering solutions.

Another significant strength is the framework's ability to translate diverse ecosystem services and environmental impacts into monetary terms. This common metric directly compares different interventions, enhancing decision-making by making trade-offs and synergies more transparent and quantifiable. Additionally, the framework's adaptability to various data availability scenarios—from detailed local studies to more generalised global datasets—demonstrates its versatility and practical applicability.

6.3.2. Weaknesses

Despite its strengths, the ES-LCA framework has several limitations. The accuracy of monetary valuations heavily depends on the quality and availability of data, which can vary widely across different regions and contexts, as mentioned in Section 6.2. This variability can introduce significant uncertainties into the valuation process, potentially affecting the reliability of the results.

6.4. Case Study Methods and Results

The application of the ES-LCA framework to a hypothetical case study in the Netherlands is a practical demonstration of its utility and effectiveness. The framework evaluated two coastal protection alternatives: sand nourishment and sea dike.

The sand nourishment alternative exhibited significant benefits regarding ecosystem services, such as enhanced tourism, recreational opportunities, and research and education. However, as reflected in the life cycle impact assessment, it also incurred higher environmental costs during the construction and maintenance phases. In contrast, the sea dike alternative demonstrated lower ecosystem service benefits and reduced environmental impacts and maintenance requirements.

The financial analysis, incorporating both net present value (NPV) and return on investment (ROI), revealed that the attractiveness of these alternatives is highly sensitive to the underlying assumptions, particularly the chosen discount rates and the monetary valuation of ecosystem services and environmental impacts. These findings underscore the importance of conducting detailed sensitivity analyses to understand the robustness of the results under various scenarios.

6.4.1. Sensitivity Analysis

The sensitivity analysis conducted in this study underscores the critical role of discount rates, ecosystem service values, and environmental impact valuation coefficients in determining the financial viability of coastal interventions. For instance, varying the discount rate from 2% to 10% significantly altered the NPV of both alternatives, with sand nourishment exhibiting a more pronounced sensitivity than the sea dike option.

Changes in the monetary value of ecosystem services also substantially affected the financial outcomes. For example, a higher valuation of recreational benefits and tourism could make sand nourishment more financially attractive despite its higher environmental costs. Similarly, adjustments in the valuation coefficients for environmental impacts demonstrated that more stringent environmental regulations or higher societal costs for pollution could favour less impactful alternatives like the sea dike.

Moreover, it was evident that fuel consumption plays a key role in the overall environmental impact cost, causing environmental costs to outweigh the higher ecosystem benefits of sand nourishment under certain conditions. This confirms that reducing fuel consumption and emissions is crucial to achieving more sustainable construction.

6.5. Framework Applicability Worldwide

The adaptability of the ES-LCA framework to different international contexts is a key consideration for its broader applicability. The case study of the Weg Naar Zee coastal protection project in Suriname illustrated the framework's potential in a developing country context. Despite the challenges associated with data availability and local capacity, the framework provided valuable insights into the trade-offs and synergies between different coastal protection measures.

The framework requires careful customisation for successful global application, accounting for local ecological, economic, and social conditions. This includes engaging local stakeholders, collecting relevant data, and calibrating the monetary valuation methods to reflect local realities. This approach guarantees the framework remains relevant and effective across diverse geographical and socio-economic settings.

6.6. Limitations and Uncertainties

The quick assessment section of the ES-LCA framework relies heavily on expert opinions and data reported in the literature for projects with similar contexts in different geographical locations. The benefit/value transfer method is then used to adapt this data to the assessed project. This methodology introduces several uncertainties and limitations, which are further amplified by the inherent complexities of environmental and social economics. Key limitations and uncertainties include:

- **Uncertainty in Benefit Transfer Method:**The use of the benefit transfer method necessitates the introduction of new assumptions in addition to those used in the original studies from which the values are being transferred. These additional layers of assumptions can compound uncertainties and affect the accuracy of the transferred values.

- **Double Counting:** There is a risk of double counting ecosystem services, where a single ecosystem feature may be inadvertently included in multiple service categories, thus exaggerating the total value of those services.

- **Discount Rates:** The selection of appropriate discount rates is fraught with uncertainties, significantly influencing the financial valuation of future benefits and costs. The economic forecasting of these values is inherently uncertain and can lead to significant variations in the calculated net present values. Another point of debate is discounting environmental impacts.

  - **Discounting Environmental Impacts:** Discounting environmental impacts over time is a contentious issue in environmental economics. A higher discount rate diminishes the present value of future environmental benefits and costs, potentially undervaluing long-term environmental sustainability. Conversely, a lower discount rate increases the present value of future impacts, emphasising long-term environmental preservation. The debate centres around key ethical issues such as intergenerational equity uncertainty and irreversibility. High discount rates can lead to policies favouring current generations over future ones, raising ethical concerns about intergenerational equity. Lower discount rates are often argued for based on fairness to future generations. Moreover, environmental impacts are often characterised by high levels of uncertainty and potential irreversibility. The consequences of climate change, biodiversity loss, and other environmental damages may be irreversible or extremely costly to reverse. Lower discount rates may better reflect these risks and the precautionary principle. It is not within the scope of this thesis to cover the ethical discussion about discounting environmental impacts. More details about the topic can be found in [124, 125, 126, 127]. In short, decisions regarding discount rates can heavily sway the valuation outcomes of project alternatives.

- **Data Availability and Quality:** The accuracy of monetary valuations depends on the quality and availability of local data. In many contexts, especially in developing countries, data may be scarce or of lower quality, necessitating reliance on generalised or proxy data, which introduces further uncertainties.

- **Temporal and Spatial Variability:** The dynamic nature of ecosystems and their services means valuations can change over time and across different locations. This temporal and spatial variability adds another layer of complexity and uncertainty to the valuation process.

These limitations highlight the need for careful consideration and transparent reporting of assumptions and uncertainties in applying the ES-LCA framework. Future research should aim to refine the methodologies, improve data collection, and enhance stakeholder engagement.

6.7. Conclusion

The development and application of the ES-LCA monetary valuation framework mark a significant advancement in the comprehensive evaluation of coastal engineering solutions. By integrating ecosystem services and life cycle assessments into a unified framework, this study provides a robust tool for balancing economic, ecological, and social considerations in coastal management.

Despite its limitations, the framework's flexibility and holistic approach make it valuable for promoting sustainable coastal engineering practices worldwide. Future research should focus on refining the valuation methods, improving data collection processes, enhancing stakeholder engagement and aiming to produce a global valuation standard for ecosystem services and environmental impacts. This would result in strengthening the framework's applicability and effectiveness further.

In conclusion, the ES-LCA framework offers an adaptable and practical approach to evaluating the sustainability of coastal engineering interventions. Its application in both developed and developing contexts underscores its potential for global implementation, paving the way for more informed and sustainable decision-making in coastal management.

7

Conclusion & Recommendation

7.1. Conclusion

This thesis set out to develop and test a holistic monetary valuation framework that integrates the Ecosystem Services Assessment (ESA) and Life Cycle Assessment (LCA) to measure and compare the benefits and impacts of different coastal solutions. It sought to address the following research questions:

How can coastal interventions' impacts and benefits (economic, social, and environmental) be monetarily evaluated?

Coastal interventions' impacts and benefits can be monetarily evaluated through the developed ES-LCA framework, which integrates Ecosystem Services Assessment (ESA) and Life Cycle Assessment (LCA). This framework enables the comprehensive quantification and monetisation of coastal engineering projects' positive and negative impacts across economic, social, and environmental dimensions. The framework translates various effects into monetary terms by systematically collecting data, defining the scope, and assessing the impacts and benefits. This approach allows stakeholders to compare different coastal engineering solutions on a common financial basis, facilitating informed decision-making considering the full range of sustainability aspects.

How can we integrate Ecosystem Services (ES) and Life Cycle Assessment (LCA) to enhance the economic valuation of coastal interventions?

Integrating Ecosystem Services (ES) and Life Cycle Assessment (LCA) enhances the economic valuation of coastal interventions by leveraging the strengths of both methodologies. ESA focuses on identifying, quantifying, and monetising the benefits of ecosystem services, such as biodiversity, recreation, and tourism. LCA assesses the project's environmental impacts over its entire lifecycle, from construction to maintenance and decommissioning. The ES-LCA framework combines these assessments by adding their respective monetary value, resulting in a holistic valuation that captures the complex interdependencies between environmental impacts and ecosystem services. This integration ensures that both the beneficial services provided by ecosystems and the potential environmental costs are fully accounted for in the economic analysis, leading to a more balanced and comprehensive valuation.

How to perform a quick economic valuation of coastal interventions?

A quick economic valuation of coastal interventions can be performed using a streamlined version of the ES-LCA framework. This involves a simplified process where essential steps are prioritised to expedite the evaluation. The process begins with defining the project's scope and collecting key data, focusing on ecosystem services that are impacted by the project. An initial assessment of the project's environmental impacts and ecosystem services uses readily available data and established coefficients to identify major impacts and benefits. Rapid monetisation techniques are then applied to convert these impacts and benefits into monetary values, often by transferring existing valuation data from similar projects or using expert elicitation. The results compare different coastal intervention options, providing a rapid yet robust assessment to inform preliminary decisions. This streamlined approach ensures that quick economic valuations are practical for early-stage project evaluations and decision-making, highlighting the most economically viable and sustainable options.

7.2. Recommendation

The study's findings suggest several areas for improvement and further research:

- **Data Availability and Quality**: The framework's effectiveness depends on the availability and quality of local data for both LCA and ESA. Future research could focus on developing methodologies for better data collection and regionalisation of generic databases to enhance the framework's applicability in diverse geographical contexts.

- **Methodological Refinements**: The framework could benefit from methodological refinements, especially in integrating ESA and LCA more seamlessly. Future studies could explore the development of unified metrics or indicators that can bridge the gap between these two assessments.

- **Deepening the Framework's Application**: While the application to the Netherlands offered important insights, testing the framework with other coastal interventions globally could enhance its generalisability and effectiveness. Studies assessing projects with various geological, environmental, and socio-economic factors will further refine the framework. It is also recommended to apply the framework to other coastal alternatives, such as mangrove restoration vs sea dike, in greater detail, similar to the case study in Chapter 4.

Technological Innovations: Emerging technologies should be explored for their impact on the environmental and economic performance of coastal engineering solutions. Future research could investigate how innovations in material science, construction techniques, and ecological restoration can enhance the sustainability of coastal interventions.

