Journal of
Marine Science and Engineering

MDPI

Article

Definition of an Artificial Reef Unit through Hydrodynamic and Structural (CFD and FEM) Models—Application to the Ares-Betanzos Estuary

María Isabel Lamas Galdo [1,*], María Jesús Rodríguez Guerreiro [1], Javier Lamas Vigo [2], Ismael Ameneiros Rodriguez [2], Ricardo Veira Lorenzo [2], Juan Carlos Carral Couce [2] and Luis Carral Couce [1]

[1] Engineering Polytechnic University College of Ferrol, University of A Coruña, Mendizabal s/n, Ferrol, 15403 A Coruña, Spain; maria.guerreiro@udc.es (M.J.R.G.); lcarral@udc.es (L.C.C.)
[2] Anta-Norte S.L., Avenida Mestre Manuel Gomez Lorenzo 30, 15885 A Coruña, Spain; javier.lamas@antanorte.com (J.L.V.); ismael@ameneirosrey.com (I.A.R.); ricardo.veira@antanorte.com (R.V.L.); jcarral@icoiig.es (J.C.C.C.)
* Correspondence: isabel.lamas.galdo@udc.es; Tel.: +34-881-013896

Abstract: The application of hydrodynamics to the definition of artificial reefs is of great interest since the positioning of the artificial reef modules on the sea floor alters the water velocity field, causing an appropriate circulation of nutrients and promoting a habitat for settling desired species. Nevertheless, the designs must be subjected to a structural calculation that will condition the constructive process to be applied. The present research proposes a methodology to determine the geometry of an artificial reef in terms of hydrodynamic and structural criteria. The solution proposed was analyzed through Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM). Using concrete as base material for artificial reefs, four different dosages were proposed with different proportions of cement and water, leading to different mechanical properties, which determine different constructive strategies, such as dwell time in the mold. From the hydrodynamic point of view, it was found that the solution proposed provides a proper replacement of nutrients. From the structural point of view, it was found that the solution proposed does not need steel reinforcements in concrete, which improves the sustainability of the artificial reef. The four different concrete dosages will condition the constructive strategy through the dwelling time in the mold and, for any established production, the necessary number of molds (formworks).

Keywords: artificial reef; hydrodynamics; structural analysis; finite element method

Citation: Galdo, M.I.L.; Guerreiro, M.J.R.; Vigo, J.L.; Rodriguez, I.A.; Lorenzo, R.V.; Couce, J.C.C.; Couce, L.C. Definition of an Artificial Reef Unit through Hydrodynamic and Structural (CFD and FEM) Models—Application to the Ares-Betanzos Estuary. *J. Mar. Sci. Eng.* **2022**, *10*, 230. https://doi.org/10.3390/jmse10020230

Academic Editor: Constantine Michailides

Received: 13 January 2022
Accepted: 7 February 2022
Published: 9 February 2022

1. Introduction

Oceans embrace more than 90% of life in the biosphere [1] and produce half of the oxygen we employ to breathe and burn fossil fuels [2]. Moreover, oceans regulate the global climate since they act as a thermal mass to store heat and CO_2 generated by human activities [3]. Consequently, the conditions of oceans present direct implications to life on our planet [4]. At the same time, oceans provide natural and mineral essential resources, as well as energy [5]. Nevertheless, the risk of overexploitation is too high unless the extractive activities start effective regulation [6]. The renewable part of these marine recourses must be managed according to sustainability criteria, especially in the case of fisheries [7]. The consequences of human activities on oceans manifest through reductions of fish populations, a threat with the extinction of others, destruction of habitats, pollution, the introduction of non-native species, ocean warming and acidification, and so on [8,9]. According to FAO (Food and Agriculture Organization of United Nations), 25% of the worldwide fisheries were overexploited, depleted or in the depletion process in 2006 [9]. Posterior research alerted that all fisheries will collapse in 2048 [10]. For their part, FAO [11] argues that the Western Central Atlantic populations present an untenable situation from the biological point of view. Aside from overfishing, marine pollution impacts ocean conditions. The particular case of the coastal areas must be added to this general issue. Its management has become an important concern for society due to the impact of human activity on environmental quality. According to this, it is necessary to optimize the strategies of aquaculture [12] and artisanal fishing [13]. This management necessity results in particular importance in Galicia (Northwest Spain), where the coastal zones, especially estuaries, have been internationally recognized due to their huge singularity and importance regarding environmental, economic and social aspects.

The artificial reef groups are constituted by a set of artificial reef unit, strategically placed on the sea floor, which emulate the characteristics of a natural reef, i.e., protecting, concentrating and improving the populations of live marine organisms [14]. These can be considered their main effects. Aside from the aforementioned advantages, artificial reefs also cause induced effects in the environment, affecting the spatial distribution (circulation) of water [15] and creating a shadow from sunlight around each unit, which produces a dark region in the water and changes the original light. For this reason, artificial reefs constitute important, influential agents when they are placed on the sea floor, modifying the topographic conditions [16]. Many researchers have indicated that fishes tend to group around reefs because the alteration in the velocity field creates favorable conditions [17–20] since the vortices created are stable and peaceful in comparison with turbulent flow. Most researchers have focused on the hydrodynamic effect of the shape and structure of the reefs. Since cubic-shaped artificial reefs constitute simple geometries and are thus cheaper, many studies have been developed over the years in order to characterize the velocity field around these reefs. Several experiments using water channels and CFD (Computational Fluid Dynamics) simulations [15,21] analyzed the influence of currents and other aspects. Liu et al. [22] concluded that the height and section of upwelling regions experiment a lower modification if cubic artificial reefs are employed. Liu and Su [23] employed CFD and a water channel to analyze the influence of the distribution of the different modules. Shao et al. [24] and Huang et al. [25] developed numerical simulations about the influence of hole sizes and inlet velocity on cubic reefs, and Fu et al. [26] analyzed the influence of the opening and shape.

The works mentioned above provide important information for designing reefs. An appropriate circulation and water velocity leads to increased renewal of nutrients favorable for larval settlement [27,28] and reduces sedimentation. Sedimentation is harmful to life since it inhibits, between other factors, nutrient renewal and dissolved gasses [29–32]. During the search for these main effects, the PROARR (Diseño y producción de un módulo de arrecife artificial para la protección y rehabilitación de ecosistemas costeros en la comunidad autónoma de Galicia) project, financed by Xunta de Galicia (Spain), arises to develop artificial reefs in the Galician estuaries [33]. This project treats green artificial reefs, i.e., environmentally friendly artificial reefs adapted to the principles of circular economy [34]. Moreover, their supply chain has been optimized in order to reduce the environmental impact [35]. Previous analyses allowed the development of a specific tool for positioning the artificial reefs [36] and the posterior adaptation of the artificial reef groups to the hydrodynamics and biological circumstances of each region [21]. The aim of the present work is to continue this previous research and develop a methodology to improve the design of the artificial reef. A new design was proposed according to hydrodynamic-structural and calculation-construction strategies. The hydrodynamic analysis was carried out through a CFD model and the structural analysis through FEM (Finite Element Method). Moreover, production and economic factors related to the manufacture were also considered through the determination of the optimal dosage and necessary constructive strategy.

