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# Integrated Methodology for Physical and Economic Assessment of Coastal Interventions Impacts

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**Abstract:** Due to economic, environmental, and social interest of coastal areas, together with their erosion problems, different coastal management strategies can be considered, with different physical (shoreline evolution) and economic (net present value, ratio benefit-cost, break-even point) consequences and impacts. Therefore, this work presents an integrated methodology that aims to compare and discuss the most promising coastal intervention scenarios to mitigate erosion problems and climate change effects, considering costs and benefits related to each intervention. The proposed methodology takes a step forward in assessing the coastal erosion mitigation strategies, incorporating three well-defined and sequential stages: shoreline evolution in a medium-term perspective; structures pre-design; and a cost-benefit assessment. To show the relevance of the methodology, a hypothetic case study and several intervention scenarios were assessed. In order to mitigate costal erosion two different situations were analyzed: the reference scenario and the intervention scenarios. 34 intervention scenarios were proposed and evaluated to mitigate the erosion verified. Depending on the parameter considered (reduce erosion areas, protect the full extension of urban waterfronts, improve the economic performance of the intervention by increasing the net present value, the benefit-cost ratio or decreasing the break-even time), best results are obtained for different scenarios. The definition of the best option for coastal erosion mitigation is complex and depends on the main goal defined for the intervention. In conclusion, costs and benefits analysis are demanded and it is considered that the proposed methodology allows choosing better physical and economic options for future coastal interventions, helping decision-making processes related to coastal management.

**Keywords:** LTC; XD-Coast; Costs and benefits; Coastal optimization; Coastal management; Climate change effects.

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## 1. Introduction

Worldwide, coastal zones experience increased rates of erosion, mainly due to fluvial sediment supply reduction, as well as coastal areas degradation and transformation due to anthropogenic actions [1-5]. Climate change effects also increase coastal erosion problems [6-8]. As a coastal erosion consequence, a growing trend of conflicts between shoreline evolution, land use and erosion mitigation measures is observed [9]. Despite coastal erosion impacts being confined to coastal areas, these areas host over 40% of the world population, as well as a wide variety of coastal ecosystems that provide various different services [10-12]. Due to the economic, environmental and social importance of coastal areas, coupled with their erosion problems, different coastal management strategies to mitigate erosion can be considered.

As described in [13-15], the IPCC (Intergovernmental Panel on Climate Change) identified three main strategies to respond to coastal erosion, flooding and sea level rise risks: i) retreat, limiting the effects of a potential dangerous event, landward resettling of the risky population centres and economic activities; ii) accommodation, considering all the strategies necessary to increase the society's resilience to coastal erosion, including land use change, emergency planning and hazard insurance [16-18]; iii) protection, involving all defence techniques used to preserve vulnerable areas, such as population centres, economic activities and natural resources; and iv) attack, by land reclamation and extending facilities towards the sea [19]. Strategies to mitigate coastal erosion are mainly reactive and tend to not include local stakeholders in the decision-making process [20]. Although some erosion impacts can be mitigated through coastal protection works, such measures may represent negative second order impacts for coastal environments and social and economic life [21].

Current coastal erosion and flooding adaptation strategies [22-24] are frequently based on the adoption of adaptation measures at the local scale, while the factual costs, impacts and benefits are determined by the suit of adopted adaptation measures at the landscape scale [25-29]. Adaptation measures should also reduce climate change vulnerability and risk [30-33], and would help to seek opportunities, to build up capacity of social environmental systems to cope with climate impacts, and mobilize that capacity by implementing decisions and actions [34]. To deal with complexity and uncertainty, action-plans requires well-developed methodologies and tools, including participatory approaches, to provide efficient and effective means of supporting decision-making [35-38].

Traditionally, coastal erosion was assessed using engineering approaches, such that the physical effectiveness of adaptation measures was assessed without taking into consideration associated cost and benefit [12, 39]. Over the last decades the focus of studies moved from physical effectiveness to a more comprehensive management of coastal zones, evaluating adaptation measures with economic tools such as cost-effectiveness, cost-benefit and efficiency analyses [40]. Moreover, when discussing climate related threats with decision-makers, cost-benefit analyses that support decisions are often demanded [41]. According to , cost-effectiveness studies provide insight in what adaptation measures achieve coastal protection objectives at least cost [42, 43]. Cost-benefit studies provide insight in what adaptation measures/strategies provide largest net benefits, assessing costs and benefits of engineering measures [10, 11, 41, 44-47, 49, 50]. In short, coastal zone managers should, amongst others, rely on cost-benefit analyses when defining protection, adaptation and/or retreat strategies [51].

Therefore, this work aims to present a methodology to analyse and discuss the most adequate adaptation strategies to coastal erosion in combination with socio-environmental-economic expertise, considering the costs and benefits related to each intervention, by applying an integrated, well-defined, and sequential cost-benefit approach. The goal of the proposed methodology is to support decision-making for planning and coastal management, by encompassing the assessment of the shoreline evolution impacts (with a shoreline evolution model, LTC [52]) , and the design of coastal structures (applying a coastal structures design model, XD-Coast [53], allowing the final costs and benefits analysis. To show the relevance of the methodology, some different interventions scenarios have been proposed to protect a hypothetical urban waterfront from a coastal erosion trend, illustrating an example of potential applications. The adopted scenarios encompass four different types of coastal interventions: groins, longitudinal revetments, artificial nourishments, and sand by-pass systems. Consequently, in the next section, the costs and benefits assessment method are described, subdivided in each of the three integrated stages. Next, a description of the hypothetical case study is presented, including the reference scenario, and all the proposed intervention scenarios.

## 2. Methodology

The proposed methodology encompass three stages (Figure 1) to evaluate physical and economic performance of different types of coastal interventions (groins, longitudinal revetments, artificial nourishments and sand by-pass systems): 1) shoreline evolution projection in a medium-term horizon (using LTC numerical model [52]), that leads to estimate the benefits of the intervention; 2) pre-design of the coastal structure and the material volume required (with the support of XD-Coast model [53]), that allows the costs estimate (construction and maintenance); and finally, 3) taking into account the previous results, a cost-benefit assessment to each intervention scenario.

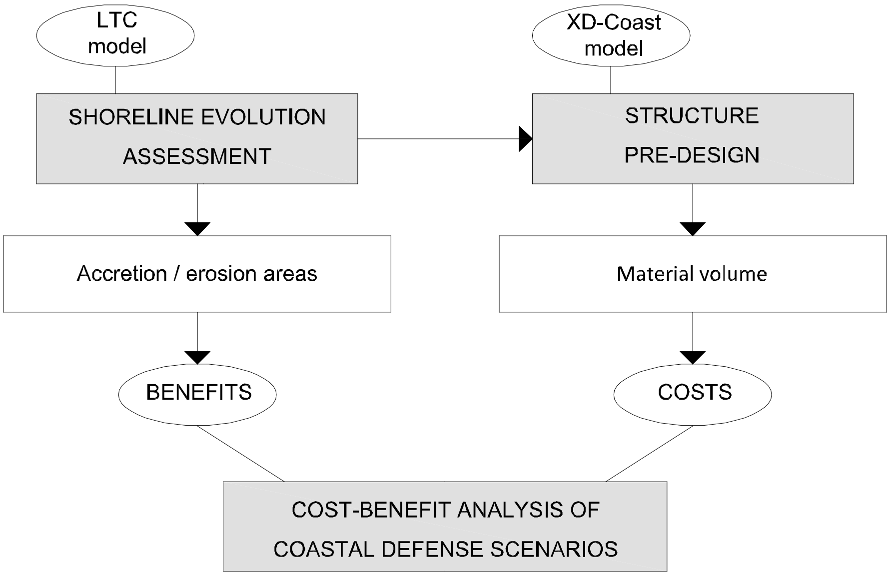


**Figure 1.** Proposed methodology to assess the physical and economic performance of different coastal interventions scenarios.

The proposed methodology is considered integrated as the structures pre-design is based on the wave characteristics and topography/bathymetry adopted in the shoreline evolution assessment. Thus, the definition of the dimensions of the intervention and consequent materials volumes are dependent of the domain characteristics assessed during the shoreline evolution numerical modelling. Then, the third step of the method (cost-benefit assessment) is associated to the shoreline evolution assessment and by adopting land use values that represent the ecosystems services that can be obtained for different uses. Thus, areas gained, maintained or lost in every year of the simulation are transferred to a monetary value, considering the correspondent land use values. At the same time, in the cost-benefits analysis it is assigned an economic value to the materials of the designed interventions (this value should consider design costs, workforce, transport and all the potential related costs of the intervention) and thus, the tested interventions also result in a monetary value. Considering the previous, in the described methodology every sequential procedure steps are well-defined.

## 2.1 Shoreline evolution assessment

The benefits of a coastal intervention scenario are estimated through the numerical modelling evaluation of the territory maintained, gained, or lost, over time. Therefore, the shoreline evolution numerical model LTC (Long-Term Configuration [52]) was considered. LTC was developed to support coastal zone planning and management in relation to coastal erosion problems [56-58]. It was firstly presented by and has been improved and largely applied since then [11, 52, 56, 58, 60-62, 64-66]. LTC combines a simple classical one-line model with a rule-based model for erosion/accretion volumes distribution along the beach profile [54]. This model was designed for sandy beaches, where the main cause of shoreline evolution is the alongshore sediment transport gradients, dependent on the wave climate, water levels, sediment's sources and sinks, sediment's characteristics and boundary conditions. The model inputs are the wave climate (being defined by the wave height, wave period and direction), water level and the bathymetry and topography of the landward adjacent zones (updated during calculation).

The longshore sediment transport volumes are estimated by a formula that considers the waves breaking direction and height (CERC formula [67]). The sediment volumes balance is defined through the continuity equation, depending on sediment transport gradients between modelled cells, similar to one-line models approach. It is assumed that there is an offshore depth of closure and an onshore upper end of the active profile, defining the limits where no significant changes happen (active width of each cross-shore profile). LTC assumes a uniform cross-shore distribution of the alongshore sediment transport along the active width of the beach's cross-shore profiles, thus performing a uniform variation of the vertical coordinates of the active profile grid points, adjusting the active profile at the boundaries, based on the sediments' friction angle [55]. This way, the variation of the shoreline position depends not only of the sediments volume variation but also of the topography and bathymetry associated with each cross-shore profile. The 3D topo-bathymetric model is continuously updated during simulation, allowing distributing erosion or accretion sediment volumes between each computational time step (Figure 2).

