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# Biological and Hydrodynamic Aspects for the Design of Artificial Reef Modules for Cephalopod Molluscs in the Ares-Betanzos Estuary

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**Abstract:** The design of an artificial reef (AR) module for improving the fishing productivity of cephalopod molluscs in the Ares-Betanzos estuary (Galicia, NW Spain) is addressed in this study. At the time of deciding on a suitable AR design, it is first necessary to assess how the different marine species use ARs so that it is possible to define the complexity of the design: its size and shape, as well as the number of nest cavities it should present and the dimensions of these cavities. Thus, two different cubic modules are proposed, both with an edge of 1500 mm. One of them can be considered as the standard design, while the other has been modified to include four open cylindrical holes. Several tools are employed to assess both proposals. Moreover, a CFD (computational fluid dynamics) model is performed. The results suggest that the flow in the interior of the tubes provides a suitable environment for cephalopod molluscs, given that circulation is produced, guaranteeing nutrient renewal. As further contributions, the present work determines how the capture of cephalopods and other species in Galician fish markets has evolved and reviews the habitat preferred by cephalopods in Galicia. It also proposes and compares two AR modules.

**Keywords:** artificial reef; nest cavity; cephalopod; mollusc; upwelling; CFD



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## 1. Introduction

Pollution and overfishing threaten marine habitats, leading to their degradation, which in turn makes it difficult to exploit their resources [1]. By way of example, cephalopods, a species of great importance all over the world [2], particularly in Galicia (NW Spain) [3], have experienced a major decline due to continued overfishing [4,5]. While public administrations have developed strategies to curtail biomass loss in marine ecosystems, studies show that those strategies are not always sufficient [5,6]. Consequently, new solutions, such as installing artificial reefs (ARs) specifically designed for certain marine species [5,7–9], must be proposed to protect marine ecosystems and to promote artisanal fishing.

In this context, the concentration of animal life around an AR mainly depends on the following four factors: (i) the aggregation behaviour of the species, (ii) the availability of shelter and nutrients, (iii) the tendency of the species to concentrate close to a solid object that breaks the uniformity of the environment, and (iv) the distance between the module and the coast [10,11]. The colonisation and evolution of AR benthic communities are directly related to the module design and, in particular, to its capacity to increase the available habitat, which is affected by the number of cavities and their sizes, as well as the AR design and orientation [10,12–15]. Therefore, Carral et al. [5] proposed the installation of ARs in the Ares-Betanzos estuary (Galicia, NW Spain) with the aim of reversing the

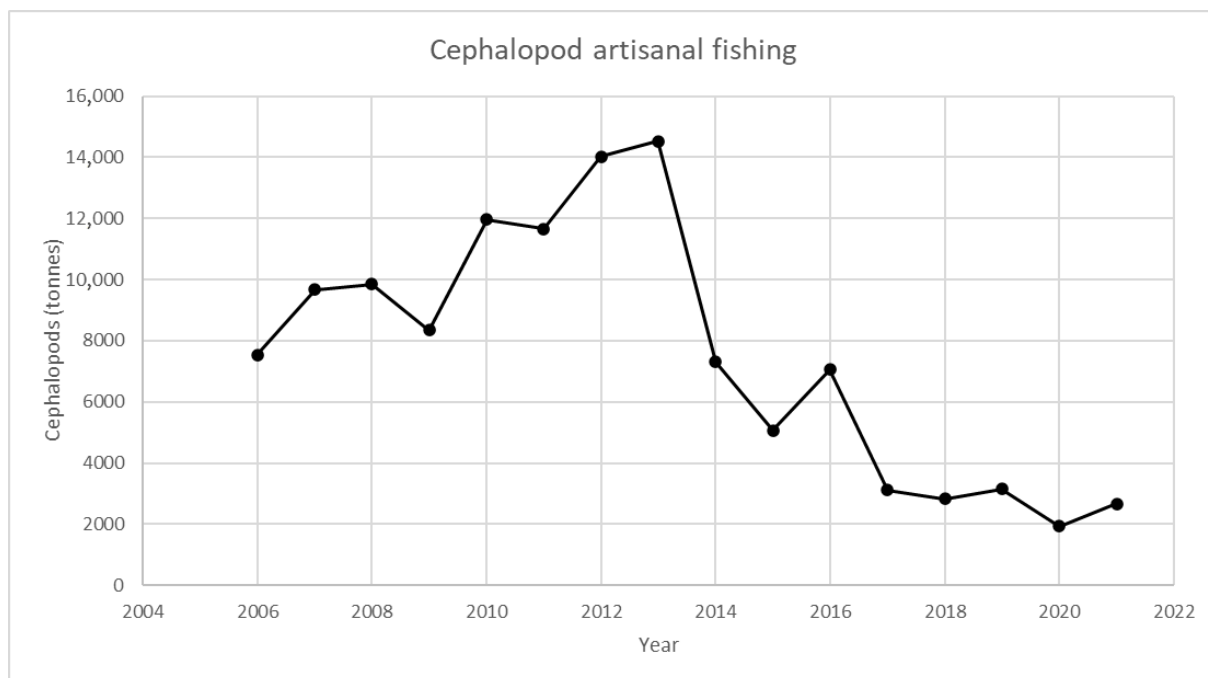
decline in artisanal fishing. This study tries to go one step further by proposing specific AR designs to improve the breeding habitat of cephalopod molluscs in the same estuary.

### 1.1. The Problem of Cephalopods in Galicia: Evolution of Artisanal Fishing

Cephalopods play a crucial role in Galicia [16–19]. The species with the greatest socio-economic impacts on the Iberian Peninsula are the common octopus (*Octopus vulgaris*), cuttlefish (*Sepia officinalis*), and squid (*Loligo vulgaris*) [20].