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A
Systematic Literature Review (SLR)

A.1. Search Strategy

A.1.1. Search String 1

Monetary Valuation methods: (”Valuation” OR ”Valuation method” OR ” Total Economic Value” OR ”Economic Valu*” OR ”Economic* Quantif*” OR ”Monetary” OR ”Monetary valuation” OR ”Monetization” OR ”Monetisation”)

A.1.2. Search String 2

Ecosystem Services: (”Ecosystem service” OR ”Provisional service*” OR ”Cultural Service*” OR ”Supporting Service*” OR ”Regulating Service*” OR ”Provisional Ecosystem service*” OR ”Cultural Ecosystem Service*” OR ”Supporting Ecosystem Service*” OR ”Regulating Ecosystem Service*” OR ”Environmental service*” OR ”natural capital” OR benefit* OR ”Co-benefit*” OR ”secondary benefit*” OR ”Social benefit*” OR ”social impact*” OR ”economic benefit*” OR ”economic impact*” OR ”Environment* benefit*” OR ”environment* impact*” OR ”natural capital”)

A.1.3. Search String 3

Coastal Ecosystem and Coastal Engineering interventions:(coast* OR marine OR beach* OR shoreline OR dune OR ”coast* ecosystem” OR ”marine Ecosystem” OR ”Coast* structure*” OR ”Coast* infrastructure” OR ”Coast* Engineering” OR ”Hydraulic Engineering” OR solution* OR ”sustainable solution” OR erosion OR flood* OR breakwater OR nourishment OR ”Flood protection” OR ”Erosion control”)

A.1.4. Search constraints

The search was limited to by the following constraints: (LIMIT-TO (SRCTYPE , ”j”)) AND (LIMIT-TO (SUBJAREA , ”ENVI”) OR LIMIT-TO (SUBJAREA , ”AGRI”) OR LIMIT-TO (SUBJAREA , ”SOCI”) OR LIMIT-TO (SUBJAREA , ”ENGI”) OR LIMIT-TO (SUBJAREA , ”EART”) OR LIMIT-TO (SUBJAREA , ”ECON”) OR LIMIT-TO (SUBJAREA , ”ENER”) OR LIMIT-TO (SUBJAREA , ”BUSI”) OR LIMIT-TO (SUBJAREA , ”DECI”) OR LIMIT-TO (SUBJAREA , ”MATE”) OR LIMIT-TO (SUBJAREA , ”MULT”))

A.1.5. Conducting the Search

The three search strings were combined with the limitation and put into the Scopus search engine ”Title, Abstract, and Keywords as follows: TITLE-ABS-KEY ((”Valuation” OR ”Valuation method” OR ” Total Economic Value” OR ”Economic Valu*” OR ”Economic* Quantif*” OR ”Monetary” OR ”Monetary valuation” OR ”Monetization” OR ”Monetisation”) AND (”Ecosystem service” OR ”Provisional service*” OR ”Cultural Service*” OR ”Supporting Service*” OR ”Regulating Service*” OR ”Provisional Ecosystem service*” OR ”Cultural Ecosystem Service*” OR ”Supporting Ecosystem Service*” OR ”Regulating Ecosystem Service*” OR ”Environmental service*” OR ”natural capital” OR benefit* OR ”Co-benefit*” OR ”secondary benefit*” OR ”Social benefit*” OR ”social impact*” OR ”economic benefit*” OR ”economic impact*” OR ”Environment* benefit*” OR ”environment* impact*” OR ”natural capital”) AND (method* OR framework* OR approach* OR concept OR proposal) AND (coast* OR marine OR beach* OR shoreline OR dune OR ”coast* ecosystem” OR ”marine Ecosystem” OR ”Coast* structure*” OR ”Coast* infrastructure” OR ”Coast* Engineering” OR ”Hydraulic Engineering” OR solution* OR ”sustainable solution” OR erosion OR flood* OR breakwater OR nourishment OR ”Flood protection” OR ”Erosion control”)) AND (LIMIT-TO (SRCTYPE , ”j”)) AND (LIMIT-TO (SUBJAREA , ”ENVI”) OR LIMIT-TO (SUBJAREA , ”AGRI”) OR LIMIT-TO (SUBJAREA , ”SOCI”) OR LIMIT-TO (SUBJAREA , ”ENGI”) OR LIMIT-TO (SUBJAREA , ”EART”) OR LIMIT-TO (SUBJAREA , ”ECON”) OR LIMIT-TO (SUBJAREA , ”ENER”) OR LIMIT-TO (SUBJAREA , ”BUSI”) OR LIMIT-TO (SUBJAREA , ”DECI”) OR LIMIT-TO (SUBJAREA , ”MATE”) OR LIMIT-TO (SUBJAREA , ”MULT”))

A.2. Screening Strategy

The screening process consisted of multiple stages, including title, abstract, retrievable, full-text skimming, and full-text analysis. Publications that did not explicitly discuss valuation in their titles were excluded from further consideration. This step resulted in a remaining pool of 548 articles, whose abstracts were evaluated based on their scope and inclusion of monetary valuation. As a result, only ninety-five publications were retained for further screening. Table A.1 shows the eligibility criteria followed in the screening process. The eligibility and exclusion criteria in Table A.1 were formulated to address the objective of the SLR, which are:

1. To provide a comprehensive overview of all the monetary valuations suitable for coastal ecosystem services, and
2. To confirm the lack of academic literature related to monetary valuation ES linked to coastal engineering interventions.

. Figure A.1 illustrates the ROSES methodological framework used for systematic literature review.

Table A.1: Eligibility and exclusion criteria applied in the systematic literature review

	Inclusion criteria	Exclusion Criteria
Title	• Mention monetary valuation explicitly or implicitly	• Does not refer to monetary valuation or monetary valuation methods • Refer to scope not relevant to coastal ecosystem or coastal areas
Abstract	• Objective of the study is monetary valuation • Method of the monetary valuation method mentioned • Scope is limited to or must include coastal ecosystem	• Not a monetary valuation study • Method of Monetary valuation not mentioned • The scope is not related to the coastal ecosystem services
Article Text Analysis	• Scope: Benefit generated from coastal protection • Method: Monetary valuation is explicitly mentioned and explained in detail how it was used • Result: Benefits were given a monetary value	• Scope: is not about coastal engineering interventions • Method: Not clear or detailed • Result: Monetary valuation not given, poor quality or not clear

I did the screening in several stages – title, abstract, retrievable, full-text skimming, and full-text analysing. During the screening process, publications that did not explicitly address valuation in their titles were

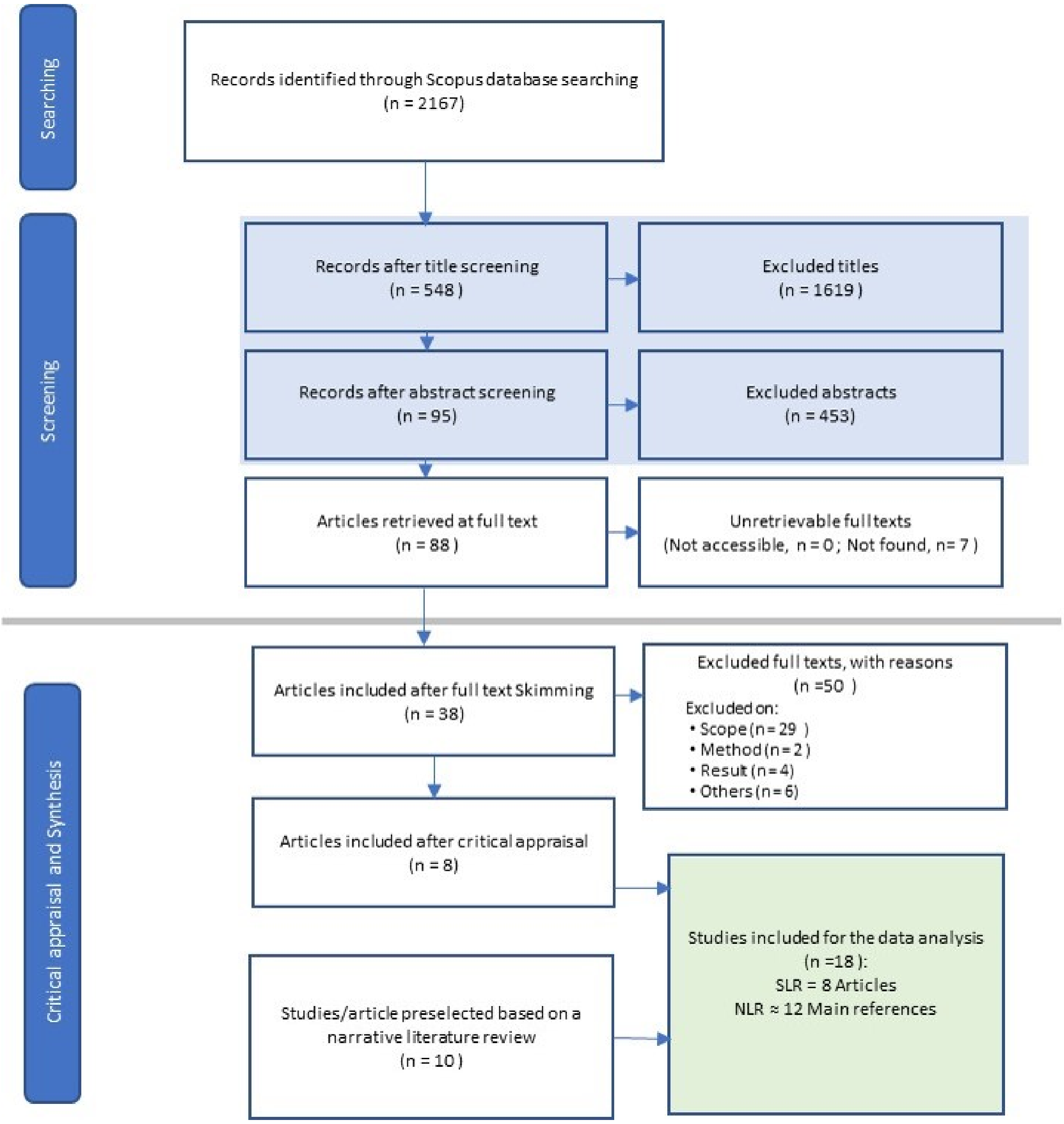

Figure A.1: ROSES methodological framework used for systematic literature review.

excluded from further consideration. This step led to a remaining pool of 548 articles, whose abstracts were assessed based on scope and inclusion of monetary valuation. Consequently, ninety-five publications were retained for further screening.

Inaccessible publications, as well as those written in languages other than English, were excluded from the final selection. After conducting an initial skim of the content, I identified and selected thirty-eight publications that meet the inclusion criteria. These were reduced further to ten articles in the critical appraisal and synthesis phase.

A.3. SLR Finding and Discussion

The SLR provided a comprehensive overview of all the monetary valuation methods. It also confirmed the knowledge gap that academic articles related to the monetary valuing of the ES of coastal grey engineering interventions are scarce, Figures A.1 and A.2.

Out of the 2160 articles screened, 548 articles were retained after the title screening and reduced to 10 articles that provide extensive information about the monetary valuation of coastal protection and erosion control services as the main benefits and their other co-benefits and to 2 articles that discuss the ES of coastal engineering infrastructure. The title screening result included all the articles that include or refer to monetary valuation in their title. These results, however, include scopes other than coastal ecosystems, such as urban, agriculture, mountains, deserts, and others, as shown in Figures A.2 and A.3.