2. Materials and Methods

2.1. Problem Definition

Carral et al. [36] established the Ares-Betanzos Estuary as an appropriate place for an experimental reef group [13]. The Ares-Betanzos Estuary is located on the Northwest coast of Spain. It is connected to the Atlantic Ocean. This estuary presents a positive subtidal circulation, even in upwelling and downwelling conditions, due to the role played by the river flows. In their research, Carral et al. [36] verified that the natural upwelling phenomenon takes place seasonally through the effects of upwelling and downwelling events. Upwelling is characteristic of seasons with a prevailing northern wind, which, by means of the Ekman pumping, generates an upwelling in the bottom of the estuaries and an exit of the superficial waters as compensation; this leads to positive residual circulation. On the other hand, during the downwelling season, the southern wind prevails and there is an inversion of this circulation pattern. Nevertheless, upwelling and downwelling are also common outside their characteristic seasons. The Ares-Betanzos Estuary, Figure 1, is small and oriented in a different way in comparison with other Galician estuaries, presenting a low influence of the upwelling effect on its bottom and, on the contrary, the tidal circulation has a greater impact. Consequently, the circulation flow of this estuary is appropriate. The characteristics are the result of the complex interaction of different forcing factors that act as generators of currents (tides, support of oceanic and continental water, wind and, under specific situations, waves).

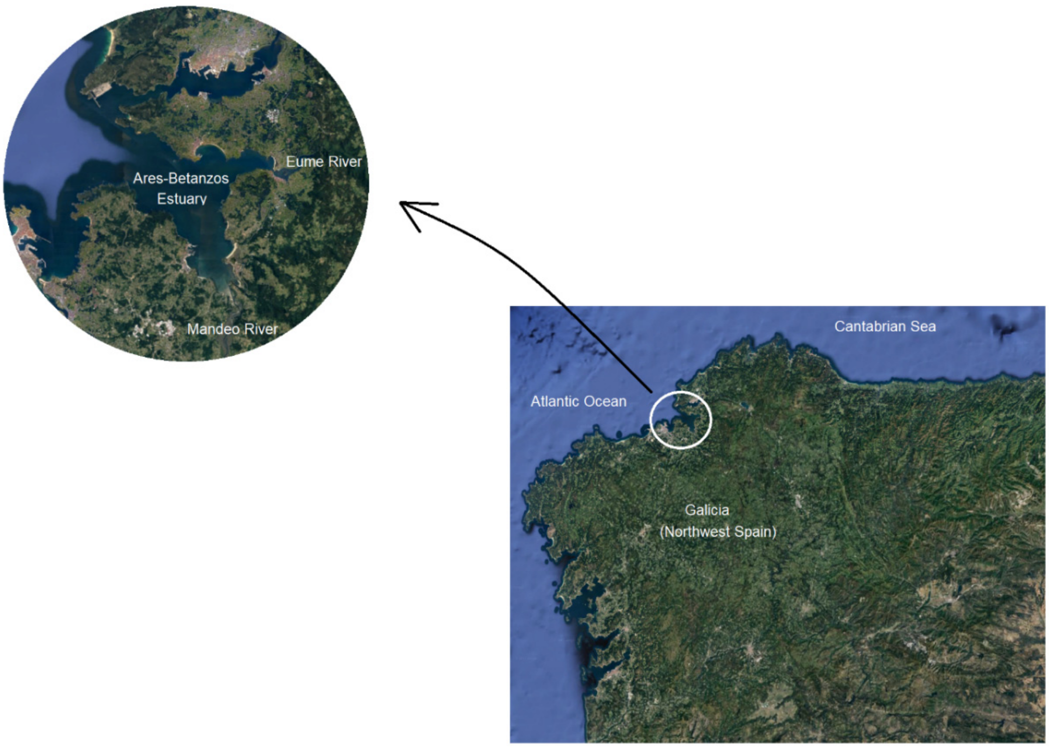

Figure 1. Ares-Betanzos Estuary (Northwest Spain).

Once the situation of the artificial reef was selected, the next step consisted of designing these artificial reefs. The flowchart with the procedure is shown in Figure 2. As can be seen in this figure, the first step consists of selecting the external dimensions. These artificial reefs will be transported from the factory building to the sea by road transport. According to logistic criteria, a cube of 1.5 × 1.5 × 1.5 m was established [35]. These artificial reefs must allocate lateral holes that ensure circulation and, thus, renewal of nutrients. The size, number and position of nest cavities were determined, and a CFD model was carried out to analyze the flow field around the artificial reef. Regarding materials, these artificial reefs are made of concrete, and the demolding process must be feasible, i.e., the artificial reefs must be rigorously designed to remove concrete from its mold. Once this stage is reached, it is important to analyze the structural availability. To this end, a FEM analysis was carried out. The loads during demolding, loading/unloading, installation and operation were taken into account to set up this model. Using concrete as the base material for the artificial reefs, the following proposals were analyzed:

- Proposal 1, with 325 kg/m^3 cement content (HA-30/B/20/IIIb according to EHE-08 [37]).
- Proposal 2, with 275 kg/m^3 cement content (HA-25/P/20/IIa according to EHE-08 [37]).
- Proposal 3, with 240 kg/m^3 cement content (HM-20/P/20/I according to EHE-08 [37]).
- Proposal 4, with 200 kg/m^3 cement content (HM-20 according to EHE-08 [37]).