Figures 1–4 provide an analysis of how cephalopod artisanal fishing evolved in all the Galician fish markets for the 2006–2021 period. The data are based on the official statistics provided by *Pesca de Galicia* [21]. It is necessary to clarify that, despite the efforts of the local administrations, limited information is available on the relative abundance of Galician marine ecosystems [22]. Furthermore, Figures 1–4 only include artisanal fishing. In other words, the figures derived from recreational fishing, as well as other catches that do not reach fish markets, were excluded.

If the figures for 2013 and 2021 are compared (Figures 1 and 2), the landing of certain species has been on a downward trend, resulting in an 82% reduction in cephalopods. Furthermore, if the year 2021 is compared with the average number of tonnes for the whole period under study, the reduction is close to 65%. Figure 1 shows the landings in tonnes of cephalopods (*O. vulgaris*, *Eledone cirrhosa*, *S. officinalis*, *L. vulgaris*, and *Illex coindetti*) in all fish auctions throughout Galicia. There are two clearly differentiated stages. In the first one, from 2006 to 2013, landings experienced a continuous increase, with the exceptions of 2009 and 2011. However, the latter period is not significant, since 2010 and 2011 present nearly the same results. Nevertheless, from 2013 onwards, the trend is the opposite. The volume of landings decreased, showing how recovery efforts were unsuccessful. In fact, the highest value was reached in 2013 (14,500 tonnes), while the lowest one was recorded in 2020 (2000 tonnes).