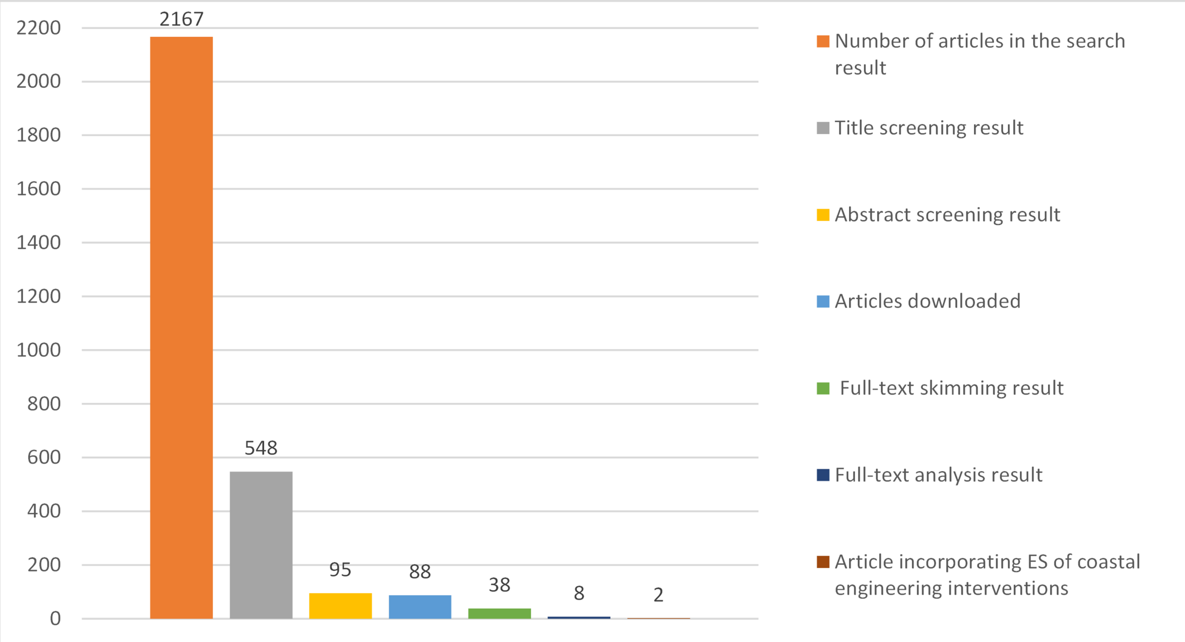

Figure A.2: Systematic literature review screening result. It shows the reduction of the number of studies, starting by considering only the study discussing monetization, then narrowing it down from all scopes to coastal and marine to coastal, then to articles discussing coastal protection and erosion control ecosystem services and their other co-benefits to human well-being.

Of the 548 articles, 204 were related to coastal ecosystem services, Figure A.4. It shows that even though the search keywords include coastal engineered infrastructures, only one article about that was found. The remaining coastal ES was linked and valued in the context of mangroves, coral reefs, coastal wetlands, and some other coastal ecosystems, which are soft (or Natural Based Solution (NBS) green) coastal solutions.

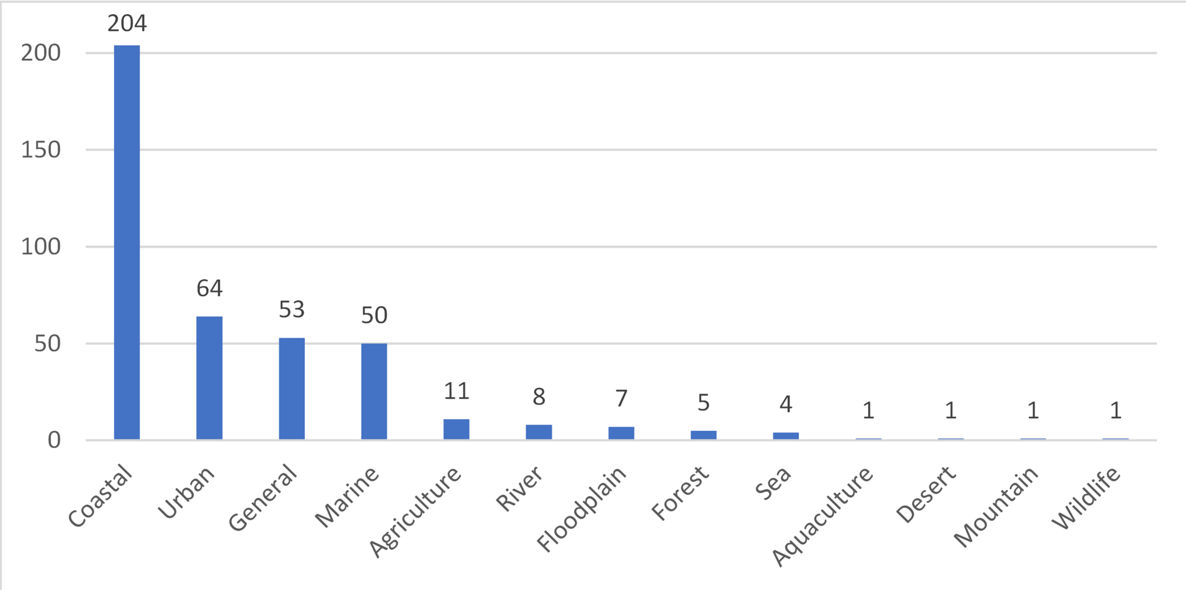

Figure A.3: Types of coastal ecosystems discussed in the systematic literature review, based on abstract screening results.

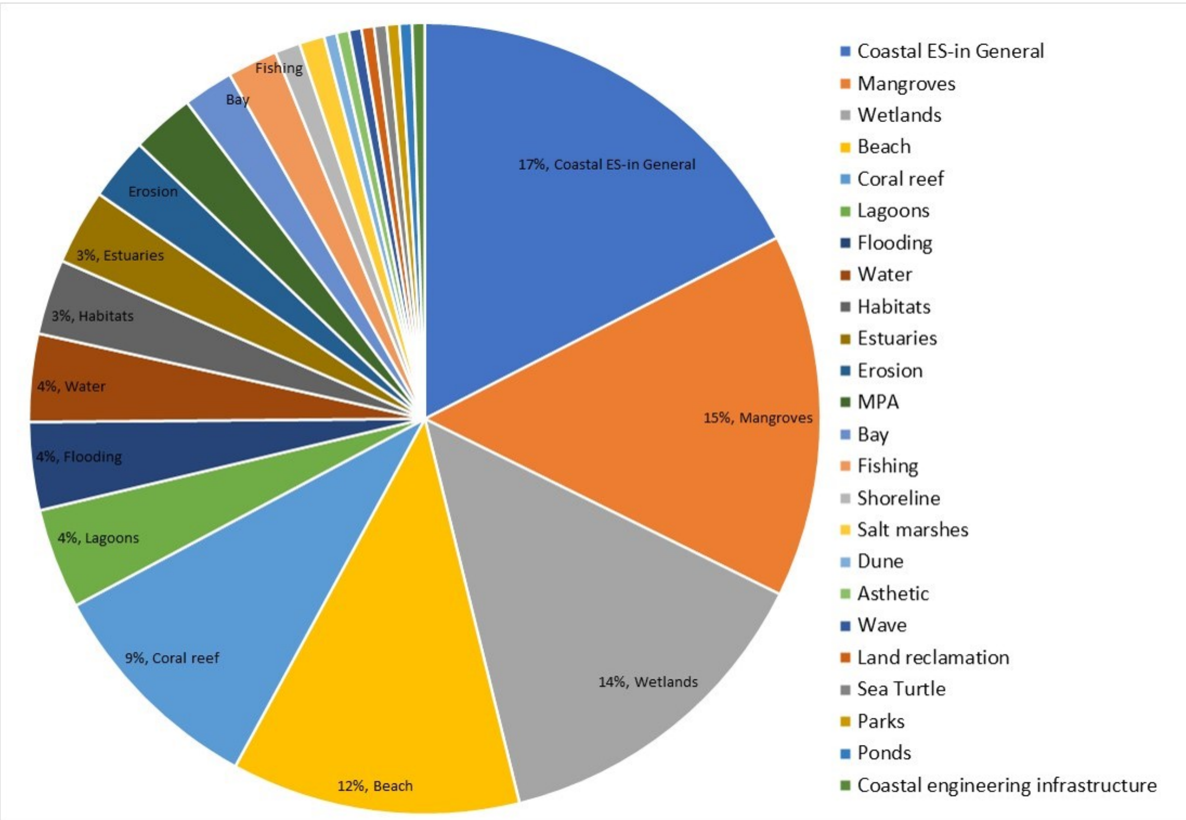

Figure A.4: Types of coastal ecosystems discussed in the systematic literature review, based on abstract screening results.

A.3.1. Spatial Trends in Valuation Research

The spatial distribution of the studies that remained after the title screening shows that the ecosystem services valuation (ESV) concept is known and researched in some countries - e.g., developed like China and the United States, compared to less developed countries like Africa and the West coast of South America, Figure A.5.

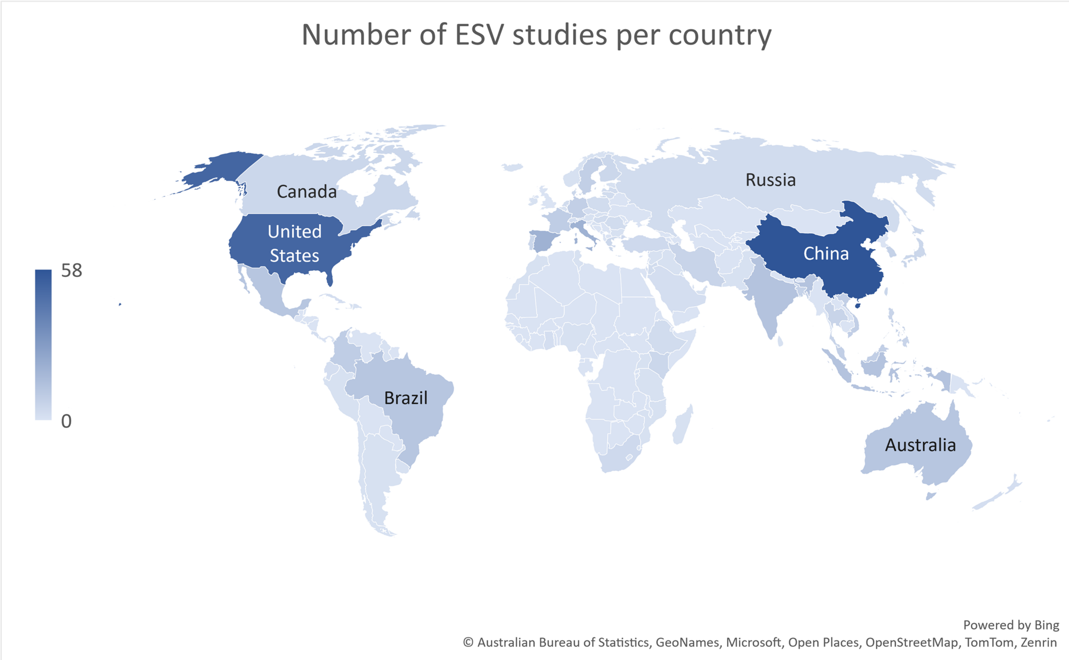

Figure A.5: Spatial distribution of ecosystem services valuation studies. Based on the remaining articles after the title screening, China, the United States, the UK, Italy, Spain, Mexico, Australia, and France top the list with 58, 51, 22, 20, 19, 11, 10, and 10 studies, respectively.