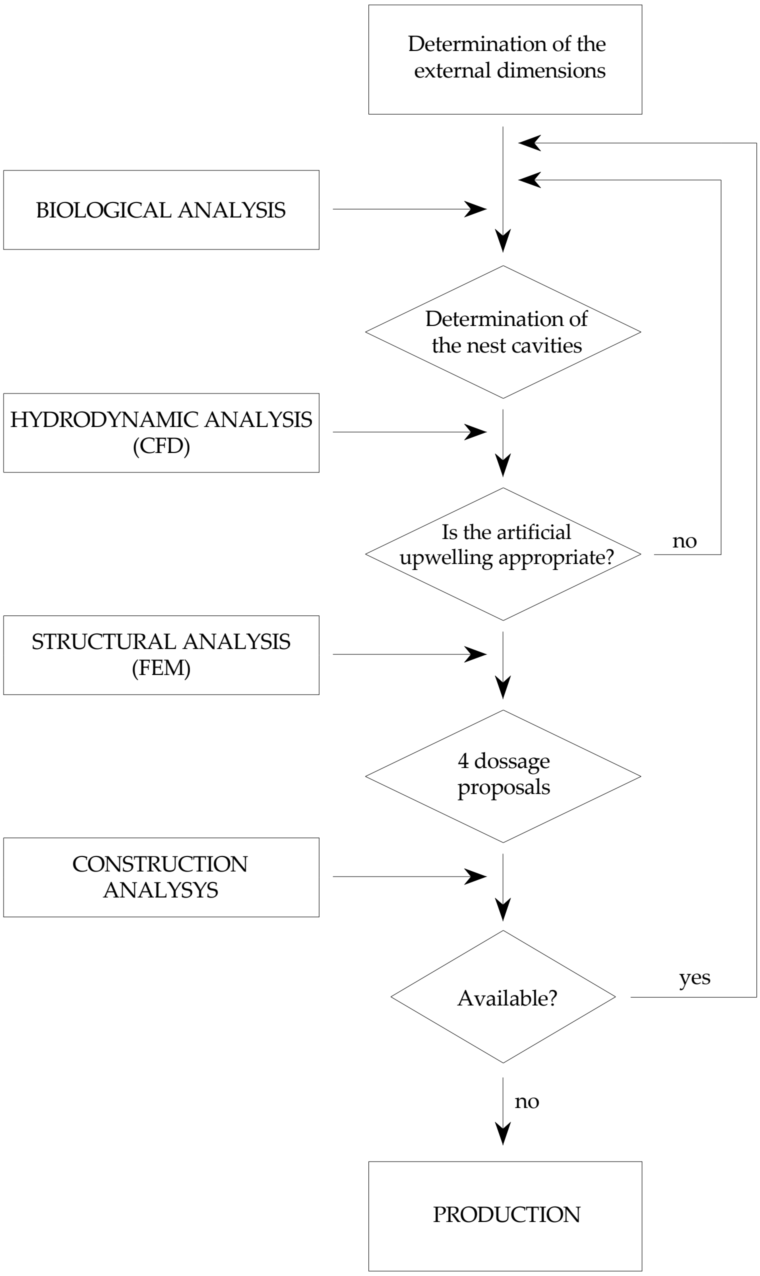

Figure 2. Flowchart used to design the artificial reefs. Dosage proposals, comparison of mechanical properties with solicitations and determination of a constructive strategy.

These four proposals lead to different mechanical properties, which allow the determination of different constructive strategies, such as dwell time in the mold. Finally, the last step is to verify that the proposed design is available for production.

The main objectives of the present work are:

- Validate the design, including the external dimensions and determining the dimensions of the nest holes.
- Providing a structural analysis through a FEM model according to the loads that take place at the production and transport stages.
- Proposing concrete dosages, experimentally characterizing the mechanical properties corresponding to each proposal.
- According to the obtained results and loads actuating on the artificial reef, determining a constructive strategy.

2.2. Methodology Employed in the CFD Model

A 3D circulation model developed in a previous work [21] was employed to characterize the hydrodynamics of the estuary along a representative period. In previous research, a complete period of spring-neap tides was selected. In order to characterize the forcing factors actuating along this period, the following forcing factors were considered as generators of currents: (i) tide, (ii) freshwater discharge and (iii) mass of oceanic water. The water circulation in the estuary presents an important intake of underground water, which penetrates through the floor from the open ocean (North Atlantic Central water). This research [21] provided an average current velocity of 0.08 m/s, which was used as the input for the CFD model.

The 3D CFD model carried out in the present work is based on the conservation equations of mass and momentum. OpenFOAM v2012 (OpenCFD Ltd., Bracknell, England) was employed. As boundary conditions, inlet and outlet boundary conditions were imposed, with an inlet velocity of 0.08 m/s. No slip was considered at the surfaces of the reef, and symmetry was assumed in order to reduce the computational requirements. The k-ε turbulence model was employed. A mesh with 2,197,762 elements was used. In order to check mesh independence, the velocity at five points of the domain was characterized using three meshes. The results are shown in Table 1. As can be seen, the results using Mesh 2 and Mesh 3 are similar. According to this, Mesh 2 was chosen for the computations carried out in the present work.

Table 1. Computational meshes checked.

Mesh	v_1 (m/s)	v_2 (m/s)	v_3 (m/s)	v_4 (m/s)	v_5 (m/s)
Mesh 1 (1,427,621 elements)	0.096	0.074	0.065	0.057	0.052
Mesh 2 (2,197,762 elements)	0.094	0.072	0.064	0.056	0.052
Mesh 3 (2,942,694 elements)	0.094	0.072	0.064	0.056	0.052

3. Results and Discussion

3.1. Biological Analysis

Cephalopods, crustaceans and fishes have a notorious relevance in the ecosystems of the Atlantic Iberian Peninsula, particularly the Galician estuaries, thanks to their commercial value and intervention on the biological cycle of many species. This is important mainly on the marine trophic relationships since the different phases of larval life contribute to the food diet of many other species. Although the Galician estuaries are ecosystems with a huge biological production, the fishing efficiency is not being incremented. According to this, artificial reefs are proposed in [38], establishing a possible general colonization pattern of an artificial reef on the first five years in the Ares-Betanzos Estuary. This research is based on data from artisan fishing of commercial species of benthic, demersal and pelagic communities on the subject area.

In the Galician estuaries, the abundance of phytoplankton shows two maximum values in spring and autumn and a minimum in winter. The minimum is due to two causes, cold water and a great degree of agitation that does not allow phytoplankton to remain suspended in the photic zone. Phytoplankton acts as a food for zooplankton, which is made up of a wide variety of fish larvae, mollusks and mainly crustaceans, for the most part, copepods, amphipods and euphausiacea. Zooplankton acts as food for planktivorous fish in the food chain. Both planktivorous and zooplankton act in equal measure as food for predatory fish, which in turn act as food for groundfish.

On dying, the organisms and their depositions go to the seabed, where they decompose through bacteria into basic elements (nutrients). As such, a concentration of nutrients is formed on the seabed, far from the photic zone. By means of sea currents, these rise to the water's surface, continuously closing the cycle, Figure 3. Groups 1, 2 and 3 are described in [38].

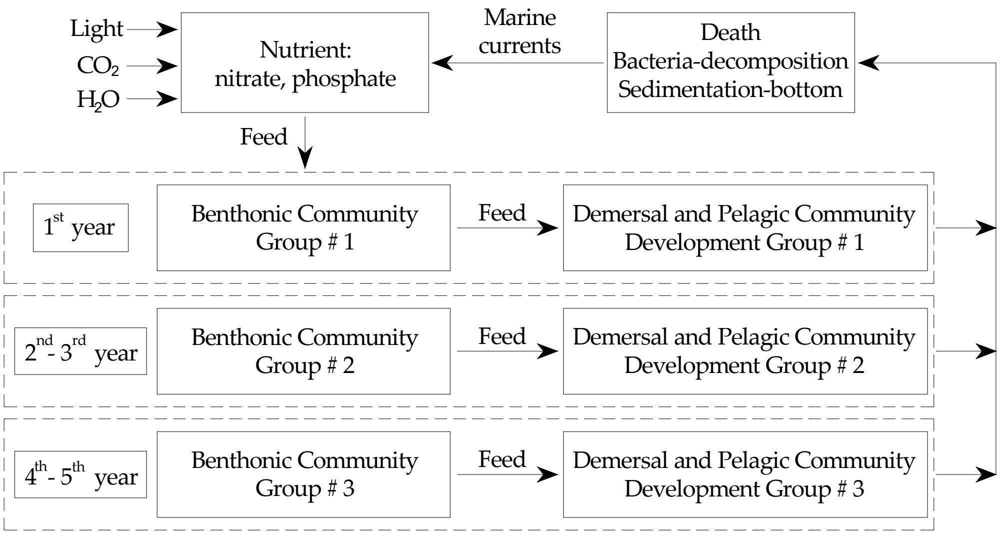

Figure 3. Development prediction of benthic, demersal and pelagic communities in the Ares-Betanzos Estuary.

Many of these organisms of this coastal region (Ares-Betanzos Estuary, Galicia) coincide their reproductive cycle with the upwelling time. Upwelling increases the primary production in water [39] since cold water, rich in nutrients, rises from deep zones to superficial ones and maintains the high production of zooplankton, observed from early spring to late autumn. Therefore, high quantities of zooplankton can be found along the coast. This increases the availability of food from the larvae of the different species [40]. Environmental pollution and climate change contribute to the deterioration of the water quality, which drastically reduces the possibilities of live and the quantity of plankton biomass [41].