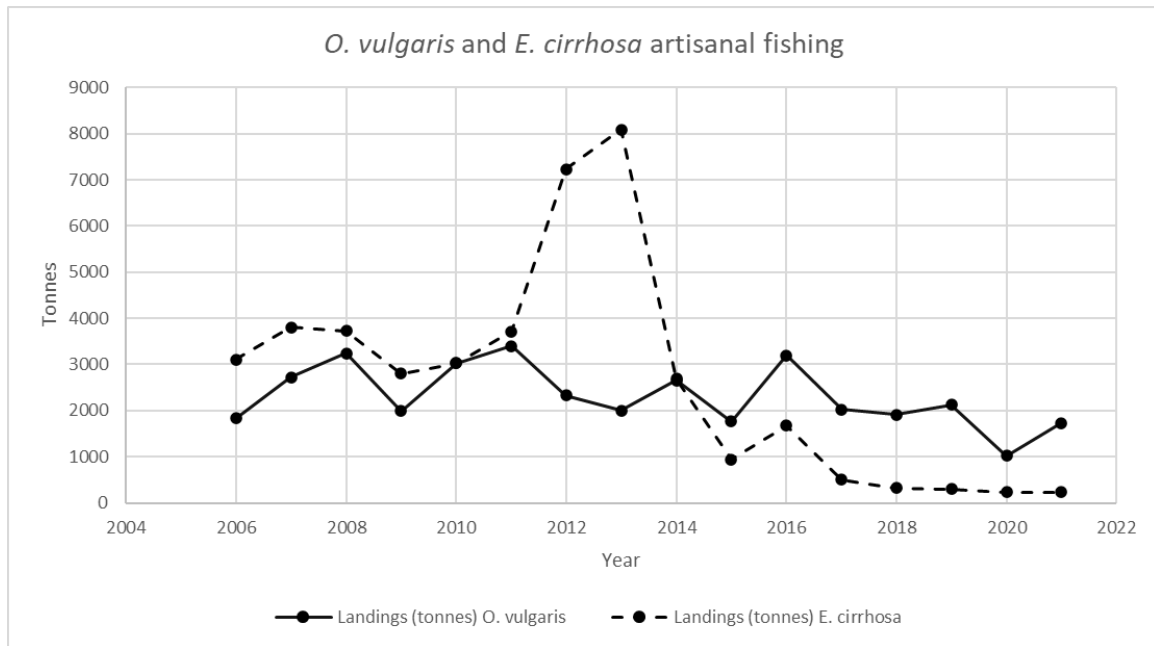


**Figure 1.** Cephalopod landing in Galician fish markets. Source: own based on Pesca de Galicia [21].

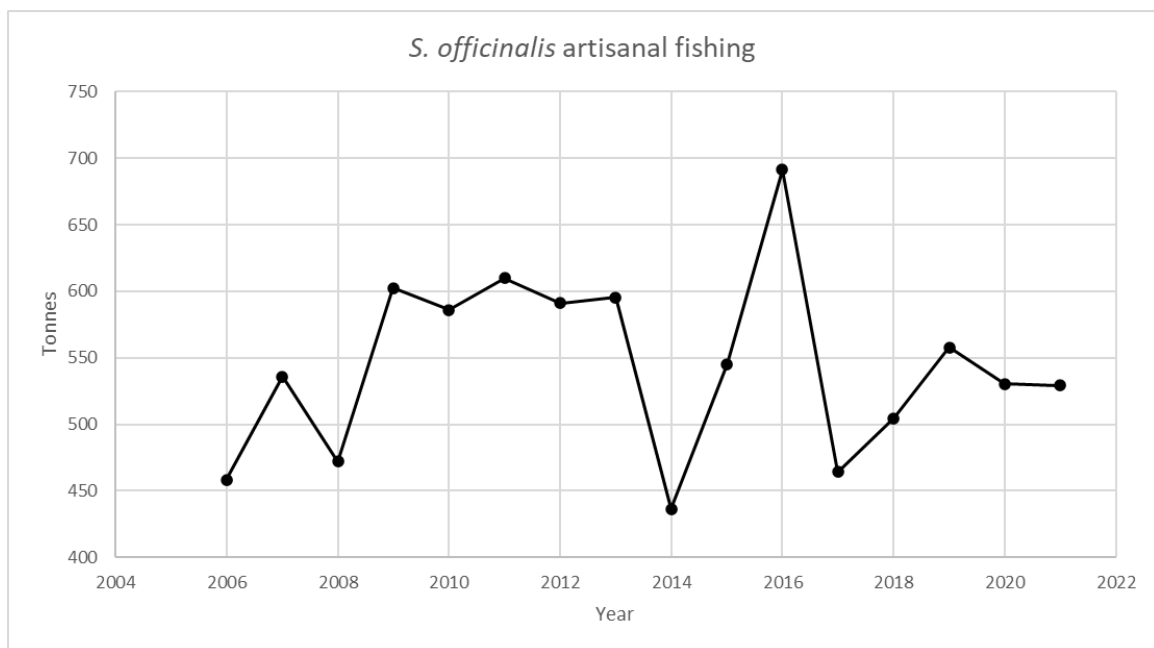
In Figure 2, the reader can find the landing evolution for both *O. vulgaris* and *E. cirrhosa* in Galician fish markets for the same time period. *O. vulgaris* decreased by 25% if 2021 is compared with the average value for the 2006–2021 period, while *E. cirrhosa* experienced an even greater decline (about 90%).

Similarly, Figure 3 includes the evolution for *S. officinalis*. Finally, Figure 4 shows the same information for the *L. vulgaris* and *I. coindetti* species. The former shows a decline of close to 70% if 2011 and 2021 are compared, while the latter shows a decrease of 98% when the figures for 2014 and 2021 are contrasted.

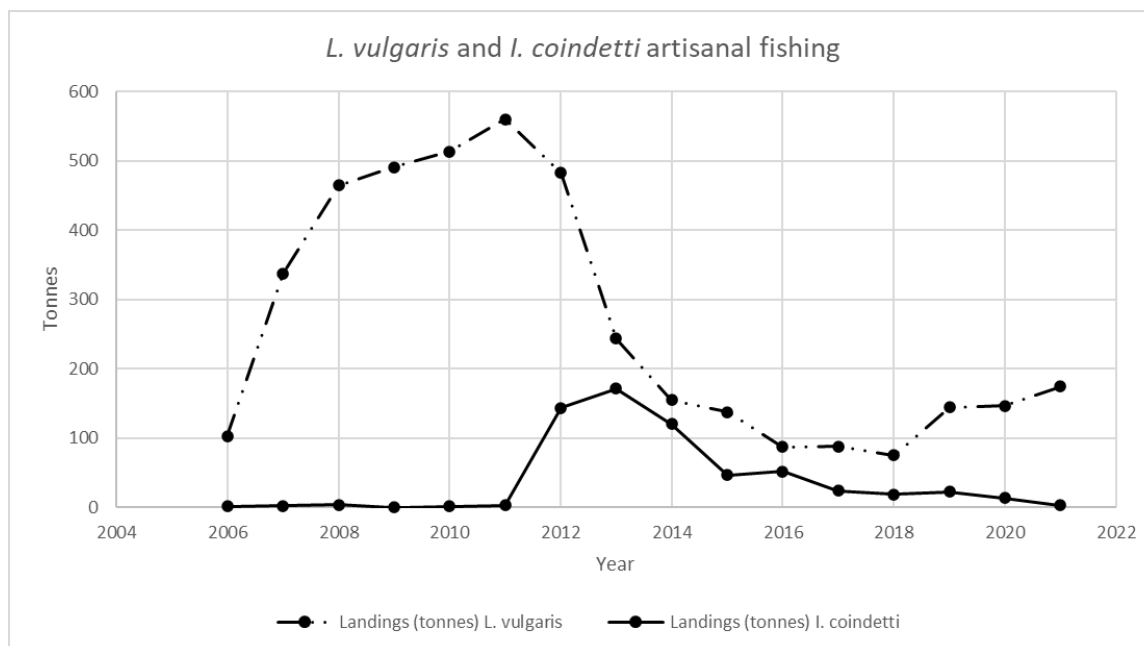
There are several reasons for this decline in the landing of these and other species. For example, overexploitation, the discharge of pollutants into the sea, the proliferation of certain biotoxins and bacteria, the appearance of invasive species and, in general, pollution (climate change, acidification of seas, among other environmental impacts).



**Figure 2.** *O. vulgaris* and *E. cirrhosa* landing in Galician fish markets. Source: own based on Pesca de Galicia [21].



**Figure 3.** *S. officinalis* landing in Galician fish markets. Source: own based on Pesca de Galicia [21].



**Figure 4.** *L. vulgaris* and *I. coindetti* landings in Galician fish markets. Source: own based on Pesca de Galicia [21].

### 1.2. Natural Breeding Habitats for Cephalopods

The natural habitat preferred by each species must meet several conditions to ensure (i) stocks are improved, (ii) a protective refuge is provided for adult individuals with reproductive capacity, (iii) the biomass in adjacent areas increases due to larval dispersal, and (iv) recruitment occurs to allow juveniles to grow [23]. These objectives should also be met in ARs [10].

In general, cephalopods are very sensitive to environmental changes [24], temperature being a key factor for the biological processes of these species. Thus, migrations take place in the quest for conditions more favourable to their development [25]. Nevertheless, some species (*O. vulgaris* and *L. vulgaris*) show greater adaptability to changing environmental conditions [26].