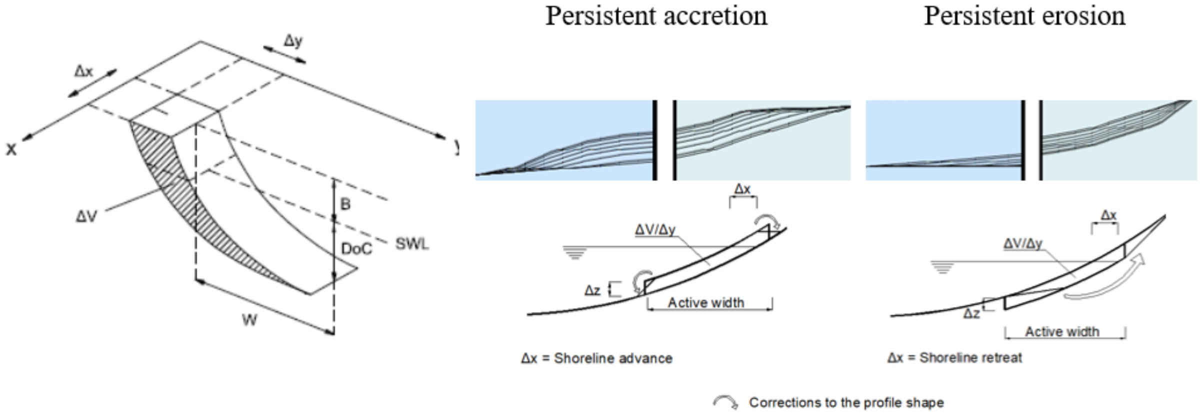


**Figure 2.** LTC definition scheme (adapted from [68, 69]).

The wave transformation by refraction, diffraction and shoaling are modelled in a simplified manner [54], always taking into account the updated bathymetric data of each time step. According to Coelho [52], the refraction effects in LTC are estimated considering the Snell's law, while the shoaling effect is computed assuming that Airy's linear theory of sinewaves is valid. The diffraction effects are only calculated for beach extensions located downdrift the groins, considering a simplified method.

Due to the importance of the boundary conditions in the model simulations, several options can be made: constant sediment transport volumes going in or out of the modelled domain; constant volume variations in the boundary sections; extrapolation from nearby conditions [63]. Moreover, combined coastal protection works may be considered, with almost no limitation of the number of structures or artificial nourishments interventions. These coastal intervention characteristics are adopted in the structures pre-design module, allowing the definition of the dimensions of each intervention. In the cost-benefit module, an annual land use value is assigned to the territory, which, in correspondence with every year area gained, maintained or lost along the shoreline evolution simulation time horizon will allow evaluate the economic benefits.

## 2.2 Structures pre-design

Coastal intervention costs estimate (construction and maintenance) is based on structures dimensions and required material. Thus, it is necessary to define the type of blocks and geometry of the structure (cross-section and length) and, consequently, the structure volume (knowing local wave climate and bathymetry and topography from the shoreline evolution assessment). The numerical pre-design tool XD-Coast was applied [71]. XD-Coast software (Xpress Design of COAstal Structures) was developed in Microsoft Visual C# language, allowing the calculation of armour layer blocks unit weight, considering different formulations and types of structures. Furthermore, the main characteristics of the cross-section are also defined, in function of the armour layer blocks unit weight [53]. Thus, the XD-Coast is divided into two main parts: estimative of the armour layer blocks unit weight; and cross-shore geometric characteristics definition.

Firstly, the user chooses the type of structure and the formulation required to calculate the block weight of its resistant layer. Afterwards, in the second part, depending on the first part results, a schematization of the cross-section can be obtained [71]. The coastal structures are exposed to several energetic loads, as waves, currents and tides, but the software only considers the load represented by the wave height. Once the cross-section is defined, knowing the bathymetry and topography at the structures location, the total dimension and the volume of each structure layer and type of material is calculated. In the cost-benefit module, monetary values are assigned to the materials volumes and structures maintenance requirements [60].

## 2.3 Cost-benefit analysis

To assess and compare the economic viability of different coastal intervention scenarios, a cost-benefit analysis is performed, considering the net present value (NPV) and the benefit-cost ratio (BCR) evaluation criteria [77]. Costs and benefits are compared to the no intervention scenario, where costs (Ct) are defined as the additional initial investment and recurrent maintenance costs (in €/year) and benefits (Bt) are defined as territory maintained, gained or lost, due to the intervention (in €/m²/year). Initial investment and recurrent maintenance costs are based on XD-Coast structures design, and erosion/accretion areas are based on LTC shoreline evolution results.

The NPV evaluation criterion is given by the sum of discounted benefits minus the sum of discounted costs that occur in each period t, over the lifetime of the project T [77], and is given by:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

where r is the time discount rate. The investment is considered economically viable when the NPV > 0, i.e., when the present value benefits (first term on right-hand side of Equation 1) exceed the present value costs (second term on right-hand side).

The BCR evaluation criterion is given by the sum of discounted benefits relative to the sum of discounted costs that occur in each period t, over the lifetime of the project T (Zerbe and Dively, 1994), and is given by:

$$\mathrm{BCR} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} \Big/ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{2}$$

The investment is considered economically viable when the BCR > 1, i.e., when the present value benefits (numerator on right-hand side of Equation 2) exceed the present value costs (denominator on right-hand side). Note that the BCR = 1 when the NPV = 0.

The benefits (positive if the territory is maintained or gained, and negative if the territory is lost) are obtained taking into account the land value (considering all the environmental, social and cultural aspects in the adopted value). [78,79] present provided services of different ecosystems that can work as preliminary reference for land use values, but in specific studies, users should support and validate the values with adequate socioeconomic databases. Maintained, gained or lost territory over time results of comparing the shoreline evolution of two different scenarios: the intervention scenario and the reference scenario. In Figure 3, the methodology for benefits calculation considered in this work is schematized. The positive benefits (green hatch) encompass the accretion area due to the coastal intervention (a groin, in the presented example) and the area not eroded due to the groin presence. The negative benefits correspond to the increased erosion in the coastal intervention scenario that would not occur in the reference scenario (red hatch).

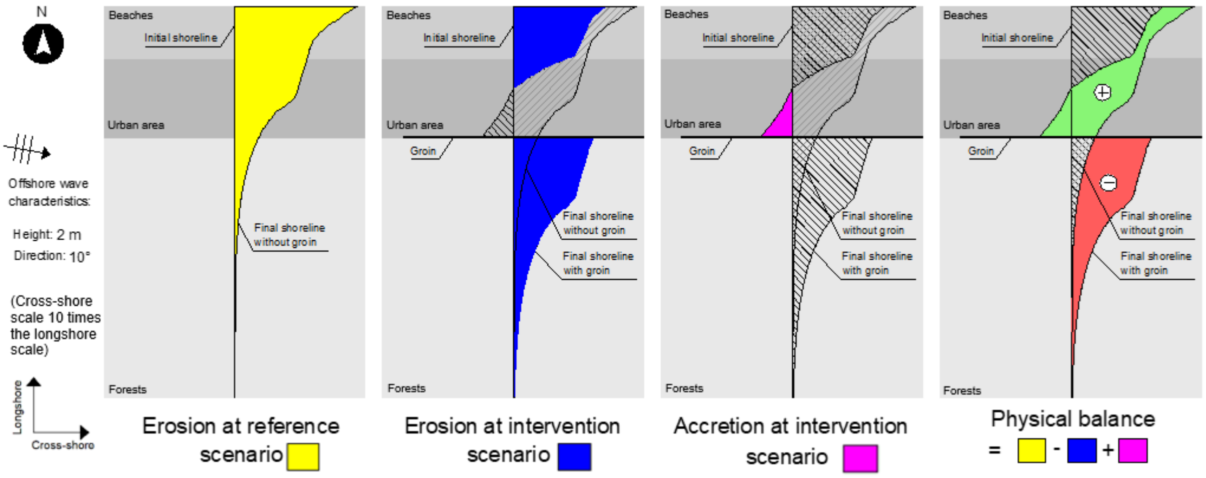


**Figure 3.** Schematization of positive and negative benefits, and resultant physical impact.

Considering Figure 3, the physical impact is understood as the difference between the erosion areas of the reference and the intervention scenarios, added to the accretion area of the intervention scenario, at the time instant under analysis. The economic performance of each coastal intervention scenario is evaluated by the net present value (NPV), the ratio between benefits and costs (BCR) and the break-even point, which represents the instant, during the simulation period, when the total benefits equal the total costs of the intervention (BCR = 1 and NPV = 0).

## 3. The case study

The reference scenario adopted in this study represents the natural shoreline evolution, without coastal interventions. Then, to exemplify the use of the methodology, 34 scenarios are presented, based on 4 different types of intervention. To allow the comparison between the different scenarios, a baseline scenario for each intervention type was defined. Starting from each baseline scenario, some intervention characteristics were changed (length, location, number of structures, volume, etc.), and thus, 30 other different scenarios were defined and analysed (10 scenarios with groins, 7 scenarios with longitudinal revetments, 9 scenarios for artificial nourishments and 4 scenarios for sand by-pass systems). This section describes the reference scenario, each of the baseline scenarios and finally, describes the interventions characteristics changed and evaluated in each of the other scenarios.

### 3.1 Reference scenario

The reference scenario is a hypothetical scenario defined by a regular topo-bathymetry, represented by a square grid (20 m spaced), with 401 x 501 points (respectively, in the cross-shore and longshore directions), which results in a spatial domain area of 8 000 x 10 000 m². The bathymetry was generated according to the Dean profile [80], considering the parameter $A$ and $m$ equal to 0.127 and 2/3, respectively. For the topography (above reference water level, 0.0 m) a constant slope of 2% was considered.