Many of these commercial species reproduce in pelagic environments, suffering may migrate in pursuit of an adequate place and moment for laying. Other species reproduce in benthonic environments, needing particular structures for laying. The main causes of mortality of these organisms are starvation and predation. Starvation arises depending on the success or failure of the larvae feeding. On the other hand, predation arises, for instance, due to the absence of refuge for hiding.

In this sense, on the one hand, artificial reefs contribute to producing an artificial upwelling inducing upward currents with a high level of nutrients. On the other hand, artificial reefs also offer a substrate and nest cavities suitable for refuging from predators or laying deposition. Artificial reefs thus provide two important advantages: a hard substrate and generation of currents that distribute the nutrients from the sea bed to the surface, i.e., an artificial upwelling which increases the nutrient concentration and improves the larvae feed in an estuary. According to this, the next section focuses on the artificial upwelling effect generated by an artificial reef in the Ares-Betanzos Estuary. The proposed artificial reef is shown in Figure 4a. The evolution of the design has allowed the concentration of more mass in the same envelope and, at the same time, maximizing the number of cavities in the faces. Regarding the system for lifting the blocks for their transport and placement, these are raised by metal wires in the concrete itself, Figure 4b. Cables or slings are introduced through the small vertical orifices, and the block is thus suspended from its base, minimizing the tractions in the element and eliminating the necessary reinforcement to absorb them.

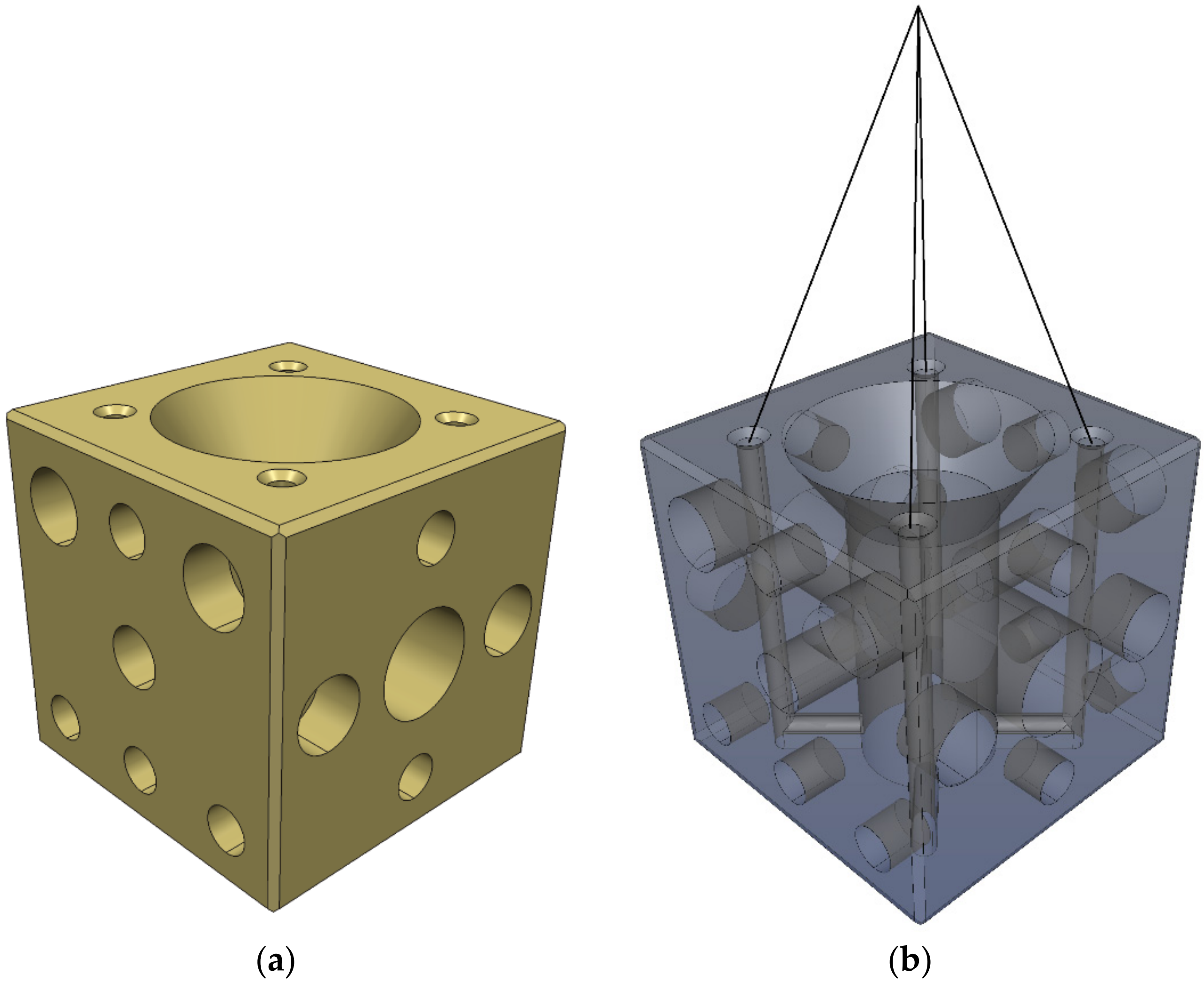

Figure 4. (**a**) Proposed artificial reef; (**b**) rising system.

The nest cavities have been defined according to the species susceptible to colonize the artificial reef. This region has many species, both benthonic and pelagic. The species that have experienced the most significant reduction in the last 10 years are cephalopods and crustaceans, with stock reductions are higher than 50% [13]. The species that are the subjects of this study and their optimum hole sizes are shown in Table 2.

Table 2. Species that are the subjects of this study and optimum hole sizes.

SPECIES	HOLE SIZE	FUNCTION	HOLLOW	TIME	SOURCE
Cuttlefishes (*Sepia officinalis*)	30–40 cm	Reproduction	Yes	January–June	[42]
Octopuses (*Octopus vulgaris*)	30–40 cm	Reproduction	No	May–November	[43]
Squids (*Loligo vulgaris*)	30–40 cm	Reproduction	No	-	[42,43]
Lobsters (*Paliinuros elephas*)	Less than 30 cm	Habitat	No	-	[44]
Crustaceans	Less than 20 cm	Habitat	No	-	[42]

3.2. Hydrodynamic Analysis

The results provided by the CFD model are shown in Figure 5, which represents the velocity field in the middle plane. As can be seen in this figure, the installation of the artificial reef on the sea floor alternates the water velocity field, leading to an adequate circulation of nutrients. The flow separates due to the presence of the artificial reef in a way that a part of the flow is directed upwards, constituting a welling, which encourages the vertical exchange of seawater. This phenomenon increases the transport of nutrients on the sea floor and improves the diffusion of them around the reef. Consequently, the effect of this artificial upwelling promotes the attraction of fish. At the same time, a part of the separated flow across the reef causes modifications in the velocity field, with the formation of vortices and alteration of the flow of sediments, which accelerates the frequency of the seawater exchange on the sea floor. Moreover, a small region with a slow and stable flow is formed behind the reef.