In the particular case of *O. vulgaris*, various physical and biotic factors condition its density and distribution patterns. The most important ones are (i) temperature [27], (ii) seafloor characteristics as well as the availability and type of shelter [28–31], and (iii) both nutrient supply and fishing pressure [32,33]. In fact, temperature changes hinder the survival of *O. vulgaris* in deep waters and, according to Avendaño et al. [24], its exploitation should be limited to depths not exceeding 30 m.

In Galicia, it is observed that *O. vulgaris* lives at depths of between 5 and 21 m [16,27,34] along rocky bottoms with cavities of varying sizes and shapes to protect it from predators and competitors as well as to facilitate egg-laying [30,35]. *O. vulgaris* needs hard structures on soft substrates or penetrable areas on hard substrates. The diameter of the natural cavities ranges from 17 to 19 cm. Significant differences between the size and the cavity diameter of *O. vulgaris* were not found. There are also linked cavities, which can be used for several generations as “permanent cavities” [34]. Most of the cavities are found at depths of 5–10 m; the distance between cavities is close to 260 m<sup>2</sup> (3.38 individuals per 1000 m<sup>2</sup>) [34]. At greater depths (15–21 m), scavenging species (starfish (*Asterias rubens*) and sea urchins (*Paracentrotus lividus*), among others) appear in all cavities. Used by females to cover the entrance of the cavities, stones and shells are common in *O. vulgaris* habitats. Guerra et al. [34] stated that half of the cavities could be permanent: narrow and deep holes whose walls are reinforced with shells.

Female *O. vulgaris*, taking advantage of warm temperatures in spring and summer, move to the coast, looking for sheltered places to lay their eggs, away from fishing areas [36–39]. After egg-laying, females fix the eggs to a common trunk or cordon at the base of the peduncles by using a sticky substance, generating clusters of variable shape and size, which are placed on the cavity ceiling [27]. Females then aerate, clean, and care for the eggs until they hatch. At this time, the female intermittently opens and closes the cavity to facilitate the exit of groups of hatchlings [40]. While the laying process may extend over days or even weeks [27], the breeding period can last for up to five months [27,41], and the hatching process can take a month and a half [24,27,42].

On the Galician coasts, the cavities used by *O. vulgaris* are at temperatures ranging from 12.9 to 19 °C [27]. The number of female egg chains can be equal to 160, and the total number of spawned eggs can exceed 200,000. The embryonic development time during the breeding period depends on the (i) laying date, (ii) temperature, (iii) position of the chain in the egg group, and (iv) position of the egg in the chain. Embryos in the basal and upper-middle parts of the egg chain are generally less developed than those occupying other positions. On the other hand, dissolved oxygen is essential to the embryonic development of egg chains [27,43,44], since large egg masses tend to obstruct the flow with less flow through them.

Regarding *S. officinalis*, the following factors should be taken into account at the time of defining an adequate breeding habitat in Galicia: (i) the type of substrate, since females carefully select where they lay their eggs, (ii) the type of zone, (iii) the depth, (iv) the temperature, and (v) the season [3,16]. *S. officinalis* also prefers rocky bottoms, with an abundance of Gorgonians where females lay their eggs (between 3500 and 6000) creating clusters similar to black grapes [3,45]. The presence of phanerogams also facilitates the survival of the species [3]. The laying process occurs close to the coast [46], with depths varying from 8 to 13 m. Occasionally, egg-laying can happen at depths of up to 25 m. The breeding period lasts for 40 to 45 days, with optimum temperatures varying from 12.5 to 14.75 °C [20]. The spawning season runs from December to April.

In the case of *L. vulgaris*, it is possible to find eggs fixed onto the ceiling of a rocky cavity [16]. This animal also has a predilection for artificial substrates, such as mooring lines or abandoned fishing nets. The egg-laying process, in clusters of eggs, is similar to that of *S. officinalis* [20]. Spawning activity occurs throughout the year [23], although most of the laying happens during the spring. Eggs are only found at depths of 18 to 50 m. The depth is closely related to the temperature. In other words, during the months with high temperatures, it is possible to find eggs at depths of 40–50 m, while in cold months, eggs only appear in shallow waters at depths of about 18 m [23]. The breeding period lasts between 40 and 45 days at 12–14 °C, 30 days at 17 °C, and 25 days at 22 °C [20]. Depending on their own size, females lay 3500 to 6000 eggs [20].

### 1.3. Objectives and Key Innovative Aspects

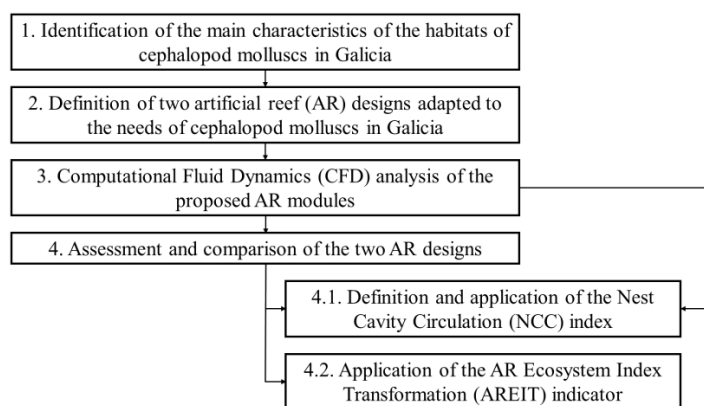
The main objective of this article is to design an artificial reef module specifically adapted to the needs of cephalopod molluscs in the Ares-Betanzos estuary. More specifically, this aim is divided into the following subobjectives:

- Defining suitable AR geometries to improve primary production by increasing autotrophic sources of substrate and nutrient circulation so that these reefs can function as a refuge and provide space for recruitment with available nest cavities.
- Performing a CFD analysis of the water flows (upwelling) generated in both the nest cavities and the vertical surfaces of the previously defined designs.
- Establishing a new tool for assessing the extent to which each design favours nutrient circulation: the Nest Cavity Circulation (NCC) index. The NCC is partially based on the results obtained in the CFD analysis.
- Comparing the AR designs by applying two indicators: the NCC index and the existing AREIT (AR Ecosystem Index Transformation) tool.