However, when looking at the spatial distribution of coastal ESV studies worldwide, more than 52 per cent of the studies were conducted in seven countries: the United States, China, Indonesia, the UK, Australia, India, and Vietnam, Figure A.6.

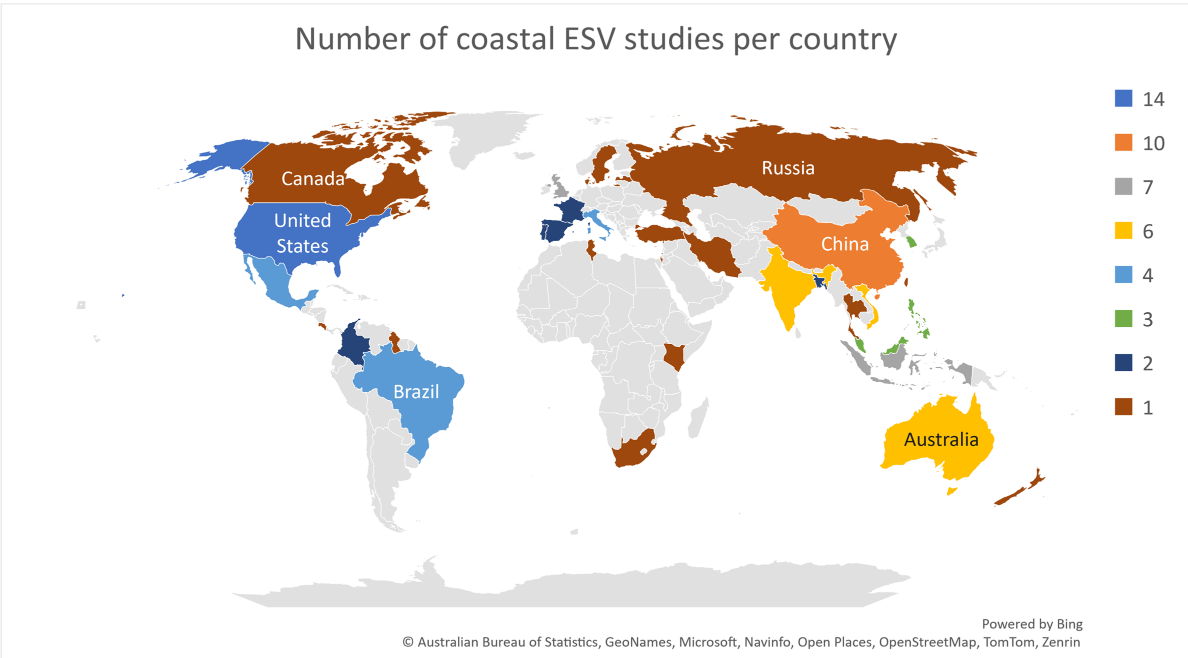

Figure A.6: Number of coastal ESV studies per country.

B

Life Cycle Assessment

B.1. Brief Description of Environmental Footprint Impact categories (EF-ICs)

The Member States – Consumption Footprint Tool employs the EF Method (EC, 2021) in the version of EF 3.1 (Andreasi Bassi et al., 2023) (Annex 2). The EF method includes the following 16 impact categories:

- **Climate change (CC)**: This indicator refers to the increase in the average global temperatures as a result of greenhouse gas (GHG) emissions. The greatest contributor is generally the combustion of fossil fuels such as coal, oil, and natural gas. The global warming potential of all GHG emissions is measured in kilogram of carbon dioxide equivalent (kg CO2 eq), namely all GHG are compared to the amount of the global warming potential of 1 kg of CO2.
- **Ozone depletion (ODP)**: The stratospheric ozone (O3) layer protects us from hazardous ultraviolet radiation (UV-B). Its depletion increases skin cancer cases in humans and damage to plants. The potential impacts of all relevant substances for ozone depletion are converted to their equivalent of kilograms of trichlorofluoromethane (also called Freon-11 and R-11). Hence the unit of measurement is in a kilogram of CFC-11 equivalent (kg CFC-11 eq).
- **Human toxicity, cancer effects (HTOX - c)**: This indicator refers to potential impacts, via the environment, on human health caused by absorbing substances from the air, water and soil. The direct effects of products on human health are currently not measured. The unit of measurement is the Comparative Toxic Unit for Humans (CTUh). This is based on a model called USEtox.
- **Human toxicity, non-cancer effects (HTOX - nc)**: This indicator refers to potential impacts, via the environment, on human health caused by absorbing substances from the air, water, and soil. The direct effects of products on human health are currently not measured. The unit of measurement is the Comparative Toxic Unit for Humans (CTUh). This is based on a model called USEtox.
- **Particulate matter (PM)**: This indicator measures the adverse impacts on human health caused by emissions of Particulate Matter (PM) and its precursors (e.g. NOx, SO2). Usually, the smaller the particles, the more dangerous they are, as they can go deeper into the lungs. The potential impact of is measured as the change in mortality due to PM emissions, expressed as disease incidence per kg of PM2.5 emitted.
- **Ionising radiation (IR)**: Exposure to ionising radiation (radioactivity) can have impacts on human health. The Environmental Footprint only considers emissions under normal operating conditions (no accidents in nuclear plants are considered). The potential impact on human health of different ionising radiations is converted to the equivalent of kilobequerels of Uranium 235 (kg U235 eq).
- **Photochemical ozone formation (POF)**: Ozone (O3) on the ground (in the troposphere) is harmful: it attacks organic compounds in animals and plants, it increases the frequency of respiratory problems when photochemical smog ("summer smog") is present in cities. The potential impact of

substances contributing to photochemical ozone formation is converted into the equivalent of kilograms of non-Methane volatile Organic Compounds (e.g. alcohols, aromatics, etc.; kg NMVOC eq).

- **Acidification (AC)**: Acidification has contributed to a decline of coniferous forests and an increase in fish mortality. Acidification can be caused by emissions to the air and deposition of emissions in water and soil. The most significant sources are combustion processes in electricity, heat production, and transport. The more sulphur the fuels contain the greater their contribution to acidification. The potential impact of substances contributing to acidification is converted to the equivalent of moles of hydron (general name for a cationic form of atomic hydrogen, mol H+ eq).
- **Eutrophication, terrestrial (TEU)**: Eutrophication arises when substances containing nitrogen (N) or phosphorus (P) are released to ecosystems. These nutrients cause the growth of algae or specific plants and thus limit growth in the original ecosystem. The potential impact of substances contributing to terrestrial eutrophication is converted to the equivalent of moles of nitrogen (mol N eq).
- **Eutrophication, freshwater (FEU)**: Eutrophication in ecosystems happens when substances containing nitrogen (N) or phosphorus (P) are released to the ecosystem. As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will increase. If algae grow too rapidly, it can leave water without enough oxygen for fish to survive. Nitrogen emissions into the aquatic environment are caused by fertilisers used in agriculture, but also by combustion processes. The most significant sources of phosphorus emissions are sewage treatment plants for urban and industrial effluents and leaching from agricultural land. The potential impact of substances contributing to freshwater eutrophication is converted to the equivalent of kilograms of phosphorus (kg P eq).
- **Eutrophication, freshwater (FEU)**: Eutrophication in ecosystems happens when substances containing nitrogen (N) or phosphorus (P) are released to the ecosystem. As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will increase. If algae grow too rapidly, it can leave water without enough oxygen for fish to survive. Nitrogen emissions into the aquatic environment are caused by fertilisers used in agriculture, but also by combustion processes. The most significant sources of phosphorus emissions are sewage treatment plants for urban and industrial effluents and leaching from agricultural land. The potential impact of substances contributing to freshwater eutrophication is converted to the equivalent of kilograms of phosphorus (kg P eq).
- **Eutrophication, marine (MEU)**: Eutrophication in ecosystems happens when substances containing nitrogen (N) or phosphorus (P) are released to the ecosystem. As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will increase. If algae grow too rapidly, it can leave water without enough oxygen for fish to survive. For the marine environment this will be mainly due to an increase of nitrogen (N). Nitrogen emissions are caused largely by the agricultural use of fertilisers but also by combustion processes. The potential impact of substances contributing to marine eutrophication is converted to the equivalent of kilograms of nitrogen (kg N eq).
- **Ecotoxicity, freshwater (ECOTOX)**: This indicator refers to potential toxic impacts on an ecosystem, which may damage individual species as well as the functioning of the ecosystem. Some substances tend to accumulate in living organisms. The unit of measurement is the Comparative Toxic Unit for Ecosystems (CTUe). This is based on a model called USEtox.
- **Land use (LU)**: Use and transformation of land for agriculture, roads, housing, mining or other purposes. The impacts can vary and include loss of species, of the organic matter content of the soil, or loss of the soil itself (erosion). This is a composite indicator measuring impacts on four soil properties (biotic production, erosion resistance, groundwater regeneration and mechanical filtration), expressed in points (Pts).
- **Water use (WU)**: The abstraction of water from lakes, rivers or groundwater can contribute to the ‘depletion’ of available water. The impact category considers the availability or scarcity of water in the regions where the activity takes place if this information is known. The potential impact is expressed in cubic metres (m3) of water use related to the local scarcity of water.
- **Resource use, fossils (FRD)**: The earth contains a finite amount of non-renewable resources, such as fossil fuels like coal, oil and gas. The basic idea behind this impact category is that

extracting resources today will force future generations to extract less or different resources. For example, the depletion of fossil fuels may lead to the non-availability of fossil fuels for future generations. The amount of materials contributing to resource use, fossils, are converted into MJ.

- **Resource use, minerals and metals (MRD)**: This impact category has the same underlying basic idea as the impact category resource use, fossils (namely, extracting a high concentration of resources today will force future generations to extract lower concentration or lower value resources). The amount of materials contributing to resource depletion is converted into equivalents of kilograms of antimony (kg Sb eq).

B.2. Monetary Valuation Coefficient (MVCs): Extra

In addition to the MVCs for the environmental footprint impact categories, Figure B.1 shows some additional MVCs according to Finnveden et al., [84].