The wave climate was considered constant in all the numerical simulations, with offshore wave height ($H_0$) of 2 m, wave period of 9.34 seconds (T) and 10 degrees West for wave direction, clockwise ($\alpha_0$). The active cross-shore profile was limited by the depth of closure ($DoC$ = 8 m) and by the wave run-up ($R_u$ = 2 m), resulting in a total active profile height of 10 m (considered constant along the time horizon of the simulations). At the northern boundary of the domain, a null input of sediments was considered and in the southern boundary, an extrapolation of the longshore sediment transport nearby conditions was adopted. A time-step of one hour and a time horizon of 20 years were admitted in all scenarios. Annual shoreline position outputs were recorded allowing the evaluation of every year eroded and accreted areas.

To estimate territory value, the provided services of the urban areas and ecosystems that are important to human well-being, health, livelihoods and survival should be considered. In this work, three different zones were defined along the coast, with landward constant value (Table 1). From North to South, beaches, an urban area and forests were considered, where the highest value was attributed to the urban area, in a longshore extension of 1.5 km. The beach allows coastal protection and recreational uses, the urban area may support several different activities and uses (restaurants, hotels, economic services, etc.) and finally, the forest provide climate regulation, timber, habitat for biodiversity, erosion control and many others [15, 78,79]. It should be noticed that the defined land values encompass at the same time economic, social, cultural and environmental aspects, and require sensitivity analysis previously its application to adequate characterize the provided services of the territory. Despite the generic case study, the adopted values for this reference scenario are inspired and in accordance with typical values in use for Portuguese Northwest coast. However, as previously referred, in specific studies, users should support and validate the values with adequate socioeconomic databases, considering all the relevant aspects in the study site. For the reference scenario, the time discount rate (r) of 3% was considered (based on 15).

Table 1. Economic land value defined in the case study (based on 15).

| | **Description (km)** | **Location** | **Extension (km)** | **Value (€/m²/year)** |
|---|---|---|---|---|
| **Zone 3** | Beaches | North limit | 1.0 | 2.00 |
| **Zone 2** | Urban area | Intermediate | 1.5 | 10.00 |
| **Zone 1** | Forests | South limit | 7.5 | 0.20 |

Considering the physical performance of the reference scenario, the recorded shoreline evolution represents important erosion problems after 20 years, meaning that if no interventions are implemented, the shoreline retreat can attain approximately 230 m in the northern boundary of the domain and all the urban waterfront extension is affected by erosion. Figure 4 shows the shoreline evolution after 5, 10 and 20 years, and the total lost area in each different zone.

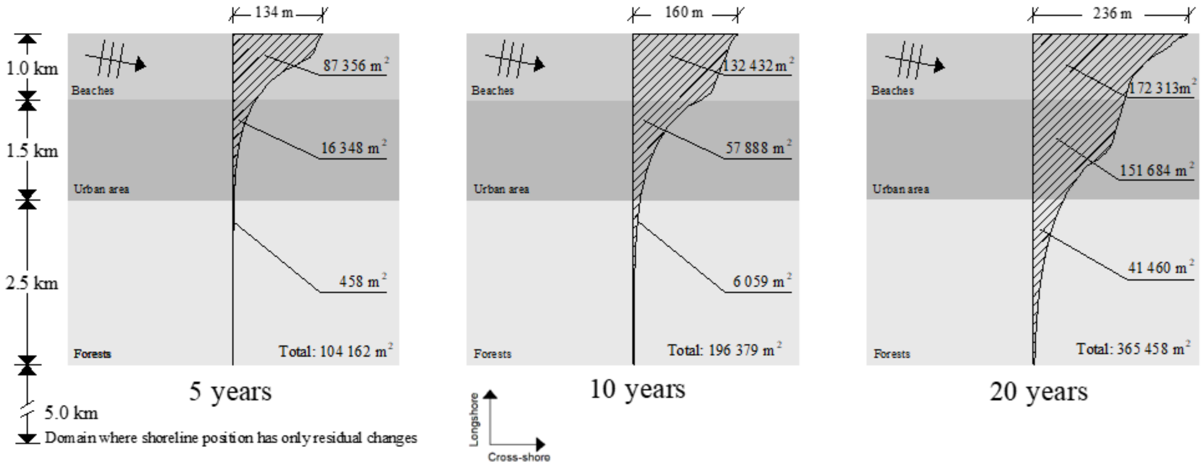


**Figure 4.** Shoreline evolution in the reference scenario, over time (cross-shore scale 10 times the longshore scale).

The economic performance is based on the unit values considered for each coastal zone (€/m²/year), Table 1. The NPV was estimated at the end of each year of simulation (the BCR value is not calculated, since for the reference scenario there are no interventions and associated costs). In the 5 years simulation, erosion and land losses represent about 0.8 million euros and after ten years, the costs exceed 3 million euros (values updated to year 0). At the end of the simulation, the land losses represent about 12 million euros.

Although hypothetical, the reference scenario shows that in coastal areas susceptible to erosion (where the sediments volume available for the littoral drift are below the potential sediment transport capacity and shoreline retreat rates are expect), important economic losses will occur due to the direct reduction of the area where the ecosystems services are provided. In fact, if no mitigation strategies are adopted, urban water fronts, beaches and forest will be lost, decreasing the benefits in the land use. Thus, different intervention scenarios are proposed to mitigate the erosion problems presented in the reference scenario.

## 3.2 Groin baseline scenario

The groin baseline scenario was characterized by a 200 m groin length, located 2.5 km far from the northern border of the modelled domain (at the southern limit of the urbanized and most valuable area of the territory), as shown in Figure 5.

Considering the simulation characteristics defined on the reference scenario, the LTC was applied to the baseline scenario to predict the shoreline evolution along the 20 years' time horizon. Smaller shoreline retreat rates near the northern border, deposition near the urban zone and updrift of the groin, are obtained due to the groin presence (Figure 6). However, the erosion trends and shoreline retreat rates are higher at downdrift. Thus, in order to evaluate the scenario effectiveness, the costs involved in the structure construction and maintenance were evaluated, by defining the groin characteristics (through XD-Coast model).

The cross-section characteristics (resistant layer and filters, crest width and elevation, and slope) were considered constants along the groin length, only changing the height, depending on the bathymetry and topography. A crest width of 10 m and a crest elevation of 6 m above the water surface reference level were considered. The groin head is located at about 4.5 m depth, and groin total volume is around 58 000 m³ (Figure 7).

Considering the groin's dimension, its direct and indirect construction costs were calculated, representing a total first investment costs of about € 1 462 200. Inspired on the Portuguese Northwest coast reality, different maintenance costs were adopted for each part of the structure (head and trunk). For the trunk of the groin, maintenance works are required every five years and consequent costs are about € 340 000, 30% of its construction cost. For the head of the structure, 50% of the respective construction cost was considered, every 2 years (about € 160 000). Benefits were defined based on shoreline evolution, taking into account every year accretion and erosion areas and the unitary land values defined in the reference scenario (Figure 6 and Table 1).