This work complements other studies conducted by the same research team with the objective of designing AR modules according to sustainability criteria [17–19,47,48].

## 2. Materials and Methods

Figure 5 shows a flowchart with the general steps followed in this study. The first phase was to identify the main characteristics that breeding habitats have to present for the most relevant cephalopod molluscs in Galicia. To this end, a state-of-the-art review was carried out (Section 1.2). After that, two AR designs, specifically adapted to the needs of cephalopod molluscs in Galicia, were proposed. Both modules were studied through a CFD analysis in the third stage. Finally, both designs were compared by means of two different indicators: the new *NCC* and existing *AREIT* indices.



**Figure 5.** Flowchart of the main steps followed in this study.

### 2.1. Proposed Artificial Reef Designs for the Embryonic Development of Cephalopod Molluscs in Galicia

Among key parameters for an AR to succeed in its purpose [10,49–55] are the design, spatial distribution, and the number and characteristics of the holes or nest cavities. The reefs that are the most complex in terms of geometry tend to be the most species-rich [10,54,56].

The free volume in most of the existing artificial reef modules is between 70 and 98% of the total volume [57,58]. The ideal size for a cavity may be between 150 and 1500 mm [59,60]. On the other hand, most species avoid closed cavities with a single opening. However, cephalopods are an exception [10]. In general, cubic modules with cylindrical holes or cavities ranging in size from 200 to 400 mm at a depth of 700 mm provide a stable substrate for the attachment of eggs, being suitable for the survival of hatchling cephalopods.

Consequently, a suitable reef module design for cephalopods could have either a cubic or a cylindrical geometry [10,14,60–63] with cubic (200–700 mm) or cylindrical cavities (200–1000 mm diameter) [10,13,59,60,62]. Each cavity should also present one or two cylindrical openings [10,60–63]. Table 1 summarises, in a qualitative way, the extent to which each of these possibilities impacts the egg-laying and embryonic development of different cephalopods.

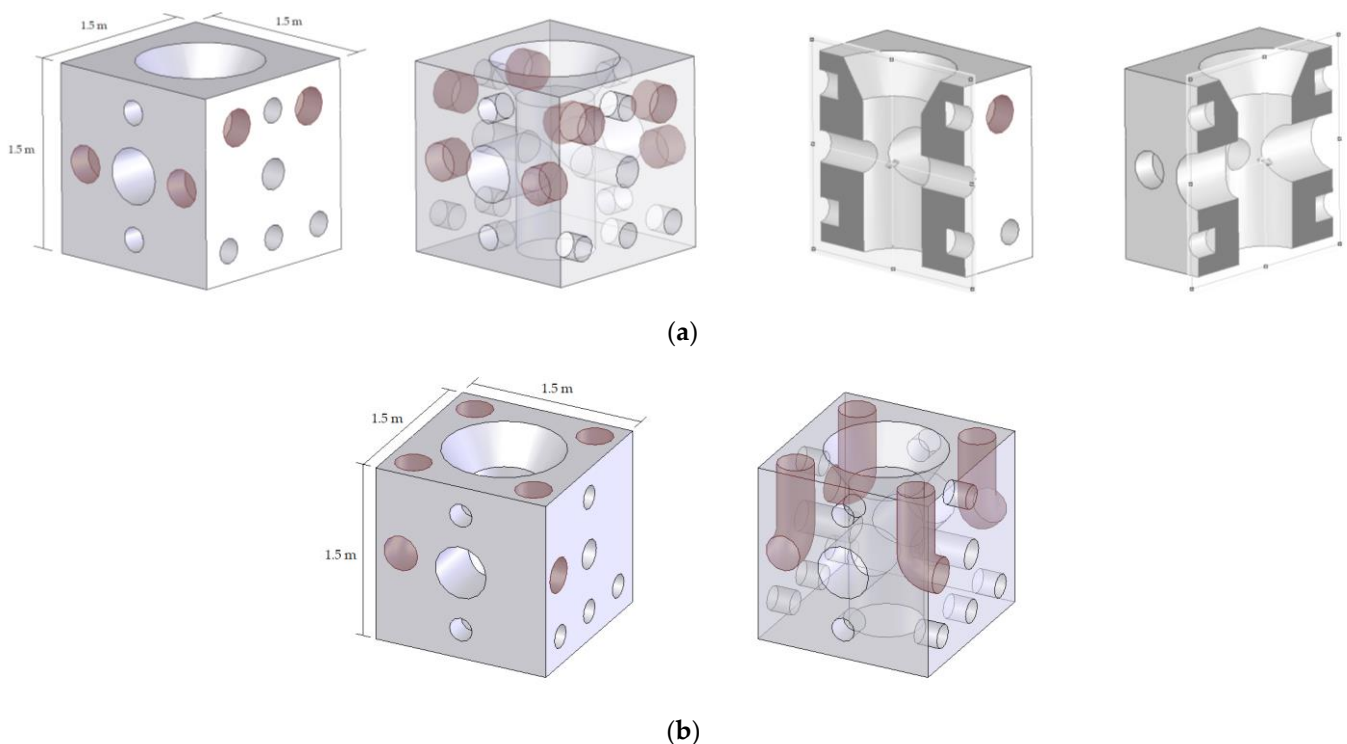
**Table 1.** Impact of each of the module design characteristics on the egg-laying and embryonic development of different cephalopods.