A: Weighting factors for Ecotax derived from taxes and fees in Sweden 2002

Intervention	Weighting factor	Tax or fee base
Extraction		
Fossil energy	0–0.15 SEK / MJ	Tax on fossil energy
Biotic energy	0–0.069 SEK/MJ	Tax on biotic energy
Emission		
CO_2	0.63 SEK/kg	Tax on carbon content in fossil fuel recalculated to CO_2-emission
Ozone depleting substances	1,200 SEK/kg	Fee for using prohibited ozone depleting substances
Nitrogen	12 SEK/kg	Tax on nitrogen content of fertiliser recalculated assuming a leakage of 15% (tax 1.80 SEK/kg)
HC	20–200 SEK/kg	Emission fee for air traffic
Sulphur	30 SEK/kg	Tax on sulphur content in fossil fuels
Toluene	17.65–36.07 SEK/kg	Tax differentiation on petrol qualities (unleaded petrol vs. alkylate petrol)
Cadmium	30,000 SEK/kg	Tax on content of cadmium exceeding 5 g/1,000kg phosphor in fertiliser
Pesticides / Copper	20 SEK/kg	Tax on active substance in pesticides

B: Weights used in minimum and maximum combinations of Ecotax 2002

Impact category	Combination	Weighting factor	Reference of the characterisation method (eq)	Weight of reference
Abiotic resources	Min	0 SEK/MJ	MJ	0 SEK/MJ
	Max	0.15 SEK/MJ	MJ	0.15 SEK/MJ
Biotic resources	Min	0 SEK/MJ	MJ	0 SEK/MJ
	Max	0 069 SEK/MJ	MJ	0.069 SEK / MJ
Global warming	Min/Max	0.63 SEK / kg CO_2	CO_2	0.63 SEK/kg
Depletion of stratospheric ozone	Min/Max	1,200 SEK / kg ozone depleting substance	CFC-11	1,200 SEK/kg
Photochemical oxidation	Min	20 SEK/kg HC	C_2H_2	48 SEK/kg
	Max	200 SEK/kg HC	C_2H_2	480 SEK/kg
Acidification	Min/Max	30 SEK/ kg Sulphur	1.2 SO_2	18 SEK/kg
Eutrophication	Min/Max	12 SEK/kg N	PO_4^{3-}	28.57 SEK/kg
Fresh water aquatic ecotoxicity	Min	17.65 SEK/kg Toluene	1,4-dichlorobenzen emitted to freshwater	60.86 SEK/kg
	Max	36.07 SEK/kg Toluene		124.37 SEK/kg
Marine aquatic ecotoxicity	Min	20 SEK/kg Copper	1,4-dichlorobenzen emitted to seawater	$1.333 \cdot 10^{-5}$ SEK/kg
	Max	20 SEK/kg Glyphosate		0.606 SEK/kg
Terrestrial ecotoxicity	Min/Max	30,000SEK/kg Cd	1,4-dichlorobenzen emitted to agr. soil	176.47 SEK/kg
Human toxicity	Min/Max	30,000SEK/kg Cd	1,4-dichlorobenzen emitted to agr. soil	1.50 SEK/kg

Figure B.1: Monetary weighting factors for mid-point indicators (for order of magnitude calculations 10 SEK=1 Euro). Source: Finnveden et al., [84]

B.3. Environmental Footprint Impact per Project's Products

B.3.1. Impact Categories for Diesel

Table B.1 presents Machine Diesel stage IV environmental performance characterized results according to NMD [113].

Table B.1: Environmental profile of the life cycle of 1 litre Diesel per Machine diesel stage IV. Source: NMD [113]

Impact Category	Unit	A1-A3	A4	B1	Total
Global warming (GWP)	kg CO_2 eq	4.43E-01	1.49E-02	3.04E+00	3.50E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	5.66E-07	2.49E-09	4.37E-08	6.12E-07
Human toxicity (HT)	kg 1,4-DB eq	3.95E-01	7.40E-03	6.56E-01	1.06E+00
Photochemical oxidation (POCP)	kg C2H4	6.51E-04	9.40E-06	4.13E-04	1.07E-03
Acidification (AP)	kg SO_2 eq	4.67E-03	5.27E-05	3.72E-03	8.79E-03
Eutrophication (EP)	kg PO_4 eq	6.44E-04	8.36E-06	8.03E-04	1.55E-03
Ecotoxicity, freshwater (FAETP)	kg 1,4-DB eq	1.51E-02	1.89E-04	5.22E-03	2.05E-02
Abiotic depletion, non-fuel (AD)	kg Sb eq	1.10E-06	1.10E-06	5.41E-06	7.62E-06
Abiotic depletion, fuel (AD)	kg Sb eq	2.06E-02	1.11E-04	3.09E-03	2.38E-02
Water, freshwater use	m^3	3.32E-04	1.54E-05	5.05E-03	5.40E-03
Ecotoxcity, marine water (MAETP)	kg 1,4-DB eq	5.44E+01	6.88E-01	1.31E+01	6.82E+01
Ecotoxicity, terrestrial (TETP)	kg 1,4-DB eq	8.52E-04	4.15E-05	9.43E-03	1.03E-02
Energy, primary, renewable (MJ)	MJ	8.18E-02	1.54E-02	4.85E-01	5.83E-01
Energy, primary, non-renewable	MJ	4.67E+01	2.57E-01	6.72E+00	5.37E+01
Secondary material (kg)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Waste, hazardous (kg)	kg	1.22E-04	6.19E-07	9.90E-06	1.32E-04
Waste, non hazardous	kg	9.95E-03	1.72E-02	9.63E-02	1.23E-01
Waste, radioactive	kg	3.17E-04	1.61E-06	2.44E-05	3.43E-04

B.3.2. Impact Categories for Marine Gas Oil

Table B.2 presents the environmental profiles per tonne of fuel based on set 2 (EN 15804+A2) according to TNO [112].

Table B.2: Environmental profile of the life cycle of 1 ton MGO pre Tier I

Impact Category	Units	A1-A3	A4	B1	D	Total
Climate change	kg CO_2 eq.	5.21E+04	2.62E+03	3.43E+05	-6.16E+03	3.92E+05
Climate change - Fossil	kg CO^2 eq.	5.19E+04	2.62E+03	3.43E+05	-6.20E+03	3.92E+05
Climate change - Biogenic	kg CO^2 eq.	1.25E+02	-5.53E+00	-6.44E+01	3.98E+01	9.53E+01
Climate change - Land use and LU change	kg CO^2 eq.	1.47E+01	8.91E-01	3.16E+01	1.86E+00	4.90E+01
Ozone depletion	kg CFC11 eq	8.63E-02	4.97E-04	2.59E-03	-2.18E-04	8.91E-02
Human toxicity, non-cancer	CTUh	6.40E-04	3.91E-05	7.80E-03	1.29E-03	9.77E-03
Human toxicity, cancer	CTUh	1.55E-05	1.27E-06	4.71E-04	-7.70E-07	4.87E-04
Human toxicity, non-cancer - organics	CTUh	2.51E-05	3.45E-06	4.95E-03	-8.17E-07	4.98E-03
Human toxicity, non-cancer - inorganics	CTUh	2.22E-04	1.03E-05	6.13E-04	-1.90E-04	6.56E-04
Human toxicity, non-cancer - metals	CTUh	3.99E-04	2.54E-05	2.24E-03	1.48E-03	4.14E-03

Table B.2: Environmental profile of the life cycle of 1 ton MGO pre Tier I (continued)

Impact Category	Units	A1-A3	A4	B1	D	Total
Human toxicity, cancer - organics	CTUh	6.21E-06	8.00E-07	4.22E-04	-4.17E-05	3.88E-04
Human toxicity, cancer - inorganics	CTUh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, cancer - metals	CTUh	9.32E-06	4.72E-07	4.90E-05	4.09E-05	9.98E-05
Particulate matter	disease inc.	3.17E-03	2.07E-04	1.92E-02	-3.36E-04	2.23E-02
Ionising radiation	kBq U-235 eq.	2.35E+04	1.50E+02	5.07E+02	4.03E+01	2.42E+04
Photochemical ozone formation	kg NMVOC eq.	3.07E+02	1.41E+01	6.42E+03	-3.76E+01	6.71E+03
Acidification	mol H^+ eq.	6.36E+02	1.48E+01	4.72E+03	-2.63E+01	5.34E+03
Eutrophication, marine	kg N eq.	6.35E+01	4.44E+00	2.34E+03	-4.59E+00	2.41E+03
Eutrophication, freshwater	kg P eq.	7.63E-01	7.50E-02	2.20E+00	-1.50E-01	2.88E+00
Ecotoxicity, freshwater	CTUe	2.64E+06	3.35E+04	6.32E+05	-2.10E+05	3.10E+06
Ecotoxicity, freshwater - organics	CTUe	3.38E+05	1.88E+03	1.56E+04	-6.38E+02	3.55E+05
Ecotoxicity, freshwater - inorganics	CTUe	8.70E+05	6.26E+03	2.61E+04	-5.96E+03	8.96E+05
Ecotoxicity, freshwater - metals	CTUe	1.43E+06	2.54E+04	5.90E+05	-2.03E+05	1.84E+06
Resource use, minerals and metals	kg Sb eq.	1.66E-02	1.53E-02	2.24E-01	3.87E-03	2.59E-01
Resource use, fossils	MJ	5.34E+06	3.86E+04	2.22E+05	-4.52E+04	5.55E+06
Water use	m^3 depriv.	2.40E+04	3.25E+01	6.68E+03	-1.05E+03	2.96E+04
Land use	Pt	6.27E+05	5.48E+04	2.42E+05	-1.03E+04	9.13E+05
Eutrophication, terrestrial	mol N eq.	7.18E+02	5.49E+01	2.57E+04	-5.32E+01	2.64E+04

B.3.3. Impact Categories for Hydraulic Asphalt

Table B.3 present the environmental performance for hydraulic asphalt, according to Leke Bak, et al. [111]

Table B.3: Environmental profile of the life cycle of 1-ton Asphalt. Source: [111]