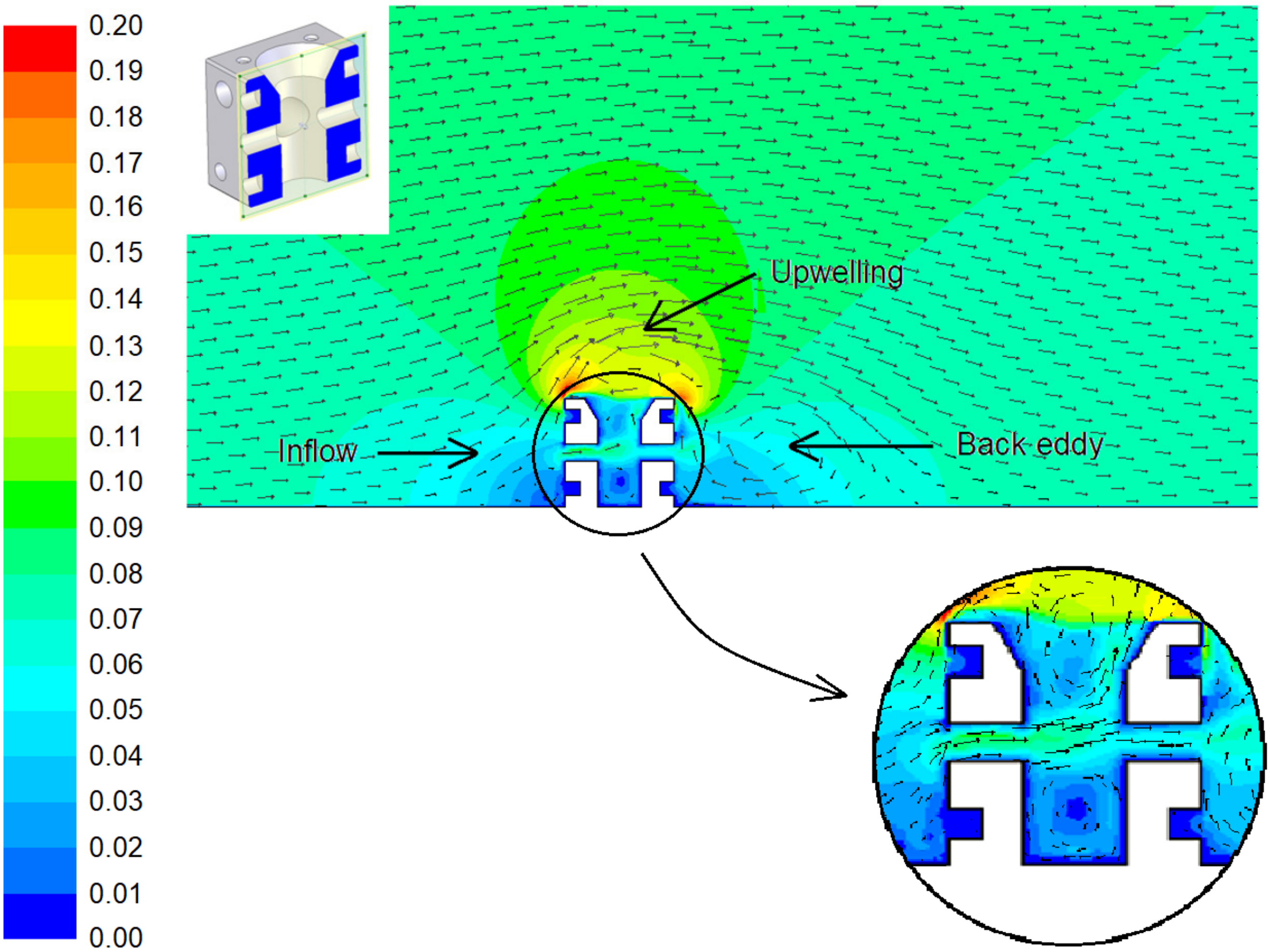

Figure 5. Velocity field (m/s).

3.3. Dossage Proposals

In Spain, the EHE-08 [37] concrete legislation constitutes the regulatory framework that establishes the requirements for concrete structures in order to fulfill the requisites of structural security, fire resistance and environmental protection. Its compliance provides technical guarantees. Based on this legislation and looking for testing concretes with different durability, four dosages were proposed. These dosages were established using four proportions of cement: 325, 275, 240 and 200 kg/m^3, as shown in Table 3. Proposals 2, 3 and 4 are low cement content alternatives. Many types of cement are available for construction and civil engineering. Between them, Portland cement is highly employed. In the present work, Portland CEM 1 was selected for all cases since this cement does not include additives, such as fly ash, silica fume or blast furnace slag (according to RC 2016, Instruction for the reception of cements, these are Clinker in 95% proportion). This is combined with gravel, fine aggregates (1–4 mm), medium aggregates (4–10 mm) and coarse aggregates (10–20 mm). A total of 14.6% of fine aggregates were replaced with 1–4 mm shells, and 11.3% of aggregates were replaced with 4–10 mm shells [13]. These (a combination of oyster and mussel shells) were made inert and crushed. The cement and aggregate types are pretty important for concrete, especially for marine structures, because the concrete will be seriously eroded by seawater [45–47]. Fine aggregates generally consist of natural sand or crushed stone, while coarse aggregates are greater particles. Fine aggregates mainly influence the concrete's workability, while coarse aggregates provide strength.

Table 3. Proposals analyzed with their mass proportions (kg) of aggregates, water and cement necessary to obtain 1 m^3 of concrete.

Components	Proposal 1 HA-30/B/20/IIIb Qb	Proposal 2 HA-25/P/20/IIa	Proposal 3 HM-20/P/20/I	Proposal 4 HM-20
10–20 mm aggregates (kg)	503	503	503	503
4–10 mm shell aggregates (kg)	200	200	200	200
1–4 mm shell aggregates (kg)	246	246	246	246
4–10 mm aggregates–limestone (kg)	384	384	384	384
1–4 mm aggregates–silica (kg)	384	384	384	384
TOTAL AGGREGATES (kg)	1717	1717	1717	1717
CEMENT (kg)	325	275	240	200
WATER (kg)	160	160	130	120

The first proposal (proposal 1) fulfills the EHE-08 requirements (duration 25–50 years) for concretes employed in marine environments. These concretes are permanently submerged and subjected to chemical attack by salts (maximum proportion water/cement 0.5, minimum cement content 325 kg/m^3 and minimum strength 30 N/mm^2). This first proposal is also the theoretically most indicated one to prefabricate concrete structures due to its high initial strength, which allows a fast demolding [35]. Proposals 2 and 3 do not fulfill the requirements for marine environments imposed by EHE-08, but they are considered suitable for the proposed application and durability and can be employed as temporal elements (3–10 years duration) according to article 5 of EHE-08. Proposal 4 does not fulfill the minimum cement content, but it is analyzed due to environmental interest. The proportion of water/cement is not fulfilled in these three proposals (proposals 2, 3 and 4), which means that the useful life will not reach the minimum 15 years imposed by EHE for maritime constructions. None of the proposals analyzed included additives in order to manufacture ecological concrete.

Proposal 1 contains the highest quantities of cement and water, while proposal 4 contains the lowest quantities. Particularly, the water/cement proportions results were 0.5, 0.58, 0.54 and 0.6 for proposals 1, 2, 3 and 4, respectively. All proposals include the same quantity of aggregates, thus providing the same sustainability index [13].