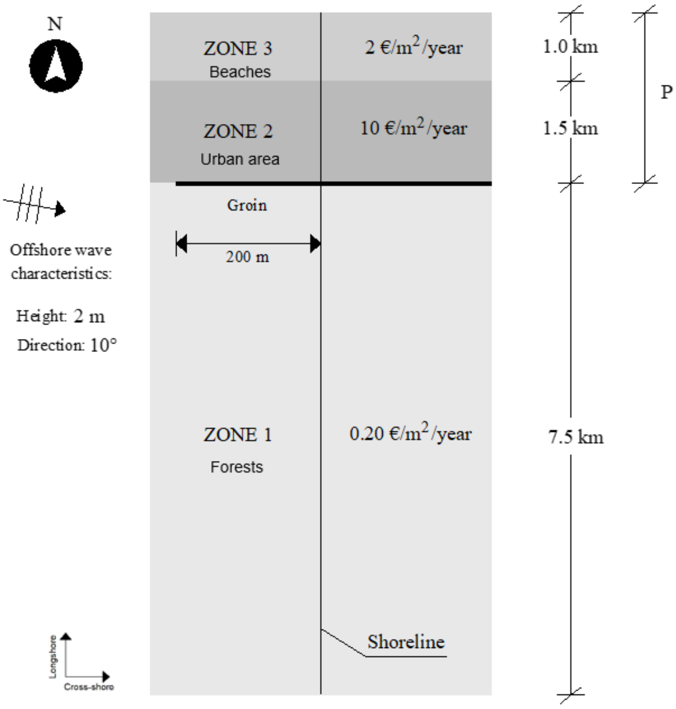


**Figure 5.** Schematization of the groin baseline scenario.

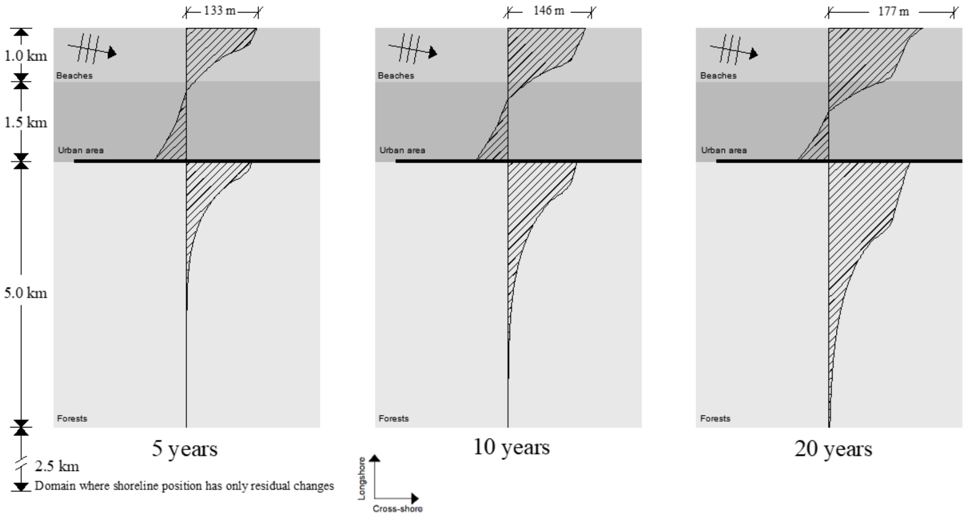


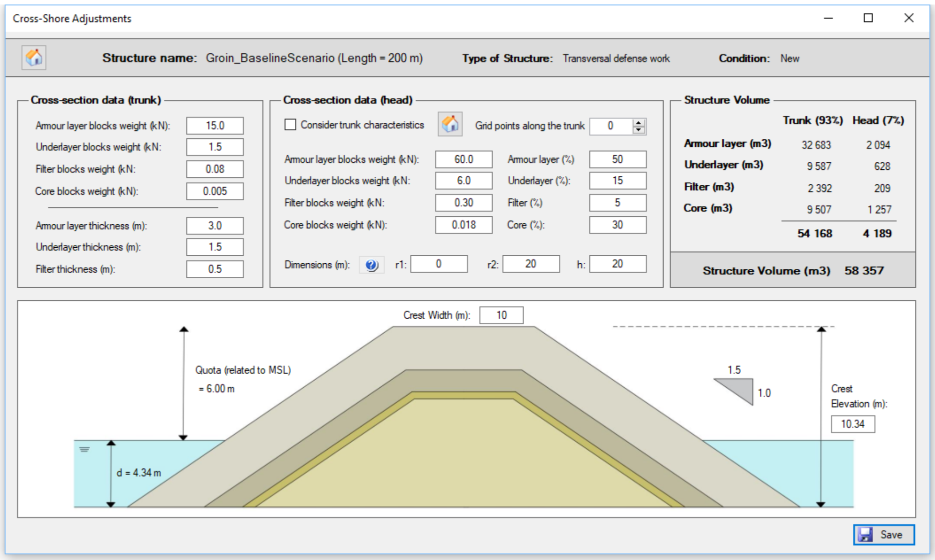
**Figure 6.** Shoreline position in the groin baseline scenario, along the time (cross-shore scale 10 times the longshore scale).

### 3.3 Longitudinal revetment baseline scenario

The longitudinal revetment baseline scenario encompasses a 1500 m' length structure, with a crest elevation of

6 m, over the entire urbanized zone (Figure 8).

This scenario ensures the total protection of the urbanized zone and results in smaller shoreline retreat rates near the northern border, when compared with the reference scenario, but similar to the ones obtained in the groin baseline scenario (Figure 9).



Cross-Shore Adjustments

**Structure name:** Groin_BaselineScenario (Length = 200 m) **Type of Structure:** Transversal defense work **Condition:** New

**Cross-section data (trunk)**

Armour layer blocks weight (kN): 15.0
Underlayer blocks weight (kN: 1.5
Filter blocks weight (kN: 0.08
Core blocks weight (kN): 0.005
Armour layer thickness (m): 3.0
Underlayer thickness (m): 1.5
Filter thickness (m): 0.5

**Cross-section data (head)**

☐ Consider trunk characteristics
Grid points along the trunk: 0
Armour layer blocks weight (kN): 60.0
Underlayer blocks weight (kN: 6.0
Filter blocks weight (kN: 0.30
Core blocks weight (kN): 0.018
Armour layer (%): 50
Underlayer (%): 15
Filter (%): 5
Core (%): 30
Dimensions (m): r1: 0 r2: 20 h: 20

**Structure Volume**

| | Trunk (93%) | Head (7%) |
|---|---|---|
| **Armour layer (m3)** | 32 683 | 2 094 |
| **Underlayer (m3)** | 9 587 | 628 |
| **Filter (m3)** | 2 392 | 209 |
| **Core (m3)** | 9 507 | 1 257 |
| | **54 168** | **4 189** |

**Structure Volume (m3)** **58 357**

Crest Width (m): 10
Quota (related to MSL) = 6.00 m
d = 4.34 m
Crest Elevation (m): 10.34

**Figure 7.** Groin cross Section in the baseline scenario (groin head section).

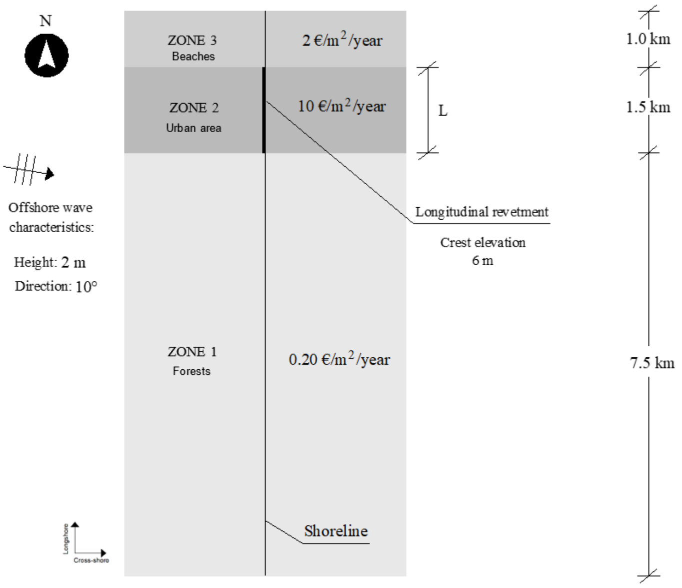


**Figure 8.** Schematization of the longitudinal revetment baseline scenario.

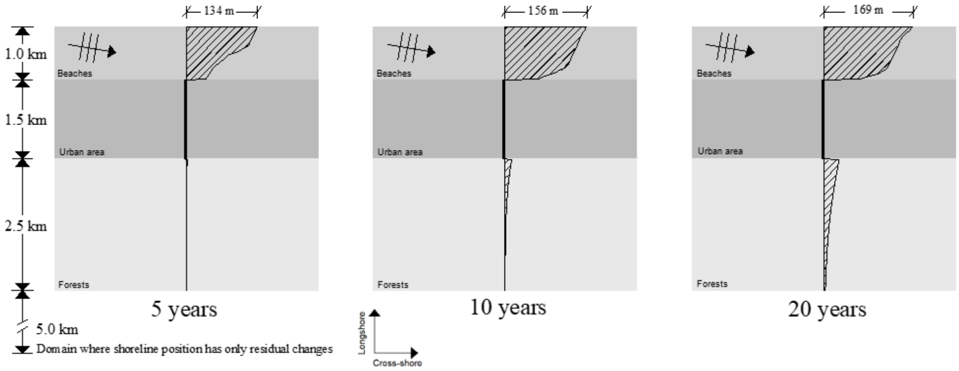


**Figure 9.** Shoreline position in the longitudinal revetment baseline scenario, along the time (cross-shore scale 10 times the longshore scale).

The longitudinal revetment cross-section presents constant characteristics (resistant layer and filters, crest width and elevation, and slope) along the coastline, similar to the ones adopted to the groin cross-section. The total volume of the structure is around 132 000 m³, which represents a construction total first investment costs of about 2 million euros. Maintenance costs were based on a percentage of the initial investment (30%, which corresponds approximately to 600 thousand euros), every 5 years. Overtopping and flooding events were not considered during the simulation period.

### 3.4 Artificial nourishments baseline scenario

The artificial nourishment baseline scenario considers the nourishment of 1 million m³ of sediments, every 5 years, at an average rate of 10 thousand m³ per day. It was estimated a unitary sediments nourishment cost of 2 €/m³. The nourished area is characterized by a longshore extension of 500 m, centred in the urbanized zone and covering the entire cross-shore active profile width, approximately 600 m (Figure 10).

Shoreline evolution numerical modelling results show that nourishing the coastal system will significantly decrease the erosion areas over the 20 years of simulation, mainly in the southern locations of the spatial domain. However, this scenario does not ensure the total protection of the urbanized zone (Figure 11).

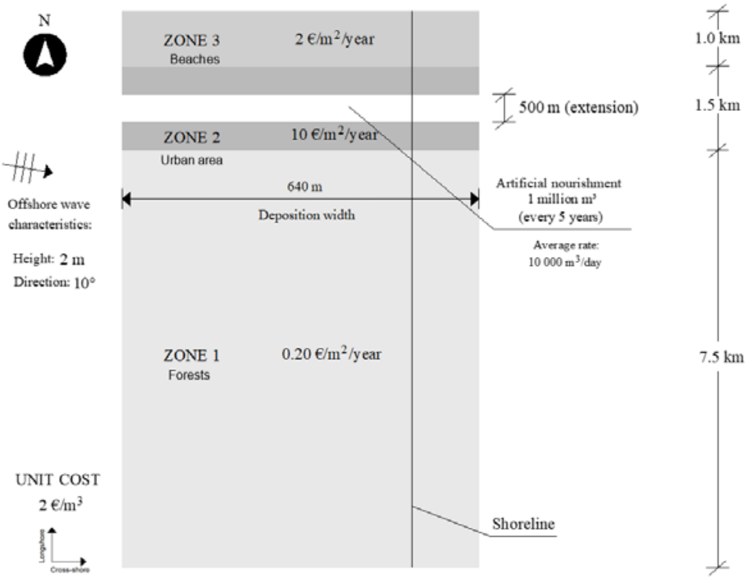


**Figure 10.** Schematization of the artificial nourishment baseline scenario.

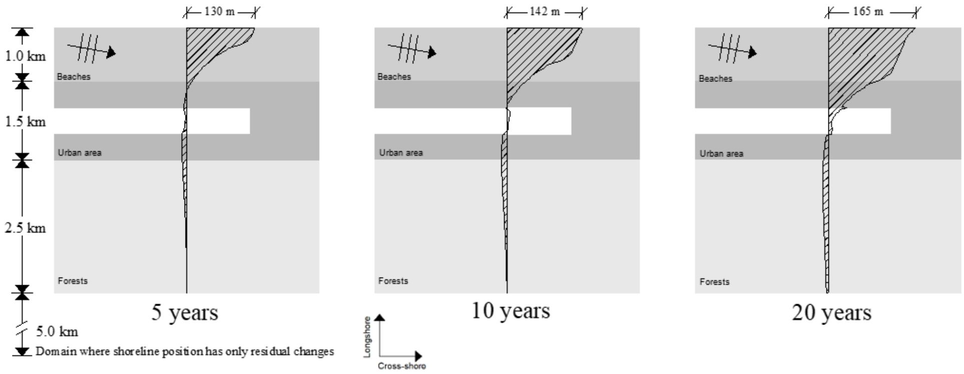


**Figure 11.** Shoreline position in the artificial nourishment baseline scenario, along the time (cross-shore scale 10 times the longshore scale).