Impact Category	Units	A1	A2	A3	A4	A5	B1	C1	C2	C4	Total
Climate change	kg CO^2 eq.	5.81E+03	2.44E+03	2.39E+03	4.49E+02	2.18E+02	0.00E+00	8.72E+01	3.69E+02	5.17E+02	1.23E+04
Climate change - total	kg CO^2 eq.	6.22E+03	2.47E+03	2.43E+03	4.53E+02	2.19E+02	0.00E+00	8.78E+01	3.73E+02	5.28E+02	1.28E+04
Ozone layer Depletion	kg CFC-11-eq	4.64E-04	3.70E-04	2.70E-04	8.51E-05	2.82E-05	0.00E+00	1.13E-05	7.03E-05	1.72E-04	1.47E-03
Ozone layer depletion	kg CFC11 eq	5.65E-04	4.61E-04	3.05E-04	1.07E-04	3.55E-05	0.00E+00	1.42E-05	8.80E-05	2.17E-04	1.79E-03
Human toxicological effects	kg 1,4-DB-eq	1.45E+03	6.99E+02	3.66E+02	9.69E+01	5.88E+01	1.67E+01	2.35E+01	1.00E+02	2.34E+02	3.04E+03
Human toxicity , carcinogen	CTUh	1.84E-06	1.15E-06	2.99E-07	1.31E-07	4.76E-08	3.13E-09	1.91E-08	1.52E-07	2.21E-07	3.86E-06
Human toxicity , non-carcinogenic	CTUh	8.55E-05	2.31E-05	5.21E-06	4.31E-06	1.01E-06	2.11E-07	4.05E-07	4.87E-06	6.79E-06	1.31E-04
Particulate matter emission	disease inc.	2.17E-04	9.57E-05	1.99E-05	3.30E-05	3.67E-06	0.00E+00	1.47E-06	3.21E-05	9.70E-05	5.00E-04
Ionizing radiation	kBq U-235 eq	1.70E+02	1.40E+02	2.77E+01	3.03E+01	9.71E+00	0.00E+00	3.88E+00	2.51E+01	6.04E+01	4.67E+02
Photochemical oxidant formation	kg ethene-eq	1.54E+01	1.45E+00	3.86E-01	2.79E-01	7.56E-02	0.00E+00	3.02E-02	2.66E-01	5.51E-01	1.84E+01
Acidification	kg SO^{2-}eq	3.96E+01	1.59E+01	2.36E+00	1.54E+00	6.79E-01	0.00E+00	2.71E-01	1.12E+00	3.78E+00	6.53E+01
Eutrophication	kg PO_4^{-3} eq	3.09E+00	3.48E+00	4.00E-01	2.89E-01	1.48E-01	0.00E+00	5.94E-02	1.87E-01	7.29E-01	8.38E+00
Eutrophication seawater	kg N eq	6.34E+00	9.15E+00	8.44E-01	6.25E-01	3.72E-01	0.00E+00	1.49E-01	3.25E-01	1.72E+00	1.95E+01
Eutrophication fresh water	kg P eq	9.10E-02	2.85E-02	2.78E-02	3.14E-03	5.99E-04	0.00E+00	2.40E-04	3.90E-03	5.90E-03	1.61E-01
Ecotoxicological effects, aquatic (freshwater)	kg 1,4-DB-eq	2.27E+02	1.85E+01	2.63E+00	4.08E+00	8.36E-01	4.94E-05	3.35E-01	3.95E+00	5.54E+00	2.63E+02

Table B.3: Environmental profile of the life cycle of 1 ton MGO pre Tier I (continued)

Impact Category	Units	A1	A2	A3	A4	A5	B1	C1	C2	C4	Total
Ecotoxicity (freshwater)	CTUe	3.74E+05	2.89E+04	8.02E+03	5.13E+03	1.36E+03	1.63E-02	5.43E+02	5.70E+03	9.55E+03	4.33E+05
Abiotic depletion _ raw materials	kg Sb-eq	6.23E-02	2.97E-02	2.34E-03	7.72E-03	2.52E-04	0.00E+00	1.01E-04	8.13E-03	4.82E-03	1.15E-01
Depletion of abiotic raw materials, minerals and metals	kg Sb eq	6.23E-02	2.97E-02	2.34E-03	7.72E-03	2.52E-04	0.00E+00	1.01E-04	8.13E-03	4.82E-03	1.15E-01
Fossil depletion _ energy carriers	kg Sb-eq	1.45E+02	1.57E+01	2.04E+01	3.35E+00	1.07E+00	0.00E+00	4.29E-01	2.82E+00	7.04E+00	1.96E+02
Abiotic depletion _ raw materials fossil fuels	kg Sb-eq from MJ	1.48E+02	1.57E+01	1.80E+01	3.38E+00	1.09E+00	0.00E+00	4.35E-01	2.83E+00	7.07E+00	1.97E+02
Water consumption	m^3	1.65E+02	5.62E+00	4.18E+00	7.60E-01	1.17E-01	0.00E+00	4.68E-02	9.84E-01	1.57E+01	1.92E+02
Water use	m^3 depriv.	6.97E+03	1.44E+02	5.61E+01	2.40E+01	3.01E+00	0.00E+00	1.21E+00	3.22E+01	6.60E+02	7.89E+03
Land use related impact / soil quality	Pt	5.69E+04	2.59E+04	1.70E+03	8.09E+03	2.89E+02	0.00E+00	1.16E+02	1.11E+04	3.09E+04	1.35E+05
Ecotoxicological effects, aquatic (seawater)	kg 1,4-DB-eq	9.98E+05	6.17E+04	1.07E+04	1.10E+04	2.91E+03	2.69E+04	1.16E+03	1.04E+04	1.98E+04	1.14E+06
Ecotoxicological effects , terrestrial	kg 1,4-DB-eq	2.90E+01	3.08E+00	2.58E+00	5.45E-01	9.91E-02	5.57E-02	3.96E-02	8.43E-01	5.87E-01	3.68E+01
Climate change – fossil	kg CO^2 eq	6.21E+03	2.46E+03	2.42E+03	4.53E+02	2.19E+02	0.00E+00	8.78E+01	3.72E+02	5.27E+02	1.27E+04
Climate change – biogenic	kg CO^2 eq	1.58E+01	3.31E+00	5.54E+00	2.23E-01	5.02E-02	0.00E+00	2.01E-02	1.53E+00	1.04E+00	2.75E+01
Climate change - land use and land use change	kg CO^2 eq	3.67E+00	3.71E+00	2.05E-01	1.13E-01	1.28E-02	0.00E+00	5.13E-03	1.44E-01	1.47E-01	8.01E+00
Acidification	mol H^+ eq	4.63E+01	2.20E+01	3.04E+00	2.00E+00	9.28E-01	0.00E+00	3.71E-01	1.41E+00	5.00E+00	8.10E+01

Table B.3: Environmental profile of the life cycle of 1 ton MGO pre Tier I (continued)

Impact Category	Units	A1	A2	A3	A4	A5	B1	C1	C2	C4	Total
Eutrophication of land	mol N eq	6.22E+01	1.01E+02	9.55E+00	6.91E+00	4.09E+00	0.00E+00	1.64E+00	3.79E+00	1.90E+01	2.08E+02
Smog formation	kg NMVOC eq	4.52E+01	2.64E+01	2.89E+00	2.17E+00	1.11E+00	0.00E+00	4.42E-01	1.36E+00	5.51E+00	8.51E+01
Use of renewable primary energy excluding renewable primary energy used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.08E+02	0.00E+00	9.08E+02
Use of renewable primary energy used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total use of renewable primary energy	MJ	2.16E+03	6.69E+02	7.19E+02	7.15E+01	1.24E+01	0.00E+00	4.97E+00	9.79E+02	1.19E+02	4.73E+03
Use of non-renewable primary energy excluding non-renewable energy used as materials [MJ]	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.96E+01	0.00E+00	7.96E+01
Use of non-renewable primary energy used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.12E-01	0.00E+00	1.12E-01
Total use of non-renewable primary energy	MJ	3.28E+05	3.46E+04	4.14E+04	7.46E+03	2.40E+03	0.00E+00	9.61E+02	6.26E+03	1.56E+04	4.37E+05
Use of secondary materials	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Use of renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Use of non-renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table B.3: Environmental profile of the life cycle of 1 ton MGO pre Tier I (continued)

Impact Category	Units	A1	A2	A3	A4	A5	B1	C1	C2	C4	Total
Dangerous waste	kg	1.31E-01	8.44E-02	4.55E-02	1.74E-02	6.16E-03	0.00E+00	2.46E-03	1.73E-02	2.20E-02	3.26E-01
Not dangerous waste	kg	5.02E+02	6.82E+02	2.86E+01	6.15E+02	2.68E+00	0.00E+00	1.07E+00	6.26E+02	1.00E+05	1.02E+05
Radioactive waste	kg	1.12E-01	2.12E-01	3.52E-02	4.79E-02	1.57E-02	0.00E+00	6.29E-03	3.93E-02	9.67E-02	5.65E-01

B.3.4. Impact Categories for Steel Sheet Pile

Table B.4: Environmental profile of the life cycle of 1 ton Steel. Source: [111]

Impact Category	Units	A1	A4	A5	C2	C4	D	Total
Environmental Cost Indicator	Euro	90.56	4.75	11.84	0.56	0.16	29.79	146.62
Global warming potential (GWP-total)	kg CO^2 eq.	8.38E+02	4.10E+01	2.65E+01	4.70E+00	1.16E+00	2.46E+02	1.16E+03
Global warming potential - Biogenic (GWP-b)	kg CO^2 eq.	1.85E+01	3.10E-02	5.57E-01	2.17E-03	2.30E-03	-2.62E+00	1.65E+01
Global warming potential - Fossil (GWP-f)	kg CO^2 eq.	8.18E+02	4.09E+01	2.59E+01	4.70E+00	1.16E+00	2.49E+02	1.14E+03
Global warming potential - Land use and land use change (GWP-luluc)	kg CO^2 eq.	1.53E+00	1.25E-02	4.63E-02	1.72E-03	3.23E-04	-1.90E-01	1.40E+00
Ozone depletion (ODP)	kg CFC 11 eq.	5.28E-05	1.01E-05	1.93E-06	1.04E-06	4.77E-07	5.91E-06	7.23E-05
Human toxicity, cancer (HTP-c)	CTUh	3.90E-06	1.28E-08	1.17E-07	2.05E-09	4.86E-10	-4.53E-09	4.03E-06
Human toxicity, non-cancer (HTP-nc)	CTUh	1.22E-04	5.80E-07	3.68E-06	6.91E-08	1.49E-08	-4.97E-05	7.66E-05
Particulate Matter (PM)	disease incidence	3.86E-05	3.59E-06	1.28E-06	4.23E-07	2.14E-07	1.42E-05	5.83E-05
Ionising radiation, human health (IR)	kBq U235 eq.	3.24E+01	2.91E+00	1.07E+00	2.97E-01	1.33E-01	-4.44E+00	3.24E+01
Photochemical ozone formation - human health (POCP)	kg NMVOC eq.	2.21E+00	1.26E-01	7.12E-02	3.02E-02	1.21E-02	1.41E+00	3.86E+00
Acidification (AP)	mol H+ eq.	3.62E+00	1.32E-01	1.14E-01	2.73E-02	1.10E-02	9.52E-01	4.86E+00
Eutrophication, marine (EP-m)	kg N eq.	5.93E-01	2.89E-02	1.91E-02	9.61E-03	3.78E-03	1.77E-01	8.31E-01
Eutrophication, freshwater (EP-fw)	kg P eqv.	6.65E-02	3.26E-04	2.01E-03	4.74E-05	1.30E-05	8.69E-03	7.76E-02
Ecotoxicity, freshwater (ETP-fw)	CTUe	7.10E+03	5.29E+02	2.31E+02	6.32E+01	2.10E+01	8.34E+03	1.63E+04
Resource use, minerals and metals (ADP-mm)	kg Sb-eq.	1.13E-03	7.29E-04	5.97E-05	1.19E-04	1.06E-05	1.71E-04	2.22E-03
Resource use, fossils (ADP-f)	MJ	1.05E+04	6.65E+02	3.38E+02	7.09E+01	3.24E+01	1.71E+03	1.33E+04