3.4. Structural Analysis

A FEM analysis was carried out using the software Salome-Meca. The first computation models were realized using a uniform mesh. Subsequently, an adaptive tetrahedral mesh was used, Figure 6a. The mesh size is variable according to the complexity of the geometry, as can be seen in Figure 6b,c.

The proposed artificial reef will be subjected to different loads throughout its life cycle, with maximum efforts taking place in the manufacturing and transport processes to the final destination. The weight was applied as suspended in the slings shown previously in Figure 4. The result was based on the elastic analysis. Material nonlinearity, geometry nonlinearity, fatigue and erosion were not considered. The geometry of the element, its own weight and the way in which it is lifted determine the stresses in the concrete with which it is manufactured, always seeking from the design to minimize or even totally eliminate the need for steel reinforcement, either for assembly or to absorb tensile forces. The properties employed were concrete C 25/30; E = 30,500 MPa; G = 12,708 MPa; ν = 0.2 and density = 2500 kg/m^3. The results are shown in Figure 7. As can be seen, both tensile and compressive stresses are too low. As expected, a concentration of compression is produced along the channels habilitated to allocate the lifting slings, but the compressive stresses are considerably lower than the compressive strength of concrete. Tensile stresses are small and concentrated in the edges due to a cantilever effect of the suspension. According to this, it was verified that the proposed design is available for production. From a practical point of view, molding and demolding is feasible, and thus, this design is considered appropriate.

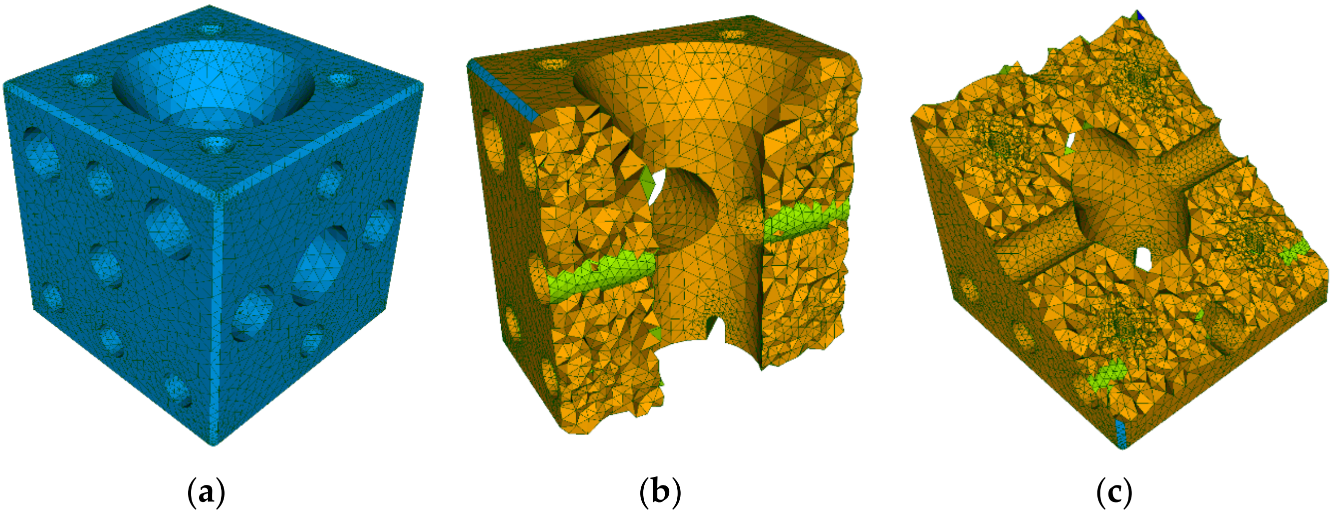

Figure 6. Computational mesh for the FEM model; (**a**) tridimensional view; (**b**) section at the middle idle; (**c**) section at an inclined plane.

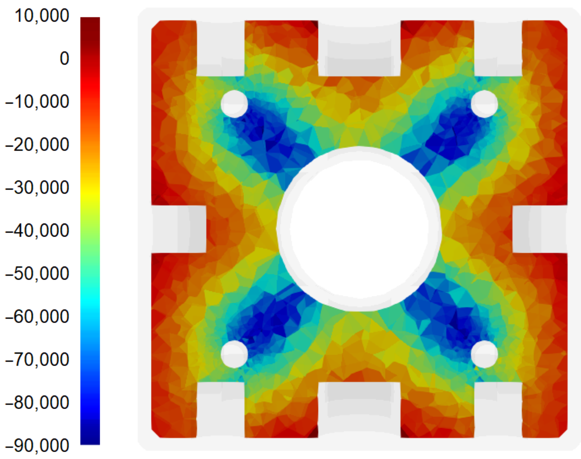

Figure 7. Stresses (N/m^2). Negative means compression in concrete, positive means tension in concrete.

3.5. Mechanical Properties of the Analyzed Dosage Proposals

The four dosage proposals shown in Table 3 were analyzed in order to obtain enough compressive strength to support the loads that take place during the demolding process. The sample analysis was realized according to UNE-EN (Una Norma Española—Europea Norma, in translation a Spanish norm – European norm) 12350-1:2020, the making and curing for strength test according to UNE-EN 12390-2:2020 and the settlement test according to UNE-EN 12350-2:2020. The study, as a fresh state, allowed the evaluation of the density in order to characterize the formulation parameters and the workability through the slump-test and compaction degree following UNE-EN 12350-2 and UNE-EN 12350-4 rules. A compressive strength analysis was realized according to UNE-EN 12390-3:2020, using 150 × 150 × 150 mm cubic samples, at 1, 2, 7 and 28 days (kN values in Table 2). A compressive strength related to a 15 × 30 cylindrical sample according to 86.3.2 section of EHE-08 was also performed (N/mm^2 values in Table 2). Proposals 1, 2 and 4 presented soft consistency, while proposal 3 was plastic (Abrahams cone–7, 9, 3, 9), with different compactness levels (0.917–0.9374). The curing process was realized by 28 days of water immersion. The compactness, quantity of solid material in the whole concrete volume, directly affects strength, durability and impermeability. As this is a pseudo-solid, it could be possible to get 97–98% compactness, but it usually reaches about 90 %.

As can be seen in Table 4, in order to obtain, for instance, 8.3 N/mm^2, proposal 1 needs one day, proposals 2 and 3 need two days and proposal 4 needs 28 days. The compressive strength obtained after the first day for proposals 1, 2 and 3 were appropriate for the demolding and transport, while this was appropriate after the second day for proposal 4. These proposals provided satisfactory performance and useful life.

Table 4. Mechanical properties reached at 1, 2, 3 and 28 days.