This coastal intervention scenario is characterized by adding 4 million m³ of sediments to the coastal system over the 20 years of simulation. The total costs are related to the material unit cost (2 €/m³), which encompasses all the nourishment operations: sediments dredging, transport and deposition. The initial investment was 2 million euros corresponding to the first nourishment and the total investment at the end of the 20 years of simulation was around 6.5 million euros, considering the discount rate applied to the 4 performed interventions along time.

### 3.5 Sand by-pass baseline scenario

The sand by-pass baseline scenario (Figure 12) was characterized by a fixed structure located in the upper limit of the urbanized zone (1 km far from the northern border of the spatial domain), which was assumed to represent an initial cost of 3 million euros (sand by-pass structure system costs). The sediments flow transposed by the system was assumed to fulfil about 90% of the potential wave climate sediment transport capacity at the beginning of the reference scenario, estimated through the CERC formula, SPM, 1984 (25 $m^3$/hour, approximately 219 000 $m^3$/year). Each $m^3$ of transposed sediments were assumed to cost 1 €/$m^3$, which simultaneously encompasses operation costs and by-pass structure system maintenance costs.

In this scenario, shoreline evolution shows smaller retreat rates near the northern border, when compared with the reference scenario (Figure 13). However, erosion is still verified in the spatial domain, which is justified due to the lower transposed sediments flow rate than the potential sediments transport capacity. Due to the adopted location for the transposition system, no shoreline retreat is observed along the urbanized zone, over the 20 years of simulation.

The costs involved in this scenario include the required initial investment to install the fixed sand by-pass transposition system (admitted being 3 million euros) and the continuous operation/maintenance costs, which was assumed to represents an annual value of 219 000 €.

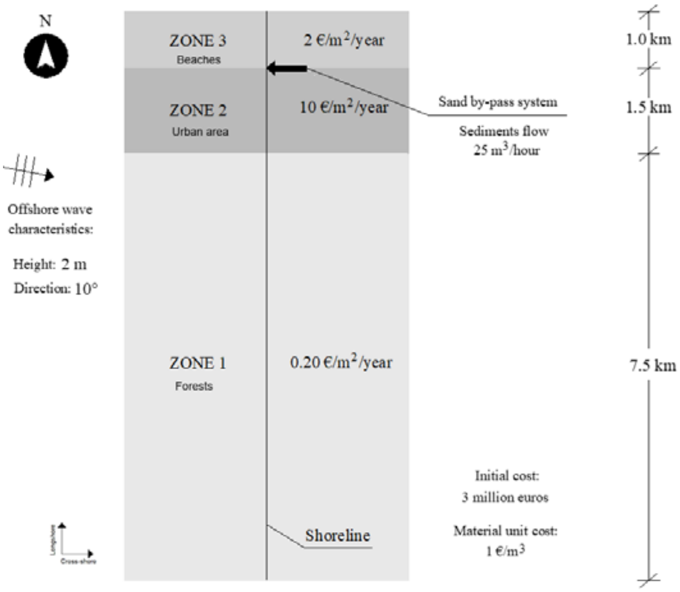


**Figure 12.** Schematization of the by-pass baseline scenario.

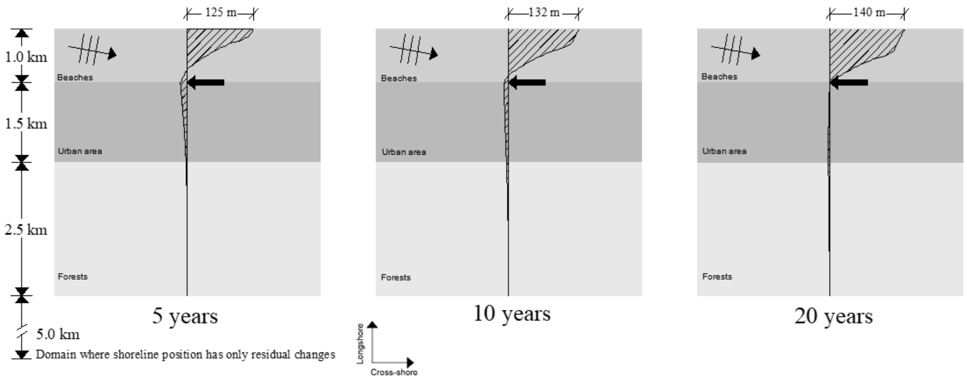


**Figure 13.** Shoreline position in the by-pass baseline scenario, along the time (cross-shore scale 10 times the longshore scale).

### 3.6 Interventions characteristics scenarios

Four different baseline scenarios were presented. However, intervention characteristics may be changed, which lead to different simulation results. Thus, different hypothetical scenarios were additionally proposed to discuss intervention characteristics influence on each type of baseline scenario (Table 2).

**Table 2.** Coastal erosion mitigation scenarios characteristics.

| | | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| Groin | Length | $i$ | $L$ = 100 m | $L$ = 300 m | $L$ = 400 m | - |
| | Location | $ii$ | $P$ = 1.5 km | $P$ = 2.0 km | $P$ = 3.0 km | $P$ = 3.5 km |
| | Number of groins | $iii$ | 2 groins spaced by 500 m | 2 groins spaced by 1000 m | 3 groins spaced by 500 m | - |
| Longitudinal revetment | Length | $iv$ | $L$ = 500 m | $L$ = 1 000 m | - | |
| | Crest elevation | $v$ | $C$ = 5 m | $C$ = 4 m | - | |
| | Combination with baseline groin | $vi$ | Groin and $L$ = 500 m | Groin and $L$ = 1 000 m | Groin and $L$ = 1 500 m | - |
| Artificial nourishments | Extension | $vii$ | 1 000 m (north) | 1 000 m (south) | 1 500 m | - |
| | Location | $viii$ | 500 m (north) | 500 m (south) | - | - |
| | Frequency | $ix$ | 400 thousand m$^3$ every 2 years | 2 million m$^3$ every 10 years | - | - |
| | Volume | $x$ | half a million m$^3$ | 2 million m$^3$ | - | - |
| By-pass | Location | $xi$ | 500 m from the northern border | - | - | - |
| | Sediments flow | $xii$ | 10% transport rate | 50% transport rate | 150% transport rate | - |

Three main aspects were considered to test the groin scenarios: length, location and number of groins. Longer structures promote a bigger barrier to the littoral drift and provide more effective protection to the updrift areas, but increase the intervention costs and the shoreline evolution negative impacts at downdrift. The best groin location should correspond to the downdrift limit of the area to protect, but it is important to understand the groin location influence in the physical and economic results over time. Groins fields consider the conjugation of different number of groins and their location. The influence of the groin length (group $i$, with three different scenarios), groin location (four scenarios in group $ii$) and number of groins (three combinations in group $iii$) were analysed.

The longitudinal revetment length must be in accordance with the coastline extension to be protected [81]. To avoid overtopping events (which can trigger the toe scour and, consequently, the rubble mound collapse), the structure height should be as large as possible. However, the high costs and/or the aesthetic constraints prevent the choice of long and high structures, making urban fronts more susceptible to erosion, overtopping and flooding events. Another important aspect are the scenarios that combine longitudinal revetment and groin, mitigating downdrift groin erosion. Thus, these aspects were analysed in additional 7 scenarios, divided by groups $iv$, $v$ and $vi$ (Table 2).

Despite the artificial nourishment's positive impacts on shoreline evolution, this type of intervention represents significant costs and is often regarded by society as ephemeral solutions. Then, strategic planning of artificial nourishments is required, depending on nourishments extension, location, frequency and volume of sediments, etc. These aspects were analysed in 9 different scenarios, combined as groups $vii$, $viii$ , $ix$ and $x$ (Table 2).

Finally, two groups of scenarios were defined to evaluate sand by-pass main characteristics, related to its location and by-passing sediments flow capacity (group $xi$ and $xii$, with one and three scenarios, respectively). The following section presents, compares and discusses the physical and economic results of each of the described scenarios.

## 4. Results

The main results of all the analysed scenarios are presented and discussed here, including each baseline scenario and the other 30 alternatives (10 groins, 7 longitudinal revetments, 9 artificial nourishments and 4 sand by-pass scenarios), organized in four different sections. Final remarks highlight the major outlines of this section, which intended to describe the type of analysis that can be developed by applying the proposed methodology.

### 4.1 Groin scenarios

Groin baseline scenario (Figure 6) shows that the groin impact on the shoreline evolution is positive at updrift, resulting in 2.4 ha accretion area (which protects partially the urbanized and most valuable zone). However, at the global level, the baseline scenario (BS) presents a total erosion area above the reference scenario, representing losses of around 4 ha, and a general negative physical impact. However, this scenario is economically positive, and after seven years, the break-even point is reached. Despite the costs with the groin, the benefits resulting from the intervention represent economic gains of about 12 million euros at the end of the 20 years (resulting from the areas gained updrift the groin, where the land value is higher). Thus, the groin baseline scenario net present value (NPV) after the 20 years' was about 8 million euros.

Table 3 shows the total accreted and eroded areas after 20 years (and the respective physical impact) and presents the economic results (BCR and NPV values after 20 years, initial and total costs and break-even point) corresponding to all the groin scenarios, allowing a quantitative comparison between them.