Table B.4: Environmental profile of the life cycle of 1 ton Steel. (continued)

Impact Category	Units	A1	A4	A5	C2	C4	D	Total
Water use (WDP)	m^3 world eq.	-9.65E+01	2.16E+00	-2.78E+00	2.54E-01	1.45E+00	4.82E+01	-4.72E+01
Land use	Pt	2.86E+03	7.61E+02	1.12E+02	6.15E+01	6.79E+01	3.80E+02	4.24E+03
Eutrophication, terrestrial (EP-T)	mol N eq.	1.02E+01	3.22E-01	3.20E-01	1.06E-01	4.17E-02	2.06E+00	1.30E+01

B.3.5. Impact Categories for Constructing a Gravel Foundation Layer

Table B.5: Environmental profile of the life cycle of 1 ton asphalt foundation layer - calculated for previous project - EN15804+A2 (Exact Value Transfer)

Impact Category	Units	A1	A3	A4	A5	Total
Global warming potential (GWP-total)	kg CO^2 eq.	6.75E+00	1.35E-01	5.28E-02	1.55E-01	7.10E+00
Global warming potential - Biogenic (GWP-b)	kg CO^2 eq.	3.12E-03	6.23E-05	1.04E-04	1.12E-03	4.40E-03
Global warming potential - Fossil (GWP-f)	kg CO^2 eq.	2.06E+00	1.97E-01	5.41E+00	2.75E+00	1.04E+01
Global warming potential - Land use and land use change (GWP-luluc)	kg CO^2 eq.	5.09E-02	1.54E-03	1.98E-03	7.55E-04	5.52E-02
Ozone depletion (ODP)	kg CFC 11 eq.	4.20E-07	4.17E-08	1.19E-06	5.95E-07	2.25E-06
Human toxicity, cancer (HTP-c)	CTUh	2.75E-09	1.21E-10	2.36E-09	8.29E-10	6.06E-09
Human toxicity, non-cancer (HTP-nc)	CTUh	5.56E-08	2.63E-09	7.96E-08	2.05E-08	1.58E-07
Particulate Matter (PM)	disease incidence	5.96E-07	5.52E-08	4.87E-07	7.54E-07	1.89E-06
Ionising radiation, human health (IR)	kBq U235 eq.	1.23E-01	1.16E-02	3.42E-01	1.63E-01	6.40E-01
Photochemical ozone formation - human health (POCP)	kg NMVOC eq.	3.23E-02	2.85E-03	3.48E-02	3.80E-02	1.08E-01
Acidification (AP)	mol H^+ eq.	1.93E-02	1.99E-03	3.14E-02	2.85E-02	8.12E-02
Eutrophication, marine (EP-m)	kg N eq.	6.57E-03	8.19E-04	1.11E-02	1.25E-02	3.10E-02
Eutrophication, freshwater (EP-fw)	kg P eq.	3.22E-04	1.01E-05	5.46E-05	1.36E-05	4.00E-04
Ecotoxicity, freshwater (ETP-fw)	CTUe	2.83E+01	1.97E+00	7.27E+01	2.32E+01	1.26E+02
Resource use, minerals and metals (ADP-mm)	kg Sb-eq.	2.65E-05	1.00E-06	1.37E-04	5.75E-06	1.70E-04
Resource use, fossils (ADP-f)	MJ	2.90E+01	2.72E+00	8.16E+01	3.80E+01	1.51E+02
Water use (WDP)	m^3 world eq.	2.49E-01	9.97E-03	2.92E-01	5.49E-02	6.06E-01

Table B.5: Environmental profile of the life cycle of 1 ton asphalt foundation layer - calculated for previous project - EN15804+A2 (Exact Value Transfer)(continued)

Impact Category	Units	A1	A3	A4	A5	Total
Land use (SQP)	Pt	1.32E+03	3.98E+01	7.07E+01	1.90E+01	1.45E+03
Eutrophication, terrestrial (EP-T)	mol N eq.	7.01E-02	8.93E-03	1.22E-01	1.38E-01	3.39E-01

B.3.6. Impact Categories for Mangrove Sand Trapping Unit

Table B.6: Environmental profile of the life cycle of 1-meter Mangrove Sand Trapping Units (in Suriname) - LCA impact profile based on EN15804+A2. Source: NMD [113]

Impact Category	Units	A1	A3	A4	A5	Total
Global warming potential (GWP-total)	kg CO^2 eq.	-1.45E+02	-4.21E+00	5.41E+00	1.24E+00	-1.43E+02
Global warming potential - Biogenic (GWP-b)	kg CO^2 eq.	-1.47E+02	-4.41E+00	2.50E-03	-1.51E+00	-1.53E+02
Global warming potential - Fossil (GWP-f)	kg CO^2 eq.	2.06E+00	1.97E-01	5.41E+00	2.75E+00	1.04E+01
Global warming potential - Land use and land use change (GWP-luluc)	kg CO^2 eq.	5.09E-02	1.54E-03	1.98E-03	7.55E-04	5.52E-02
Ozone depletion (ODP)	kg CFC 11 eq.	4.20E-07	4.17E-08	1.19E-06	5.95E-07	2.25E-06
Human toxicity, cancer (HTP-c)	CTUh	2.75E-09	1.21E-10	2.36E-09	8.29E-10	6.06E-09
Human toxicity, non-cancer (HTP-nc)	CTUh	5.56E-08	2.63E-09	7.96E-08	2.05E-08	1.58E-07
Particulate Matter (PM)	disease incidence	5.96E-07	5.52E-08	4.87E-07	7.54E-07	1.89E-06
Ionising radiation, human health (IR)	kBq U235 eq.	1.23E-01	1.16E-02	3.42E-01	1.63E-01	6.40E-01
Photochemical ozone formation - human health (POCP)	kg NMVOC eq.	3.23E-02	2.85E-03	3.48E-02	3.80E-02	1.08E-01
Acidification (AP)	mol H^+ eq.	1.93E-02	1.99E-03	3.14E-02	2.85E-02	8.12E-02
Eutrophication, marine (EP-m)	kg N eq.	6.57E-03	8.19E-04	1.11E-02	1.25E-02	3.10E-02
Eutrophication, freshwater (EP-fw)	kg P eq.	3.22E-04	1.01E-05	5.46E-05	1.36E-05	4.00E-04
Ecotoxicity, freshwater (ETP-fw)	CTUe	2.83E+01	1.97E+00	7.27E+01	2.32E+01	1.26E+02
Resource use, minerals and metals (ADP-mm)	kg Sb-eq.	2.65E-05	1.00E-06	1.37E-04	5.75E-06	1.70E-04
Resource use, fossils (ADP-f)	MJ	2.90E+01	2.72E+00	8.16E+01	3.80E+01	1.51E+02
Water use (WDP)	m^3 world eq.	2.49E-01	9.97E-03	2.92E-01	5.49E-02	6.06E-01
Land use (SQP)	Pt	1.32E+03	3.98E+01	7.07E+01	1.90E+01	1.45E+03

Table B.6: Environmental profile of the life cycle of 1-meter Mangrove Sand Trapping Units (in Suriname) - LCA impact profile based on EN15804+A2. (continued)

Impact Category	Units	A1	A3	A4	A5	Total
Eutrophication, terrestrial (EP-T)	mol N eq.	7.01E-02	8.93E-03	1.22E-01	1.38E-01	3.39E-01

B.4. Life Cycle Assessment Midpoint & Endpoint Impact Indicators

In Life Cycle Impact Assessment (LCIA), midpoint and endpoint impact indicators are used to assess the potential environmental impacts of a product or process. These indicators are presented in Figure B.2 and defined as follows:

Midpoint Impact

Midpoint impact indicators represent the intermediate stages in the cause-effect chain of an environmental impact. They provide a more detailed and specific description of the environmental mechanism linking environmental interventions (like emissions or resource use) to potential impacts.

Endpoint Impact

Endpoint impact indicators represent the final outcomes of the environmental impact mechanism. They aggregate the effects of midpoints into broader areas of protection that reflect actual damages to human health, ecosystems, and resources.

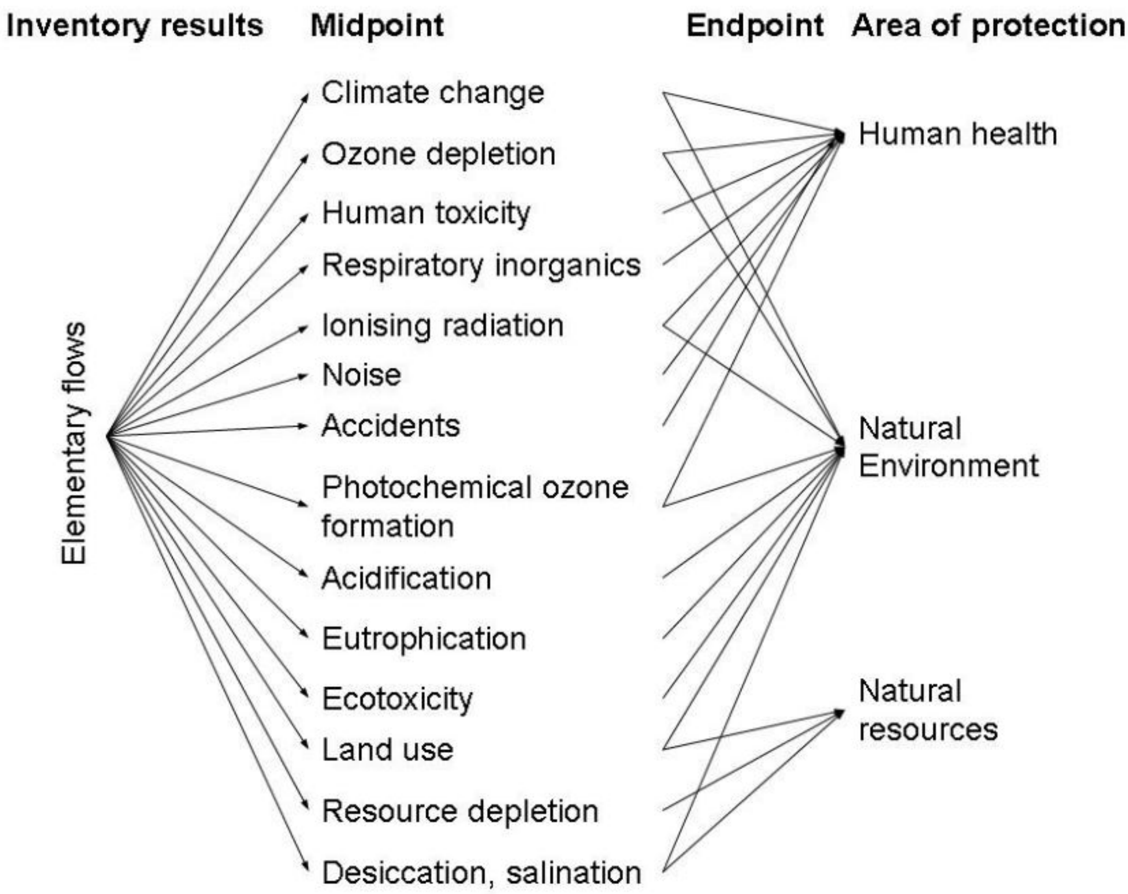

Figure B.2: Framework of impact categories for characterisation modelling at midpoint and endpoint (Area of Protection) levels. Source: JRC [77]

Figure B.2 illustrates the connection between elementary flows from inventory analysis, such as emissions and resource use, to midpoint categories and then to endpoint categories. It shows how specific environmental issues at the midpoint level, like climate change or acidification, contribute to broader endpoint impacts on human health, the natural environment, and natural resources. In summary, midpoint indicators track specific mechanisms of environmental change, while endpoint indicators aggregate these changes into broader impact categories that are easier to understand.