	Proposal 1 HA-30/B/20/IIIb Qb	**Proposal 2 HA-25/P/20/IIa**	**Proposal 3 HM-20/P/20/I**	**Proposal 4 HM-20**
Compressive strength				
1 day (kN)	177.93	129.36	83.00	0.10
1 day (N/mm^2)	10.05	7.3	4.7	0.0
2 days (kN)	280.55	203.45	146.16	76.84
2 days (N/mm^2)	15.85	11.5	8.3	4.3
7 days (kN)	399.13	302.25	223.69	118.86
7 days (N/mm^2)	22.6	17.1	12.7	6.7
28 days (kN)	480.97	399.15	246.19	144.79
28 days (N/mm^2)	27.2	22.6	13.9	8.2
Compactness (%) (3)	0.917	0.9313	0.901	0.9374
Real density (kg/m^3)	2227	2209	2173	2045

4. Conclusions

The present work proposes a methodology for designing an artificial reef according to hydrodynamic-structural calculation-construction criteria. Since artificial reefs alter the water velocity field, promoting an appropriate habitat for settling desired species, it is very important to analyze the geometry of the artificial reef carefully. A hydrodynamic analysis based on a CFD simulation was carried out to characterize the velocity field around the artificial reef. This CFD model provided an appropriate renewal of nutrients. A structural analysis based on a FEM simulation was carried out to analyze the structural availability. The installation process was also considered, designing a novel reef suspension method. This model provided that the solutions proposed do not exceed the strength of the concretes analyzed. According to this, these concretes do not need steel reinforcements, which makes the artificial reefs more sustainable. Four concretes using different dosages and replacing aggregates with oyster and mussel shells to make an eco-efficient concrete, were analyzed. The goal was to obtain an ecological concrete that uses a low proportion of cement. An option with a low cement content, proposal 3, was selected as the most appropriate for the present work. The reason is the constructive strategy since proposal 4 needs 2 days in the mold before demolding. This means that the number of molds must duplicate the number of production reefs. In future research, phenomena such as material nonlinearity, geometry nonlinearity and fatigue will be considered.

Author Contributions: Conceptualization, L.C.C.; methodology, M.I.L.G., M.J.R.G., L.C.C., J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and J.C.C.C.; validation, J.L.V., I.A.R., R.V.L. and J.C.C.C.; formal analysis, M.I.L.G., M.J.R.G. and L.C.C.; investigation, M.I.L.G., M.J.R.G. and L.C.C.; resources, M.I.L.G., M.J.R.G., L.C.C., J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and J.C.C.C.; data curation, J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and

J.C.C.C.; writing—original draft preparation, M.I.L.G., M.J.R.G. and L.C.C.; writing—review and editing, M.I.L.G., M.J.R.G. and L.C.C.; visualization, M.I.L.G., M.J.R.G., L.C.C., J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and J.C.C.C.; supervision, M.I.L.G. and L.C.C.; project administration, M.I.L.G., M.J.R.G., L.C.C., J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and J.C.C.C.; funding acquisition, M.I.L.G., M.J.R.G., L.C.C., J.L.V., I.A.R., R.V.L. and J.C.C.C.; software, J.L.V., I.A.R., R.V.L. and J.C.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors gratefully acknowledge the financial support from the regional government of Galicia, Xunta de Galicia, through the project CN-10MMA003CT. This study was also funded through the collaboration agreement between Xunta de Galicia, Universidade da Coruña and the Universidade da Coruña Foundation (FUAC) to give continuity to the previous project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Worm, B.; Lotze, H. Marine biodiversity and climate change. In *Climate Change*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2015.
2. Pörtner, H. Ocean systems. In *Climate Change. Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*; Intergovernmental Panel on Climate Change (IPCC): Cambridge, UK; New York, NY, USA, 2014.
3. Costanza, R. The ecological, economic, and social importance of the oceans. *Ecol. Econ.* **1999**, *31*, 199–213. [CrossRef]
4. Sumaila, U.R.; Bellmann, C.; Tipping, A. Fishing for the future: An overview of challenges and opportunities. *Mar. Policy* **2016**, *69*, 173–180. [CrossRef]
5. Visbeck, M.; Kronfeld-Goharani, U.; Neumann, B.; Rickels, W. Securing blue wealth: The need for a special sustainable development goal for the ocean and coasts. *Mar. Policy* **2014**, *48*, 184–191. [CrossRef]
6. Rickels, W.; Dovern, J.; Quaas, M. Beyond fisheries: Common-pool resource problems in oceanic resources and services. *Glob. Environ. Chang.* **2016**, *40*, 37–49. [CrossRef]
7. FAO. Food and Agriculture Organization of the United Nations. 2017. Available online: http://www.fao.org/fishery/statistics/tuna-catches/es (accessed on 12 January 2022).
8. Lotze, H.K.; Guest, H.; O'Leary, J.; Tuda, A.; Wallace, D. Public perceptions of marine threats and protection from around the world. *Ocean Coast. Manag.* **2018**, *152*, 14–22. [CrossRef]
9. FAO. El Estado Mundial de la Pesca y la Acuicultura 2006. Available online: http://www.fao.org/3/a0699s/a0699s.pdf (accessed on 12 January 2022).
10. Chatterjee, R. Incentives to fish sustainably. *Environ. Sci. Technol.* **2009**, *43*, 239. [CrossRef] [PubMed]
11. FAO. El Estado Mundial de la Pesca y la Acuicultura 2016. Contribución a la Seguridad Alimentaria y la Nutrición Para Todos. 2016. Available online: http://www.fao.org/3/i5555s/i5555s.pdf (accessed on 12 January 2022).
12. Bacher, C. Modelling the effect of food depletion on scallop growth in Sungo Bay (China). *Aquat. Living Resour.* **2003**, *16*, 10–24. [CrossRef]
13. Carral, L.; Alvarez-Feal, J.C.; Tarrio-Saavedra, J.; Rodriguez Guerreiro, M.J.; Fraguela, J.A. Social interest in developing a green modular artificial reef structure in concrete for the ecosystems of the Galician rías. *J. Clean. Prod.* **2018**, *172*, 1881–1898. [CrossRef]
14. Kim, D.; Woo, J.; Yoon, H.S.; Na, W.B. Efficiency, tranquillity and stability indices to evaluate performance in the artificial reef wake region. *Ocean Eng.* **2016**, *122*, 253–261. [CrossRef]
15. Wang, G.; Wan, R.; Wang, X.; Zhao, F.; Lan, X.; Cheng, H.; Tang, W.; Guan, Q. Study on the influence of cut-opening ratio, cut-opening shape, and cut-opening number on the flow field of a cubic artificial reef. *Ocean Eng.* **2018**, *162*, 341–352. [CrossRef]
16. Baine, M. Artificial reefs: A review of their design, application, management and performance. *Ocean Coast. Manag.* **2001**, *44*, 241–259. [CrossRef]
17. Bohnsack, J.; Sutherland, D. Artificial reef research: A review with recommendations for future priorities. *Bull. Mar. Sci.* **1985**, *37*, 11–39.
18. Collins, K.J.; Jensen, A.C.; Lockwood, A.P.M. Fishery enhancement reef building exercise. *Chem. Ecol.* **1990**, *4*, 179–187. [CrossRef]
19. Godoy, E. Fish assemblages and environmental variables on an artificial reef north of Rio de Janeiro, Brazil. *ICES J. Mar. Sci.* **2002**, *59*, S138–S143. [CrossRef]
20. Kim, D.; Woo, J.; Yoon, H.S.; Na, W.B. Wake lengths and structural responses of Korean general artificial reefs. *Ocean Eng.* **2014**, *92*, 83–91. [CrossRef]
21. Carral, L.; Lamas, M.I.; Rodriguez, M.J.; Vargas, A.; Alvarez, J.C.; Lopez, I.; Carballo, R. Configuration methodology for a green variety reef system (AR group) based on hydrodynamic criteria—Application to the Ría de Ares-Betanzos. *Estuar. Coast. Shelf Sci.* **2021**, *252*, 107301. [CrossRef]
22. Liu, Y.; Zhao, Y.; Cui, Y.; Dong, G. Experimental study of the flow field around cube artificial reef. *Ocean Eng.* **2012**, *30*, 103–130.