Characteristic	Species		
	<i>Octopus vulgaris</i>	<i>Sepia officinalis</i>	<i>Loligo vulgaris</i>
Cubic geometry	Optimal	Optimal	Sufficient
Cylindrical geometry	Sufficient	Sufficient	Optimal
Cavity with one opening	Optimal	Optimal	Sufficient
Cavity with two openings	Sufficient	Sufficient	Optimal



Two cubic modules with an edge of 1500 mm are proposed. The cubic shape was selected with the characteristics of the Ares-Betanzos estuary in mind. This estuary presents a stable current direction [64]; the cubic AR shape can be positioned according to the prevailing current direction. It is worth mentioning that, in other places where the current direction is variable, a cylindrical AR shape would provide omnidirectionality. On the other hand, the size and shape of the module are not particularly decisive factors for attracting cephalopod molluscs, as long as the AR unit provides adequate circulation of nutrients, nest cavities with the appropriate characteristics for the targeted species, and surfaces with adequate solar energy collection. In fact, size and shape are usually conditioned by transport and installation requirements. One of the AR modules can be considered as the standard or starting design (Figure 6), as proposed in previous works [12,65,66]. The other, which is the modified one, includes four cylindrical, open L-shaped holes with diameters of 300 mm, as seen in Figure 6. The differences between both designs are indicated in red in this figure. The modified design was proposed in view of the cephalopods' needs for substrates and nest cavities to facilitate the development of their life cycle. In both cases, the size ( $1500 \times 1500 \times 1500$  mm) and shape of the concrete modules were proposed, taking into account possible transport, construction, and logistical limitations. Both modules have an interior vertical hole with a diameter of 600 mm, which is linked to two horizontal holes, 250 and 450 mm in diameter. Moreover, nest cavities with diameters of 200 and 300 mm have been added to make space for specific organisms. At the time of proposing a module design, it is important to take into account that the number and size of nest cavities must not compromise the structural integrity of the AR [65].

Two sides of the modules have smooth surfaces, providing verticality in a way that favours the upwelling effect, the movement of nutrients from deep layers to shallower ones. All holes serve as shelters and, at the same time, facilitate water currents, which are also necessary for embryonic development, particularly for *L. vulgaris* [10].



**Figure 6.** AR proposals: (a) standard design and (b) modified design for cephalopods.

### 2.2. Computational Fluid Dynamics (CFD) Analysis

As indicated previously, a CFD model was carried out to study the AR from a hydrodynamic point of view. The CFD model was performed through the open software OpenFOAM. The model is based on the RANS (Reynolds-averaged Navier–Stokes) equations. The standard  $k-\epsilon$  was employed as a turbulence model. Water was considered a Newtonian, incompressible, and single-phase fluid. The temporal performance was established as steady. Taking these aspects into account, the governing equations of the conservation of mass and momentum are those illustrated by Equations (1) and (2), respectively. The pressure–velocity coupling was treated through the SIMPLE (Semi Implicit Methods Pressure Linked Equations) algorithm. A second-order upwind scheme was used to discretize the governing equations.

$$\frac{\partial u_i}{\partial x_j} = 0 \tag{1}$$

$$\rho \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \tag{2}$$

In the equations above,  $u_i$  and  $u_j$  represent the velocity components for  $x$ ,  $y$ , and  $z$ ,  $\rho$  is the density,  $p$  is the pressure, and  $\tau_{ij}$  is the viscous stress tensor.

The computational domain and boundary conditions corresponding to the standard design are shown in Figure 7a. A  $20,000 \times 5000 \times 4000$  mm domain was employed with the AR inside. The computational domain and boundary conditions corresponding to the modified design are shown in Figure 7b. Since the modified design is not symmetrical, a  $20,000 \times 5000 \times 8000$  mm domain was employed. The current velocity was modelled as an inlet boundary condition. A value of 0.05 m/s was set according to typical values in this estuary [64]. The reef and seafloor were modelled as no-slip surfaces and the lateral and upper surfaces as free-slip.

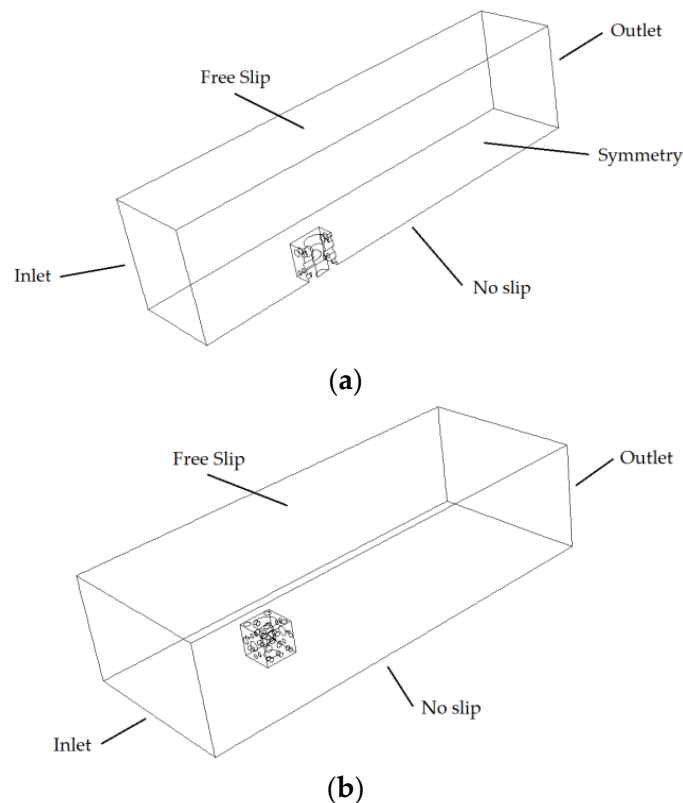


Figure 7. Computational domain and boundary conditions; (a) standard design; (b) modified design.