C

Ecosystem Services

C.1. Monetized Coastal Ecosystem Services for Benefits transfer

The following tables provide estimated values for various coastal ecosystem services. for these values to be used, it is important to consult the reference source to get a full understanding of the assumption surrounding the value estimation.

Table C.1: Valuing a Caribbean coastal lagoon using the choice experiment method: The case of the Simpson Bay Lagoon, Saint Martin. [47]

Ecosystem Service Valued	Value	Unit	Method
Storm protection	4,001,272	US$/year	Choice Experiment
Water quality improvement	1,105,615 – 4,415,878	US$/year	Choice Experiment
Habitat for Species	4,669,248	US$/year	Choice Experiment
Increase in Stay-over tourists	2,296,783 – 4,590,275	US$/year	Choice Experiment
Mangrove Restoration	22,987,573	US$/year	Choice Experiment
Installation of Sewage Treatment Plant	16,528,282	US$/year	Choice Experiment
Combined interventions (mangrove restoration and sewage treatment)	26,343,903	US$/year	Choice Experiment

Table C.2: The economic benefit of coastal erosion control in Korea. By Chang, J. I., & Yoon, S. [95]

Ecosystem Service Valued	Value	Unit	Method
Damage reduction (through erosion control)	5,708.60	KRW (per household per year)	Choice Experiment
Beach Restoration (1.5 times wider beach)	5,514	KRW (per household per year)	Choice Experiment
Eco-waterfront space (Coastal trails)	8,261.60	KRW (per household per year)	Choice Experiment
Eco-waterfront space (Eco-Space)	7,922.70	KRW (per household per year)	Choice Experiment

Table C.3: Global values of coastal ecosystem services: A spatial economic analysis of shoreline protection values. By Rao et al., [50]

Ecosystem Service Valued	Value	Unit	Method
Shoreline Protection*	0.4-1998	$/ha/year	Meta-analysis & Benefit Transfer
Shoreline Protection**	0.51-2530	$/ha/year	Meta-analysis & Benefit Transfer

Shoreline protection value range from (*) 0.4-1998 $/ha/year in 2003 to (**) 0.51-2530 $/ha/year in 2013.

Table C.4: The value of estuarine and coastal ecosystem services [43]

Ecosystem Service Valued	Value	Unit	Method
Mangrove			
Raw materials and food	484–585	US$/ha/yr	Replacement cost
Coastal protection	8966–10821	US$/ha	
Erosion control	3679	US$/ha/yr	
Maintenance of fisheries	708-987	US$/ha	
Carbon sequestration	30.5	US$/ha/yr	
Sand beaches and dunes			
Raw materials	Estimate N/A	-	
Coastal protection	Estimate N/A		
Erosion control	4.45	US$/household	
Water catchment and purification	Estimate N/A		
Maintenance of wildlife	Estimate N/A		
Carbon sequestration	Estimate N/A		
Tourism, recreation, education, and research	166	US$/trip	
Tourism, recreation, education, and research	1574	US$/visiting household/yr	

Table C.5: Valuing the storm protection service of estuarine and coastal ecosystems. [44]

Ecosystem Service Valued	Value	Unit	Method
Mangrove			
Storm Protection	25,504,821	US$/18km2 mangrove loss	Replacement cost
	3,382,169	US$/18km2 mangrove loss	Replacement cost
	4,869,720	US$/3.44km2 mangrove loss	Expected damage function
	645,769	US$/3.44km2 mangrove loss	Expected damage function

Table C.6: Mangrove ecosystem service values and methodological approaches to valuation: Where do we stand?: Annual economic value of marine and coastal ecosystem services in Vanuatu, 2013 (US$) [128]

Ecosystem Service Valued	Value	Unit	Method
Subsistence fishery	6.49	US$ million	
Commercial fisheries (total)	7.01	US$ million	
Minerals and aggregates	0.17	US$ million	
Tourism and recreation	9.59	US$ million	
Coastal protection	18.37	US$ million	
Carbon sequestration	1.41	US$ million	
Research, management and education	4.9	US$ million	

Table C.7: Economic valuation of the ecosystem services provided by the mangroves of the Gulf of Nicoya using a hybrid methodology [48]

Ecosystem Service Valued	Value	Unit	Method
Provisioning Services			
Food	39,896,691	US$	-
Fodder	14,760	US$	-
Timber and fuelwood	49,618,917	US$	-
Regulating Services			
Climate regulation	15,011,447	US$	-
Coastal Protection	152,187,141	US$	-
Cultural Services			
Recreation/tourism	804,021	US$	-
Supporting Services			
Biodiversity protection	212,214,578	US$	-

Table C.8: The Recreational Benefits of Beaches; Weighted Averages of Marginal Willingness-To-Pay Estimates for the Valuation Alternatives. source: [116]

Alternatives	Recreational Value	Unit	Method
Wider beaches with similar shoreline armouring	607,016	US$/yr	Willingness-To-Pay
Wider beaches with minimal shoreline armouring (No management policy specified)	759,895	US$/yr	Willingness-To-Pay
Wider beaches with minimal shoreline armouring (Beach nourishment specified)	8,821,697	US$/yr	Willingness-To-Pay
Wider beaches with minimal shoreline armouring (The adoption of a retreat policy specified for management)	8,074,698	US$/yr	Willingness-To-Pay

Table C.9: The economic value of mangrove ecosystem services in the Jiulong River Estuary, China, in 2015. Source: [129]

Ecosystem Service Valued	Value	Unit	Method
Coastal protection	1398	US$/ha/yr	-
Carbon sequestration	73	US$/ha/yr	-
Nutrient retention	145	US$/ha/yr	-

D

Case Study: Raw Data and Extra Relevant Information

D.1. Overview of Distinctive Effects of the Sea Dike vs Sand Nourishment Alternatives

Related to ecosystem services valuation, Table D.1 presents the seven-point scale in the qualitative assessment of the effects of the different alternatives according to ARCADIS's report [115]. Table D.2 shows an overview of the distinctive effects of the sea dike vs sand nourishment alternative.

Table D.1: Application of seven-point scale in qualitative assessment of the effects. Source: [115]

Score	Description	Score (#)
++	Strongly positive compared to the reference situation	1
+	Positive compared to the reference situation	0.5
0/+	Slightly positive compared to the reference situation	0.25
0	Neutral	0
0/-	Slightly negative compared to the reference situation	-0.25
-	Negative compared to the reference situation	-0.5
–	Strongly negative compared to the reference situation	-1

Table D.2: Overview of distinctive effects of the sea dike vs sand nourishment alternatives. Source: [115].

Assessment criterion	Alternatives	
	Sea Dike	Sand Nourishment
Coast and sea		
Influencing maintenance needs	-0.25	-0.5
Safety		
Security level	0.5	0.5
Degree of robustness	0.25	1
Soil and water		
Influence on cables and pipes	-0.5	-0.5
Landscape, cultural history and archaeology		
Landscape		
Influencing landscape structures, elements and patterns	0.25	1
Influence on scale characteristics	0	0.5
Experience/readability of landscape	0.25	1
Starting points	0	1
Influence on geological monuments -	-0.25	-0.5

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Table D.2 – continued from previous page

Assessment criterion	Alternatives	
	Sea Dike	Sand Nourishment
Cultural history		
Influence individual objects	-0.25	-0.5
Archaeology		
Influence on archaeological expected value	-0.25	-0.5
Nature		
Natura 2000 areas		
Influencing conservation objectives Dunes Den Helder-Callantsoog	-0.25	-0.5
Development potential Dunes Den Helder-Callantsoog	0.5	1
Influencing conservation objectives Swan Water and Pettemer-duinen	0	-1
Development potential Zwanenwater and Pettemerduinen	0	0.5
EHS area		
Influence on essential values and characteristics of dune areas	-0.25	-1
Development potential in dune areas	0.25	1
Recreation and tourism		
Recreation		
Attraction of the coast	0.25	1
Possibilities for use of the new coast	0.25	1
Influencing quality of stay	0.25	1
Development potential for expanding recreational offerings	0.25	1
Shifting sand	-0.25	-0.5
Tourism		
Product offer	0.25	1
Economic value (use phase)	0.25	1
Identity	0.25	1

From table D.2, an indicator of the possible ratio/weighting factors can be extracted by taking the average of all elements considered for each category. For example, for the tourism category, the sea dike and sand nourishment scored an average of -0.0357 and 0.2857, indicating that sand nourishment performs 9 times better than the sea dike, compared to a reference situation.

D.2. Impact of Material's Volume and Installation Methods

Table D.3: Impact of Material's Volume and Installation Methods.

Category	Material	Unit	0.5* Base Case		Base Case		1.5* Base Case	
			Dune	Dike	Dune	Dike	Dune	Dike
Materials Quantities	Sand	m^3	14,325,000	1,419,894	28,650,000	2,839,788	42,975,000	4,259,682
	Clay	ton	-	283,979	-	567,958	-	851,936
	Asphalt	ton	-	35,347	-	70,694	-	106,041
	Steel	ton	-	25,312	-	25,312	-	25,312
	Gravel	ton	-	835,692	-	1,671,384	-	2,507,076
Fuel Consumption	Marine Gas Oil	ton	10,047	1,984	20,094	3,968	30,141	5,952
	Diesel	liter	438,394	483,486	876,789	966,972	1,315,183	1,450,458
Lifetime Environmental Costs	Construction	Million Euro	(201)	(66)	(402)	(131)	(603)	(196)
	Maintenance	Million Euro	(6)	(3)	(12)	(5)	(18)	(8)
Lifetime Ecosystem Services Benefits	Net	Million Euro	583	208	583	208	583	208
Investment	CAPEX	Million Euro	(91)	(107)	(181)	(214)	(272)	(321)
	OPEX	€/year	(377,703)	(86,580)	(755,405)	(173,161)	(1,133,108)	(259,741)