**Table 3.** Summary of the physical and economic results of the groin scenarios.

| **Scenario** | | **Territory area (ha)** | | | **$BCR_{20\ yr}$ (-)** | **$NPV_{20\ yr}$ (€)** | **Costs** | | **Break-even (years)** |
|---|---|---|---|---|---|---|---|---|---|
| | | **Accretion** | **Erosion** | **Impact** | | | **Initial (€)** | **Total* (€)** | |
| *BS* | Figure 5 | 2.4 | 43.2 | -4.2 | **3.31** | 8 316 103 | 1 462 293 | 3 602 359 | **7** |
| $i.1$ | $L$ = 100 m | 892 | 380 523 | **-14 173** | 1.48 | 1 263 061 | **975 627** | **2 615 491** | 15 |
| $i.2$ | $L$ = 300 m | 74 985 | 474 373 | -33 930 | 2.96 | **11 612 679** | 2 291 617 | 5 925 785 | 9 |
| $i.3$ | $L$ = 400 m | 82 665 | 478 971 | -30 849 | 2.06 | 9 150 555 | 3 263 128 | 8 670 313 | 11 |
| $ii.1$ | $P$ = 1.5 km | 18 079 | 408 178 | -24 641 | -0.82 | -6 556 228 | 1 462 293 | 3 602 359 | - |
| $ii.2$ | $P$ = 2.0 km | 20 264 | 420 936 | -35 214 | 1.20 | 714 226 | | | 19 |
| $ii.3$ | $P$ = 3.0 km | 30 406 | 442 447 | -46 583 | 2.18 | 4 259 681 | | | 11 |
| $ii.4$ | $P$ = 3.5 km | 37 796 | 454 131 | -50 878 | 1.45 | 1 624 686 | | | 16 |
| $iii.1$ | 2 groins spaced by 500 m | 38 066 | 446 802 | -43 278 | 2.01 | 7 291 156 | 2 924 586 | 7 204 718 | 11 |
| $iii.2$ | 2 groins spaced by 1000 m | 36 084 | 435 472 | -33 930 | 1.79 | 5 678 216 | | | 13 |
| $iii.3$ | 3 groins spaced by 500 m | 34 478 | 432 924 | -32 988 | 1.24 | 2 560 639 | 4 386 879 | 10 807 077 | 17 |

*Values updated for initial simulation instant, according to the discount rate (r).

### 4.1.1 Length

Three additional groin lengths were tested to compare the results with the baseline scenario (BS with 200 m): 100 m, 300 m and 400 m, respectively: scenario i.1, i.2 and i.3 (Table 2). Each scenario total initial costs range from approximately € 1 million to € 3.3 million, depending on groin length. After 20 years, shoreline evolution shows a physical negative impact (regardless the groin length, Table 3), increasing the erosion areas when compared to the reference scenario. The sediments deposition updrift the 100 m groin resulted in a small accretion area (less than 0.1 ha), but when extending the groin length, sediments deposition is higher, increasing the protection effectiveness of the urbanized zone. All the scenarios show generalized erosion at downdrift the groin and the total erosion area increases with the length of the groin.

The economic impact at the end of the simulation period (20 years) is positive in all the scenarios. The highest BCR corresponds to the baseline scenario. If there are initial financial constrains to perform an intervention, the scenario corresponding to the smaller groin (100 m) may be a more feasible option (groin construction and maintenance cost over time is lower). However, this scenario break-even is reached after 15 years. If the intervention main goal is increasing the beach area in front of the urbanized zone, the two longer groin scenarios are more effective. The groin with 300 m corresponds to the scenario that returns the highest net present value after 20 years. The 400 m groin results in larger accretion areas. In conclusion, each groin length scenario presents advantages and simultaneously disadvantages and thus, the decision on adequate groin length will depend on the goals of the intervention.

### 4.1.2 Location

Four different groin locations were tested: 500 and 1000 m north and south of the initially stipulated position (resulting in scenario ii.1, ii.2, ii.3 and ii.4). In this analysis, the costs are the same for all the scenarios, reason why the economic indexes are only affected by the gained/lost areas. Economically, the baseline groin scenario location is the most advantageous, but this scenario is not the one that presents the highest accretion areas (Table 3).

If the groin position is moved to the south, the largest accretion areas will occur in less valuable territory zones. On the other hand, if the groin position is moved to the north, there will be higher erosion in the most valuable zones. Thus, scenario ii.1 (groin located 1.5 km far from the northern border) is not economically adequate. However, this is the scenario with the best physical results after 20 years. Scenario ii.2 is economically effective after 19 years and corresponds to the second best physical impact. The scenarios where the groin is located south of the groin baseline scenario (ii.3 and ii.4) are economically efficient (although the BCR values are lower than those obtained in the baseline scenario), but the erosion areas are higher than those obtained for the baseline scenario (erosion area increases with increasing distance from the groin to the northern border).

Summarizing, the better economic groin location scenario corresponds to the baseline scenario, where the groin is considered in the southern limit of the urbanized zone. However, if the decision criteria are to avoid generalized erosion, the better groin location should be as far from the north as possible, even if the accretion areas at the urbanized zone are lower and consequently, represent less protection to this zone.

### 4.1.3 Number of groins

Three different groin field scenarios were considered, always keeping the groin characteristics and the groin of the baseline scenario: scenario iii.1, groin located 500 m to the north (2.0 km far from the northern border); scenario iii.2, groin located 1000 m to the north; and scenario iii.3, considering three groins, combining the two previous location scenarios. The number of groins considered in each scenario has a direct influence on construction and maintenance costs along the 20 years. Initial costs are € 1 462 293, € 2 924 586 and € 4 386 879, respectively, to one, two or three groins. As previously referred, scenario iii.1 presents negative physical impacts when compared to the baseline scenario (Table 3). However, the scenarios iii.2 and iii.3 shoreline evolution impacts are less negative, resulting in lower erosion (about 1 ha difference). In opposition to the physical analysis, the scenario with the highest BCR corresponds to the baseline scenario and the worst economic results are obtained for the three groins scenario. Thus, the increased investment associated with the construction and maintenance of the three groins, despite being monetized approximately after 17 years, is not as economic competitive as the baseline scenario.

## 4.2 Longitudinal revetments scenarios

An overall analysis of the longitudinal revetment baseline scenario shows that this coastal intervention presents both physical and economic positive impacts. In addition, this scenario guarantees the total protection of the urbanized zone during all the analysed period and, comparing with the reference scenario, territory losses of about 20 ha are avoided. From the economic point of view, the longitudinal revetment baseline scenario break-even is obtained after 13 years, with an updated total investment of approximately 4 million euros. The physical and economic indexes resulting from the longitudinal revetment baseline scenario are shown in Table 4, which also summarizes the results obtained for the remaining 7 longitudinal revetment scenarios.

**Table 4.** Summary of the physical and economic results of the longitudinal revetment scenarios.

| **Scenario** | | **Territory area (ha)** | | | **BCR<sub></sub>** | | **Costs** | | **Break-even** |
|---|---|---|---|---|---|---|---|---|---|
| | | **Accretion** | **Erosion** | **Impact** | **(-)** | **(€)** | **Initial (€)** | **Total$^*$ (€)** | **(years)** |
| $BS$ | Figure 8 | 0 | 16.6 | **20.0** | 2.34 | 5 078 161 | 2 052 484 | 3 777 949 | 13 |
| $iv.1$ | $L$ = 500 m | 0 | 32.7 | 3.8 | 1.15 | 188 168 | **684 161** | **1 259 317** | 19 |
| $iv.2$ | $L$ = 1 000 m | 0 | 25.4 | 11.0 | 1.77 | 1 950 645 | 1 368 322 | 2 518 633 | 16 |
| $v.1$ | $C$ = 5 m | 0 | 16.6 | **20.0** | 1.76 | 3 828 289 | 1 761 598 | 5 027 822 | 14 |
| $v.2$ | $C$ = 4 m | | | | 1.41 | 2 557 708 | 1 481 963 | 6 298 402 | 16 |
| $vi.1$ | Groin and $L$ = 500 m | 2.4 | 24.6 | 14.3 | 2.51 | 7 336 235 | 2 146 454 | 4 861 675 | **9** |
| $vi.2$ | Groin and $L$ = 1 000 m | | 22.4 | 16.5 | 2.00 | 6 123 709 | 2 830 615 | 6 120 992 | 11 |
| $vi.3$ | Groin and $L$ = 1 500 m | | 20.9 | 18.1 | 1.66 | 4 893 780 | 3 514 777 | 7 380 308 | 13 |

$^*$Values updated for initial simulation instant, according to the discount rate (r).

### 4.2.1 Length

Two different longitudinal revetment lengths were tested: scenario $iv.1$, structure with 500 m; and scenario $iv.2$, with 1 000 m (both adjacent to the southern limit of the urbanized zone). For the smaller length scenario, a total structure volume of 44 000 m³ was estimated, resulting in an initial cost of € 684 161 and for the longer one, 88 000 m³ (corresponding to an initial cost of € 1 368 322). All the scenarios present a similar shoreline evolution behavior and consequently, similar physical impacts. However, shorter lengths result in larger erosion areas. Economically, the best BCR is obtained for the baseline scenario. The scenario $iv.1$ is the one with higher break-even and lower economic indexes (see Table 4).

### 4.2.2 Crest elevation

The longitudinal revetment crest elevation influences not only the dimension and consequent related costs (construction and maintenance), but also the frequency of eventual flooding and overtopping events. Thus, the economic relationship between the costs reduction due to the decrease of the revetment crest elevation and the increased annual costs due to damages by eventual overtopping events and consequent floods should be analysed.

Thus, two complementary scenarios were defined: scenario $v.1$, where a crest elevation of 5 m and an annual cost due to the overtopping and flooding events of around 120 thousand euros were defined; and scenario $v.2$, where the crest elevation is only 4 m and is hypothetically assumed annual costs of 240 thousand euros due to overtopping and consequent floods (Table 5).

**Table 5.** Longitudinal revetment volume, construction cost and related damages, for different crest elevation scenarios.

| | | **Volume (m³)** | **Initial cost (€)** | **Damage costs (€)** |
|---|---|---|---|---|
| $CB$ | $C$ = 6 m | 132 000 | 2 052 484 | 0 |
| $v.1$ | $C$ = 5 m | 107 625 | 1 761 598 | 120 000 |
| $v.2$ | $C$ = 4 m | 85 500 | 1 481 963 | 240 000 |

Lowering the crest of the longitudinal revetment has no impact in the shoreline evolution, and thus, all the scenarios present the same shoreline positive impacts, compared with the reference scenario (about 17 ha of erosion after 20 years, rather than the 37 ha lost in the reference scenario). The three scenarios also show positive economic performance after the 20 years, but the BCR decreases with the decrease of the crest elevation (see Table 4).

For the defined assumptions, the annual damages resulting from the overtopping and flooding events do not monetarily compensate the costs reduction due to the lower crest elevation. However, there are social impacts resulting from the higher crest elevation revetments, such as the reduced views and less coastline attractiveness. In a real context, these issues (social, touristic, recreational, etc.) should be evaluated and accounted in an economic point of view.