The standard design was validated with experimental results for a towing tank [66]. Regarding the orientation with respect to the current velocity, the following two options were considered.

- Orientation A: 250 mm diameter hole parallel to the current velocity.
- Orientation B: 450 mm diameter hole parallel to the current velocity.

As is indicated in Section 2.3, the effects of the upwelling, back eddy, and circulation (inside the AR) were considered. In order to quantify these effects, the following parameters were employed.

- Upwelling volume ( $V_{upwelling}$ ): volume of the vortex formed above the AR where the x-component of the velocity is negative.
- Back eddy volume ( $V_{backeddy}$ ): volume of the vortex formed behind the AR where the x-component of the velocity is negative.
- Average flow velocity inside the AR ( $v_a$ ): average flow velocity considering only the volume inside the AR.

A mesh independence analysis was carried out. The mesh independence analysis consisted of comparing these parameters using different meshes. Three meshes were tested for the standard AR design: mesh 1 (with around  $1.4 \times 10^6$  elements depending on orientation A or orientation B), mesh 2 (with around  $2.2 \times 10^6$  elements depending on orientation A or orientation B), and mesh 3 (with around  $2.9 \times 10^6$  elements depending on orientation A or orientation B). Since the symmetry was not applied in the modified AR design, another three meshes with approximately double the elements were also tested for the modified AR design. Regarding the near-wall cells, a boundary layer with five layers was employed with a layer growth rate of 1.2. The size of the first layer provided  $y+$  values of between 30 and 300 for all cases analysed. The results are summarised in Table 2. As can be seen, the results obtained with these meshes were too similar, showing their adequacy. According to this, mesh 3 was selected for the present work.

**Table 2.** Results of the mesh independence study.

Design	Mesh	Orientation	$V_{upwelling}$ (m <sup>3</sup> )	$V_{backeddy}$ (m <sup>3</sup> )	$v_a$ (m/s)
Standard	Mesh 1 standard (symmetry)	Orientation A	0.181	0.593	0.013
		Orientation B	0.146	0.472	0.023
	Mesh 2 standard (symmetry)	Orientation A	0.188	0.617	0.014
		Orientation B	0.152	0.491	0.024
	Mesh 3 standard (symmetry)	Orientation A	0.189	0.619	0.014
		Orientation B	0.152	0.492	0.024
Modified	Mesh 1 modified (no symmetry)	Orientation A	0.196	0.625	0.021
		Orientation B	0.158	0.523	0.029
	Mesh 2 modified (no symmetry)	Orientation A	0.204	0.650	0.022
		Orientation B	0.164	0.544	0.030
	Mesh 3 modified (no symmetry)	Orientation A	0.206	0.652	0.022
		Orientation B	0.165	0.546	0.031

### 2.3. AREIT and NCC Indices

Carral et al. [12] proposed a new index (AREIT: AR Ecosystem Index Transformation) to evaluate the transformation that the ecosystem can experience with the installation of an AR module. A summary of the most relevant aspects of the AREIT is included below. However, the reader is also referred to Ref. [12] for more information.

This index serves to compare different AR designs according to three transcendence aspects for the ecosystem: energy, nutrients, and habitat for settling individuals. The AREIT

index incorporates three intermediate indexes: *EM* (Energy Modification), *NM* (Nutrient Modification), and *HM* (Habitat Modification), as shown in Equation (3) [12]. On the other hand, it is important to note that the *AREIT* and its three subindices are relative indicators. In other words, they serve to measure the performance of a new design in relation to a base one. Consequently, all subindices for the base design will adopt a value of 1, while the *AREIT* will be equal to 3. The new design will obtain values greater than 1 for the subindices if its positive impact on the ecosystem is higher than that of the base design. Values lower than 1 will be obtained otherwise. Similarly, the *AREIT* index for the new design will be higher than 3 if it outperforms the base design. The opposite is also possible. In this case, the standard AR module was defined as the base design.

$$AREIT = EM + NM + HM \tag{3}$$

The *AREIT* index presents limitations when two designs, such as the ones proposed in this study, are being compared. In particular, the index is not able to differentiate between open and closed cavities. For this reason, certain species prefer cavities with a single opening, while others prefer completely open cavities. Furthermore, it also fails to adequately assess the circulation and its potential positive impact on nutrients and the habitat. A new index is needed to fill these gaps: the one related to Nest Cavity Circulation (*NCC*). This index consists of two intermediate indices: *NCM* (Nutrient Circulation Modification) and *HCM* (Habitat Circulation Modification), Equation (4).

$$NCC = NCM + HCM \tag{4}$$

The *NCM* index is made up of three terms, since the hydrodynamic effect that modifies nutrient circulation is produced by three phenomena: upwelling ( $U_{effect}$ ) and back eddy ( $B_{effect}$ ) effects as well as circulation inside the interior cavities ( $I_{effect}$ ), Equation (5). The reader should bear in mind that iron, nitrogen, and phosphorus are some of the nutrients present in marine ecosystems. They belong to the first trophic level of the marine food chain, and they move within water flows. Furthermore, these nutrients serve as food for other species that are at the bottom of the food chain. These species serve as food for other species. Consequently, it seems reasonable to assume that nutrient renewal and water circulation around and inside the AR module are correlated. The upwelling region can be defined as the one corresponding to the vortex formed above the AR. It is important to remark that the upwelling phenomenon favours the vertical exchange of seawater, increasing the transport of nutrients and also enhancing their diffusion around the AR module. In other words, this upwelling effect is likely to attract different species, including cephalopod molluscs. The back eddy region comprises the region corresponding to the vortex behind the reef. Both the upwelling and back eddy regions play roles in the delivery of nutrients.