23. Liu, T.L.; Su, D.T. Numerical analysis of the influence of reef arrangements on artificial reef flow fields. *Ocean Eng.* **2013**, *74*, 81–89. [CrossRef]
24. Shao, W.; Liu, C.; Nie, H.; Zheng, D. Analysis of hydrodynamic characteristics and flow field around artificial reefs. *Chin. J. Hydrodyn.* **2014**, *29*, 580–585.
25. Huang, Y.; Fu, D.; He, W. Three-dimensional numerical simulation on influence of cut-opening ratio of artificial reef on flow effect. *J. Water Resour. Water Eng.* **2014**, *25*, 39–43.
26. Fu, D.; Luan, S.; Zhang, R.; Chen, Y. Two-way analysis of variance of effects of cut-opening ratio and surface shape facing flowing in artificial fish reefs on the flowing field. *J. Dalian Ocean Univ.* **2012**, *27*, 274–278.
27. Perkol-Finkel, S.; Zilman, G.; Sella, I.; Miloh, T.; Benayahu, Y. Floating and fixed artificial habitats: Spatial and temporal patterns of benthic communities in a coral reef environment. *Estuar. Coast. Shelf Sci.* **2008**, *77*, 491–500. [CrossRef]
28. Piedracoba, S.; Álvarez-Salgado, X.A.; Labarta, U.; Fernández-Reiriz, J.M.; Gómez, B.; Balseiro, C. Water flows through mussel rafts and their relationship with wind speed in a coastal embayment (Ría de Ares-Betanzos, NW Spain). *Cont. Shelf Res.* **2014**, *75*, 1–14. [CrossRef]
29. Smith, S.V.; Roy, K.J.; Schiesser, H.G.; Shepherd, G.L.; Chave, K.E. Flux of suspended calcium carbonate ($CaCO_3$), Fanning Island Lagoon. *Pacific Sci.* **1971**, *25*, 206–221.
30. Aller, R.; Dodge, R. Animal-sediment relations in a tropical lagoon: Discovery Bay, Jamaica. *J. Marit. Res.* **1974**, *32*, 209–232.
31. Loya, Y. Community structure and species diversity of hermatypic corals at Eliat, Red Sea. *Mar. Biol.* **1972**, *13*, 100–123. [CrossRef]
32. Bak, R.P.M. Lethal and sublethal effects of dredging on reef corals. *Mar. Pollut. Bull.* **1978**, *9*, 14–16. [CrossRef]
33. Carral Couce, L.; Rodriguez Guerreiro, M.; Fraguela Formoso, J.; Alvarez Feal, J.; Filgueira Vizoso, A. Green artificial reef proarr: Repopulation of coastal ecosystems and waste recycler of the maritime industries. In Proceedings of the 25th Pan-American Conference of Naval Engineering—COPINAVAL, Panama City, Panama, 16–19 October 2017; pp. 363–373.
34. Carral, L.; Camba Fabal, C.; Lamas Galdo, M.I.; Rodríguez-Guerreiro, M.J.; Cartelle Barros, J.J. Assessment of the materials employed in green artificial reefs for the Galician estuaries in terms of circular economy. *Int. J. Environ. Res. Public Health.* **2020**, *17*, 8850. [CrossRef]
35. Carral, L.; Cartelle Barros, J.J.; Carro Fidalgo, H.; Camba Fabal, C.; Munín Doce, A. Greenhouse gas emissions and energy consumption of coastal ecosystem enhancement programme through sustainable artificial reefs in Galicia. *Int. J. Environ. Res. Public Health.* **2021**, *18*, 1909. [CrossRef]
36. Carral, L.; Alvarez-Feal, C.; Jesús Rodríguez-Guerreiro, M.; Vargas, A.; Arean, N.; Carballo, R. Methodology for positioning a group of green artificial reef based on a database management system, applied in the estuary of Ares-Betanzos (NW Iberian Peninsula). *J. Clean. Prod.* **2019**, *233*, 1047–1060. [CrossRef]
37. Real Decreto 1247/2008, de 18 de julio, por el que se aprueba la instrucción de hormigón estructural (EHE-08). Available online: https://www.boe.es/eli/es/rd/2008/07/18/1247 (accessed on 12 January 2022).
38. Rodríguez-Guerreiro, M.J.; Álvarez-Feal, J.C.; Fraguela-Formoso, J.A.; Castro-Santos, L.; Carral-Couce, L. Application of a general pattern of colonization of a 'verde-PROARR' artificial reef in the Ría de Ares-Betanzos (Spain). In Proceedings of the VI International Ship Design & Naval Engineering Congress (CIDIN) and XXVI Pan-American Congress of Naval Engineering, Maritime Transportation and Port Engineering—COPINAVAL, Cartagena de Indias, Colombia, 13–15 March 2019; 2019; pp. 365–372.
39. Layman, C.A.; Allgeier, J.E. An ecosystem ecology perspective on artificial reef production. *J. Appl. Ecol.* **2020**, *57*, 2139–2148. [CrossRef]
40. Fossheim, M.; Tande, K.S.; Semenova, T.; Timonin, A. Capelin larvae (Mallotus villosus) and community structure of zooplankton off the coast of northern Norway. *J. Plankton Res.* **2006**, *28*, 585–595. [CrossRef]
41. Lishchenko, F.; Perales-Raya, C.; Barrett, C.; Oesterwind, D.; Power, A.M.; Larivain, A.; Laptikhovsky, V.; Karatza, A.; Badouvas, N.; Lishchenko, A.; et al. A review of recent studies on the life history and ecology of European cephalopods with emphasis on species with the greatest commercial fishery and culture potential. *Fish. Res.* **2021**, *236*, 105847. [CrossRef]
42. Herrera, R. Dinámica de las comunidades bentónicas de los arrecifes artificiales de Arguineguín (Gran Canaria) y Lanzarote. 1998. Available online: https://dialnet.unirioja.es/servlet/tesis?codigo=425 (accessed on 12 January 2022).
43. Franquet, F.; Brito, A. Especies de interés pesquero de Canarias. Consejería de Pesca y Transportes del Gobierno de Canarias. *St. Cruz. Tenerife* **1995**, 101–108.
44. Spanier, E. Artificial reefs off the Mediterranean Coast of Israel. In *Artificial Reefs in European Seas*; Springer: Dordrecht, The Netherlands, 2000; pp. 1–19.
45. Camba, C.; Mier, J.L.; Carral, L.; Lamas, M.I.; Álvarez, J.C.; Díaz, A.M.; Tarrío, J. Erosive degradation study of concrete augmented by mussel shells for marine construction. *J. Mar. Sci. Eng.* **2021**, *9*, 1087. [CrossRef]
46. Kim, H.S.; Kim, C.G.; Na, W.B.; Woo, J.; Kim, J.K. Physical and chemical deterioration of reinforced concrete reefs in Tongyeong coastal waters. *Mar. Technol. Soc. J.* **2008**, *42*, 110–118. [CrossRef]
47. Kim, H.S.; Kim, C.G.; Na, W.B.; Kim, J.K. Chemical degradation characteristics of reinforced concrete reefs in South Korea. *Ocean Eng.* **2008**, *35*, 738–748. [CrossRef]