### 4.2.3 Longitudinal revetment combined with groin

The zone located downdrift the groin baseline scenario (Figure 5) corresponds to a low value zone (forests, 0.20 €/m²/year), but in spite of that, a longitudinal revetment structure was considered to protect this area from the erosion trend anticipated by the groin. Three different longitudinal revetment length scenarios (located immediately downdrift the groin) were considered: 500 m (scenario $vi.1$), 1 000 m (scenario $vi.2$) and 1 500 m (scenario $vi.3$). Table 6 presents the material volumes and the total cost of the scenarios that combine a groin and a longitudinal revetment.

**Table 6.** Volume and construction cost of the combined groin and longitudinal revetment scenarios.

| | | **Volume (m³)** | **Total cost (€)** |
|---|---|---|---|
| $CB$ | $L$ = 1 500 m | 132 000 | 2 052 484 |
| $vi.1$ | Groin and $L$ = 500 m | 102 357 | 2 146 454 |
| $vi.2$ | Groin and $L$ = 1 000 m | 146 357 | 2 830 615 |
| $vi.3$ | Groin and $L$ = 1 500 m | 190 357 | 3 514 777 |

Longitudinal revetment and groin scenario combination results in a significant erosion reduction over the 20 years (Table 4). The avoided losses are higher, as the considered length of the longitudinal revetment increases. However, the erosion areas of all the combined scenarios are larger than in the longitudinal revetment baseline scenario, as those areas are not compensated by the accretion verified at updrift the groin (Table 4).

The time required to reach the break-even point increases and the BCR and NPV decreases, with the increasing length of the longitudinal revetment (Table 4). After 20 years, scenarios $vi.1$ and $vi.2$ present an economic advantage over the longitudinal revetment baseline scenario, although in scenario $vi.2$ the BCR value is lower. In summary, combined scenarios do not present global positive physical impacts, but scenarios $vi.1$ and $vi.2$ are economically interesting. However, these two scenarios imply higher investment and maintenance costs over the 20-year simulation, which, due to financial constraints often imposed, may be a hindrance to their implementation.

## 4.3 Artificial nourishments scenarios

Artificial nourishment baseline scenario presents a positive physical impact (relative to the reference scenario) and reaches the economic equilibrium point before 20 years. Table 7 summarizes the values obtained for the artificial nourishment scenarios. The physical analysis of the baseline scenario shows an erosion reduction of about 23 ha, when compared to the reference scenario. Economically, after 13 years, the benefit inherent to the gained and not lost areas exceeds the performed investment. After 20 years, it is verified that the benefits are about 70% higher than the total investment costs (BCR = 1.73).

In the following sections, changes on artificial nourishments baseline scenario characteristics are analysed.

**Table 7.** Summary of the physical and economic results of the artificial nourishments scenarios.

| Scenario | | Territory area (m²) | | | BCR$_{20\ yr}$ | NPV$_{20\ yr}$ | Costs | | Break-even |
|---|---|---|---|---|---|---|---|---|---|
| | | Accretion | Erosion | Impact | (-) | (€) | Initial (€) | Total* (€) | (years) |
| $BS$ | Figure 10 | 2.6 | 16.6 | 22.6 | 1.73 | 4 733 343 | 2 000 000 | 6 497 129 | 13 |
| $vii$.1 | 1 000 m (north) | 2.1 | 15.0 | 23.7 | 1.82 | 5 356 332 | 2 000 000 | 6 497 129 | 12 |
| $vii$.2 | 1 000 m (south) | 3.5 | 17.5 | 22.5 | 1.68 | 4 441 918 | | | 13 |
| $vii$.3 | 1 500 m | 2.9 | 16.0 | 23.4 | 1.76 | 4 917 737 | | | 13 |
| $viii$.1 | 500 m (north) | 1.3 | 13.4 | 24.5 | 1.80 | 5 167 493 | 2 000 000 | 6 497 129 | 13 |
| $viii$.2 | 500 m (south) | 3.6 | 19.0 | 21.2 | 1.51 | 3 311 101 | | | 14 |
| $ix$.1 | 400 thousand m³ every 2 years | 2.9 | 15.5 | 24.0 | 1.75 | 4 643 467 | **800 000** | **6 220 104** | 12 |
| $ix$.2 | 2 million m³ every 10 years | 3.3 | 16.9 | 23.0 | 1.98 | 6 856 026 | 4 000 000 | 6 976 376 | **8** |
| $x$.1 | half a million m³ | 0.4 | 23.8 | 13.2 | **2.11** | 3 606 909 | 1 000 000 | 3 248 565 | 9 |
| $x$.2 | 2 million m³ | 11.9 | 8.9 | 39.6 | 1.68 | **8 842 361** | 4 000 000 | 12 994 259 | 12 |

*Values updated for initial simulation instant, according to the discount rate (r).

### 4.3.1 Extension

Different extension areas for nourishment may result in differences on the sediments dynamics and on the shoreline evolution and, consequently, in erosion and accretion areas along time. Thus, three scenarios were considered, corresponding to extended nourished areas: scenario $vii$.1, extending the nourishment area in 500 m in the north direction; scenario $vii$.2, with the same extension of the previous scenario, but prolonged in the south direction; scenario $vii$.3, which covers all the extension of the urbanized area (1 500 m). In the cross-shore direction, the nourishment extends along the total active profile width, in all the analysed scenarios.

Table 7 summarize the results obtained for the three scenarios. Despite the small differences registered between scenarios, scenario $vii$.1 presents simultaneously better physical and economic performances. This scenario also corresponds to an earlier break-even (12 years instead of the 13 years of the baseline scenario). Considering the adopted assumptions, it is slightly positive to extend the nourishment area by 500 m to north.

### 4.3.2 Location

The nourishment location may also result in an optimization of the shoreline impacts during the analysed time horizon. Two additional scenarios were considered, scenarios $viii$.1 and $viii$.2, which correspond, respectively, to move the nourishment area in 500 m to the north and 500 m to the south, in relation to the location adopted in the baseline scenario (considering always the initial extension of 500 m). From the analysis of Table 7, it is observed that the northern nourishment location results in a smaller loss of territory and, simultaneously, it represents the most positive economic scenario (BCR = 1.80, with the break-even reached after 13 years, as in the baseline scenario).

### 4.3.3 Frequency

The artificial nourishment operations frequency is often related to financial availability and/or the need to intervene as a consequence of a storm event. However, for a strategic planning of coastal management, it is important to assess and compare the physical and economic performance of frequent nourishments, with a lower volume of sediments, or larger volumes in less frequent interventions. For the baseline scenario, 1 million m³ of sediments was considered every 5 years. Two other scenarios were considered: more frequent interventions, nourishing 400 thousand m³ of sediments every 2 years (scenario $ix$.1); and spaced interventions in time, with higher nourishment volumes (scenario $ix$.2, nourishing 2 million m³, every 10 years).

The results obtained for the two scenarios (Table 7) show that the most positive shoreline evolution impacts do not correspond to the best economic solution. Considering shorter time intervals between artificial nourishments (scenario $ix$.1), there are smaller land losses over the 20 years, but the economic benefit is higher if only two interventions of two million m³ each are performed (scenario $ix$.2). Although in scenario $ix$.2 the break-even point is lower and the NPV is higher (after 20 years), this scenario requires a higher initial investment (4 million euros, while in the scenario $ix$.1 only 800 thousand euros are needed), which may be a constrain, as the initial financial availability is often a conditioning factor in the choice of the coastal mitigation intervention.

### 4.3.4 Volume

In the previous analysis, artificial nourishment scenarios were based on the nourishment of the same total sediment volume (4 million m³), which resulted in approximately the same total intervention costs. Two additional artificial nourishment total volume scenarios were analysed: scenario $x.1$, which considers the nourishment of 500 thousand m³ of sediments every 5 years; and scenario $x.2$, which represents the nourishment of 2 million m³, again, every five years. As expected, scenario $x.2$ is physically more attractive, avoiding territory losses of around 40 ha (when compared to the reference scenario), while in scenario $x.1$, a positive physical impact of 13 ha was achieved. After 20 years, scenario $x.2$ resulted in global accretion when compared to the initial instant (year 0). Despite the physical benefits of higher nourishment volumes, the BCR value of scenario $x.2$ is lower than the one corresponding to the scenario $x.1$ (Table 7). However, the solution corresponding to a volume of 2 million m³ (scenario $x.2$) is considered attractive after 12 years and, although it represents a higher initial and total investment cost, it presents important shoreline evolution benefits.

## 4.4 Sand by-pass scenarios

The shoreline evolution model applied to the sand by-pass baseline scenario (Figure 13) results in lower erosion rates at the northern border than those obtained for the reference scenario. Due to the sand by-pass system location, there is no shoreline retreat in the urbanized zone, guaranteeing its protection throughout the 20 years. Globally, this is the most physically attractive coastal defense intervention, because it simultaneously presents smaller land losses (positive impact of about 29 ha, when compared to the reference scenario) and promotes the total protection of the urbanized zone. Table 8 also shows positive economic impacts, by summarizing the indexes obtained for the sand by-pass scenarios, which analysed the influence of the sand by-pass system location and sediments flow capacity.

**Table 8.** Summary of the physical and economic results of the sand by-pass scenarios.

| **Scenario** | | **Territory area (m²)** | | | **BCR$_{20\ yr}$ (-)** | **NPV$_{20\ yr}$ (€)** | **Costs** | | **Break-even (years)** |
|---|---|---|---|---|---|---|---|---|---|
| | | **Accretion** | **Erosion** | **Impact** | | | **Initial (€)** | **Total* (€)** | |
| $BS$ | Figure 12 | 9 946 | 84 454 | 290 950 | 1.89 | 5 548 634 | 3 000 000 | 6 258 167 | 13 |
| $xi.1$ | 500 m from the northern border | 85 | 65 055 | 300 487 | 1.80 | 4 912 989 | 3 000 000 | 6 127 840 | 14 |
| $xii.1$ | 10% transport rate | 0 | 311 298 | 54 160 | 0.73 | -977 698 | | **3 625 568** | - |
| $xii.2$ | 50% transport rate | 63 | 197 531 | 167 989 | 1.61 | 2 930 383 | 3 000 000 | 4 824 574 | 15 |
| $xii.3$ | 150% transport rate | 119 620 | 6 099 | **478 979** | **2.07** | **9 211 946** | | 8 630 113 | **12** |

*Values updated for initial simulation instant, according to the discount rate (r).

### 4.4.1 Location

In the sand by-pass baseline scenario, the system location was chosen to mostly protect the urbanized zone. A new scenario was considered, where the by-pass is located 500 m north of the baseline scenario (scenario $xi.1$). Table 8 allows to compare both scenarios, showing that, although there are positive physical impacts by locating the by-pass system to the north (a benefit of about 1 ha), this is not economically the best solution. The baseline scenario location results in higher BCR ratios and reaches equilibrium one year before the scenario $xi.1$.

### 4.4.2 Sediments flow

Three scenarios were defined to test the sediments flow rates capacity, two of them with a lower flow than the baseline scenario, representing 10% and 50% of the wave climate sediments transport capacity, respectively, scenario $xii.1$ and $xii.2$, and a scenario with 50% higher capacity than the wave climate sediments transport capacity (scenario $xii.3$).

As expected, greater sediment flow transposed by the system results in smaller land losses (Table 8). Comparing with the reference scenario, losses of about 5, 16 and 48 ha are avoided, respectively, in scenarios $xii.1$, $xii.2$ and $xii.3$. The economic performance of the scenarios follows the same trend line, since the scenarios corresponding to the greater capacity also correspond to better economic indexes. The scenario $xii.1$ is not monetized within the 20 years' time horizon and the scenario $xii.3$ is the most attractive, both physically and economically, with the benefits exceeding twice the total costs after the 20 years (BCR = 2.07). In this scenario, at the end of the 20 years, accretion was achieved when compared to the initial instant (about 11 ha). As a conclusion, it was verified that the economic performance of the by-pass systems increases with the increased transposition capacity and it is ineffective when considering lower sediment flows.

### 4.5 Final remarks

The considered case study intended to highlight the potential capacity of the proposed physical and economic assessment methodology. The costs and benefits evaluation shown that the main goal of the intervention needs to be very well-defined, because a better scenario in one specific aspect may be worst in another one. Although, the adopted modelling parameters and values chosen to estimate costs and benefits are representative of a generic coastal zone in erosion, the needs of a careful definition of the intervention goals are common to real situations, where the evaluation of all the assumptions is required (numerical modelling and adopted monetary values).

Concerning the case study, all the presented groin scenarios result in a negative physical impact, being the 100 m groin scenario the one with lower erosion areas and at the same time, presenting the lower initial and total investment costs. The groin scenario presenting the earlier break-even is the baseline scenario (groin with 200 m, located at the south border of the urbanized zone). The highest net present value after 20 years was obtained to the 300 m groin scenario and the scenario corresponding to the longer groin is the most effective in protecting the urbanized zone.

In the longitudinal revetment scenarios it was verified that: smaller extension than the one adopted in the baseline scenario (1500 m long, in front of all the urbanized zone) results in less attractive physical and economic indexes; lower crest elevation lead to an increased number of overtopping events and, consequently, increases the required structure maintenance costs (this was the worst economic scenario); and a groin combined with a longitudinal revetment scenario was not economically attractive.

The results obtained for the artificial nourishments scenarios have shown that moving the nourishment location and extend its area to the north, represents physical and economic advantages. Frequent nourishment interventions with lower sediment volumes will induce larger accretion areas over time, but the greater economic gains correspond to a larger nourishment volume with lower intervention frequencies. A higher total volume of nourished sediments in the coastal system provides larger accretion areas over all the analysed time period and simultaneously results in a higher net present value after 20 years.

The adopted location of the sand by-pass system baseline scenario was the northern boundary of the urbanized zone but moving the system 500 m north results in improved physical impacts (lower erosion). To increase the by-passing sediments volume capacity results both in better physical and economic indexes.

## 5. Discussion

The coastal management entities are often asked about the negative effect of a groin at downdrift, the landscape degradation due to rocky revetments, or the sediments quick disappearance after artificial nourishment interventions, among many other doubts. The goal of the proposed methodology is to contribute to support decision-makers on coastal management and planning. The main relevance of the proposed methodology is to follow well-defined and sequential stages in an integrated way, considering numerical modelling, coastal interventions pre-design, and costs and benefits assessment. All the three stages may result in discussion due to the inherent uncertainties to each process. The presented case study was inspired in values adequate for the Portuguese Northwest coast (wave climate, shoreline erosion rates, intervention structural characteristics, land use values and intervention costs). However, the proposed methodology is adaptable to different shoreline evolution numerical models and assumptions, different coastal structures pre-design formulations and mainly, it is easy to test different considerations about the land use monetary values and interventions costs. Thus, the presented case study allows to get an idea of the type of assessment that may be performed, but the application of the methodology to specific situations require an evaluation of every site characteristics [82].

Cost-benefit analysis (CBA) is a decision-support tool which incorporates social, economic, and environmental impacts. According to [83], robust CBAs that identify the relative costs and benefits of the management options will assist coastal local councils, public authorities, and their consultants, helping to make informed choices about which management option (or options) will provide the greatest net benefits to their community. However, it is not a means of providing a definitive statement of which management option council should adopt. The decision on which option council should implement is likely to depend on several other considerations which are not addressed in a CBA. However, a well-constructed CBA can provide an important contribution to the information council can use in its decision-making processes [83]. In the proposed methodology, the costs and benefits of alternative management options are compared with the costs and benefits of the reference scenario to identify any incremental differences between this scenario and the alternative ones. A cost-benefits analysis considers direct costs and benefits for different groups and also any other positive or negative effects, such as the changes in the value of beach recreation and amenity. It should be noted that although individual groups in the community may benefit from a particular management action, others may be disadvantaged. However, if the sum of the benefits of a particular option exceeds the sum of the costs incurred, the option would appear to provide an overall benefit. The cost-benefits analysis also considers the timing of each of the costs and benefits associated with particular options and converts future costs and benefits into today's prices so that all impacts can be meaningfully compared regardless of timing. In this way, the proposed methodology can enable a comparison of options that deliver different streams of benefits and costs over time.

To understand the benefits of coastal intervention scenarios, long-term shoreline evolution estimates are required. Long-term simulations of beach change are more reasonably formulated based on total or bulk transport models. These models have fewer coefficients than three-dimensional models and provide no details of the sediment transport profile. However, they may be calibrated and verified to include the integrated effect of all the local processes on the total transport. Thus, one-line models are considered adequate to fulfil the goal of the proposed methodology, simulating coastal stretches of 10 to 100's km and long-term (years to decades) coastline evolution that results from gradients in alongshore sediment transport. These models allow exploring how the patterns and rates of shoreline erosion and accretion are affected by shifts in wave climate and alongshore sediment transport characteristics. Moderate shifts on these parameters can alter the patterns of shoreline erosion and accretion, with consequent impact on the developed analysis.

Pre-design of coastal structures may follow several different formulations, mainly based on the incident wave heights to define the adequate block for the armour layer. XD-Coast was developed by [53] in order to facilitate the calculation processes, allowing a quick comparison between several alternative solutions, and to allow sensitivity analysis about variables involved in the calculations. Therefore, it is considered that the model is resourceful, with an intuitive and easy graphical interface, allowing not only isolated calculations, but also repeated calculations with increment of several calculation steps for some variables, generating tables of results. These tables allow understanding the influence of each parameter in armour layer blocks unit weight, making easy to compare the structures definition impacts.

Finally, as previously referred, the land use provided services are essential to define the value of the territory and an adequate sensitivity analysis should be performed to well characterize the land use value. [84] refers that benefit transfer is a technique in which the results of studies on monetary land use valuation are applied. This is a controversial technique because of academic and political reservations over the usefulness and technical feasibility of economic valuation of tools to demonstrate the importance of land use values in project or programme appraisals. An important part of the land use economics profession is to value land use in monetary terms, i.e., estimate how much people are willing to give up of other goods and services they consume in exchange for a better land use. The rationale is to make the benefits of a better land use transparent and comparable with other costs and benefits in private and public decision-making that typically have market values, such as goods, working hours, etc. Different land use values have increasingly been recognized as an important decision-making support in developing multi-functional policies. The use of such values in policy-making is already common. Increased use is fed by demand from public agencies, as well as growing academic interest. Therefore, many practical applications by different public agencies and consultancies use information about values from existing studies and transfer to unstudied, similar sites of policy interest. The approach tries to mitigate this gap in the usual procedures, making easier to develop and include costs and benefits assessments on coastal erosion mitigation strategies definition.

## 6. Conclusions

This work aimed to present a well-defined and sequential approach, applied in an integrated way, to evaluate costs and benefits of different coastal intervention scenarios. The methodology was applied to a hypothetical case study, to compare and discuss different coastal intervention scenarios (groins, longitudinal revetments, artificial nourishments and sand by-pass systems), through assessing their physical and economic effectiveness.

34 coastal intervention scenarios were evaluated (4 baseline scenarios and 30 scenarios discussing different intervention characteristics) to mitigate persistent coastal erosion problems identified in a reference scenario. In all the baseline scenarios, it was verified that it is economically adequate to perform interventions to mitigate the coastal erosion problems. However, despite the investment made in all the intervention scenarios, it was also observed a general trend of land losses along the 20 years analysed period, when compared to the initial instant (year 0). The no intervention scenario represents high economic losses. When performing the different coastal intervention scenarios, significant physical (reducing land losses) and economic improvements can be achieved. The obtained results also show that it is difficult to combine, in the same intervention scenario, the best option considering both physical and economic factors. Thus, when defining and designing the intervention it is fundamental to make clear all the objectives of the intervention, considering the extension of the urban zone to protect, the initial investment, the generalized erosion, the time needed to recover the investment made, the general physical impacts or net present value, etc.

The potential application of the presented hypothetical study case results to real world situations is naturally limited by the specific conditions of each situation (land use values, but also wave climate conditions, coastal intervention characteristics and scenarios, etc.). However, the case study is demonstrative that the methodology can be replicable to other study sites, considering their specific characteristics. The easy approach defined by the methodology allows a quick sensitivity analysis to those conditions, permitting its general worldwide application. Thus, it is considered that the proposed methodology represents one step toward a well-supported decision-making process, helping on coastal management and planning.

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