$$NCM = U_{effect} + B_{effect} + I_{effect} \tag{5}$$

The three effects included in Equation (5) are measured using a scale of three values: 1 (poor result), 2 (acceptable result), and 3 (optimal result). These values are assigned on the basis of the circulation results obtained through CFD analyses. Consequently, the *NCM* varies from 3 (the worst possible result) to 9 (the best possible performance). As indicated previously, in the particular case of the  $U_{effect}$  and  $B_{effect}$ , the values are assigned according to the volume of the region where the x-component of the velocity is negative [67]. The volume of this region is normalised to the total volume of the module, and the following values are established for the  $U_{effect}$ : 1 if the volume of the upwelling region ( $V_{upwelling}$ ) is equal to or less than 5% of the total volume of the module ( $V_{AR}$ ), 3 if  $V_{upwelling}$  is equal to or greater than 10% of the value of  $V_{AR}$ , and 2 in all other cases. Similarly, the values for  $B_{effect}$  are defined according to the following rules: 1 if the volume of the back eddy effect ( $V_{backeddy}$ ) is equal to or less than 10% the value of  $V_{AR}$ , 3 if  $V_{backeddy}$  is equal to or higher than 15% the value of  $V_{AR}$ , and 2 in all other cases. The value for the circulation inside the

interior cavities ( $I_{effect}$ ) is defined from the average flow velocity inside the module ( $v_a$ ) and from the current velocity ( $v_c$ ). The closer  $v_a$  is to  $v_c$ , the better the circulation of nutrients. If the average flow velocity ( $v_a$ ) is 0.25 times the current velocity ( $v_c$ ) or less, the worst possible value (1) is assigned. If the average flow velocity is more than 0.25 times  $v_c$  but less than half of the value adopted by the current velocity, the acceptable value (2) is given. If  $v_a$  is 0.5 times the current velocity or higher, the best possible result (3) is adopted.

On the other hand, the HCM index takes three aspects into consideration: (i) the number of nest cavities ( $N_{NC}$ ), (ii) their size ( $S_{NC}$ ) and (iii) their type ( $T_{NC}$ ) (open or closed), Equation (6). Analogously to the NCM, each one of these terms is assessed through a dimensionless scale of values: 1 (poor result), 2 (acceptable result), and 3 (optimal result). It is important to note that the  $N_{NC}$  is a comparative metric. In other words, when several designs are being compared, the best one adopts a value of 3 (optimal result). The results for the other designs are assigned according to a set of rules. For instance, the AR module with the largest number of cavities adopts a value of 3 for the  $N_{NC}$ . The other designs take a value of 1 if there are no cavities or if the number of cavities is between zero and one-third of the largest number of cavities. A value of 3 is assigned to all the designs in which the number of cavities is equal to or greater than two thirds of the largest number of holes. In all other cases, a value of 2 is given. Similarly, the  $S_{NC}$  adopts a value of 1 if only one-third or fewer of the cavities are of a suitable size for the corresponding species, in this case cephalopod molluscs (Sections 1.2 and 2.1). The best possible value (3) is assigned if two-thirds or more of the cavities present an appropriate size for the targeted species. A value of 2 is defined in all other cases. Regarding  $T_{NC}$ , three values are also possible: 1 if only one-tenth or fewer of the cavities are closed, 3 if at least half of the cavities are open, and 2 if the AR design is between the previous two cases. In contrast to other subindices, the level of exigency needed to obtain acceptable and optimal results in  $T_{NC}$  is lower. The reason for this is to obtain a balance between the species that prefer open cavities and those that prefer holes with only one opening. Therefore, the HCM varies from 3 to 9, the worst and best possible results, respectively.

$$HCM = N_{NC} + S_{NC} + T_{NC} \quad (6)$$

### 3. Results and Discussion

As indicated above, two AR designs (standard and modified) were proposed and analysed in this study. The AREIT and NCC indices were calculated for both modules. Two factors must be considered. One is that the egg chain must be oxygenated, particularly in the case of *O. vulgaris*. A second factor is the need for current in the tubular structures of the vertical, hollow model, especially for the embryonic development of *L. vulgaris*. Thus, two CFD studies were carried out with the aim of observing how water circulates in these cavities. The upwelling generated on the side faces of the two module types was also studied.

#### 3.1. AREIT Index Results

The final ARs designs presented in Section 2.1 were assessed through the AREIT index. In this case, the parameters EM and NM adopted the same value for both designs, while the parameter HM corresponding to the nest cavities was different, as shown in Table 3.

The reference design, that is, the standard model, adopted a value of 1 for all partial indices included in Equation (1). The modified AR unit obtained the same results with only one exception: HM took a value of 0.7. In other words, the standard design presented an AREIT index equal to 3, while the modified model obtained a value of 2.7. This suggests that the modified design is more likely than the reference one to generate a lower positive impact on the ecosystem. Nevertheless, as previously indicated in Section 2.3, the AREIT index failed at the time of considering some potential positive impacts. This is the reason why it is also necessary to estimate the NCC index for both designs. As a preliminary step, the results derived from the CFD analysis are presented in the following subsection.

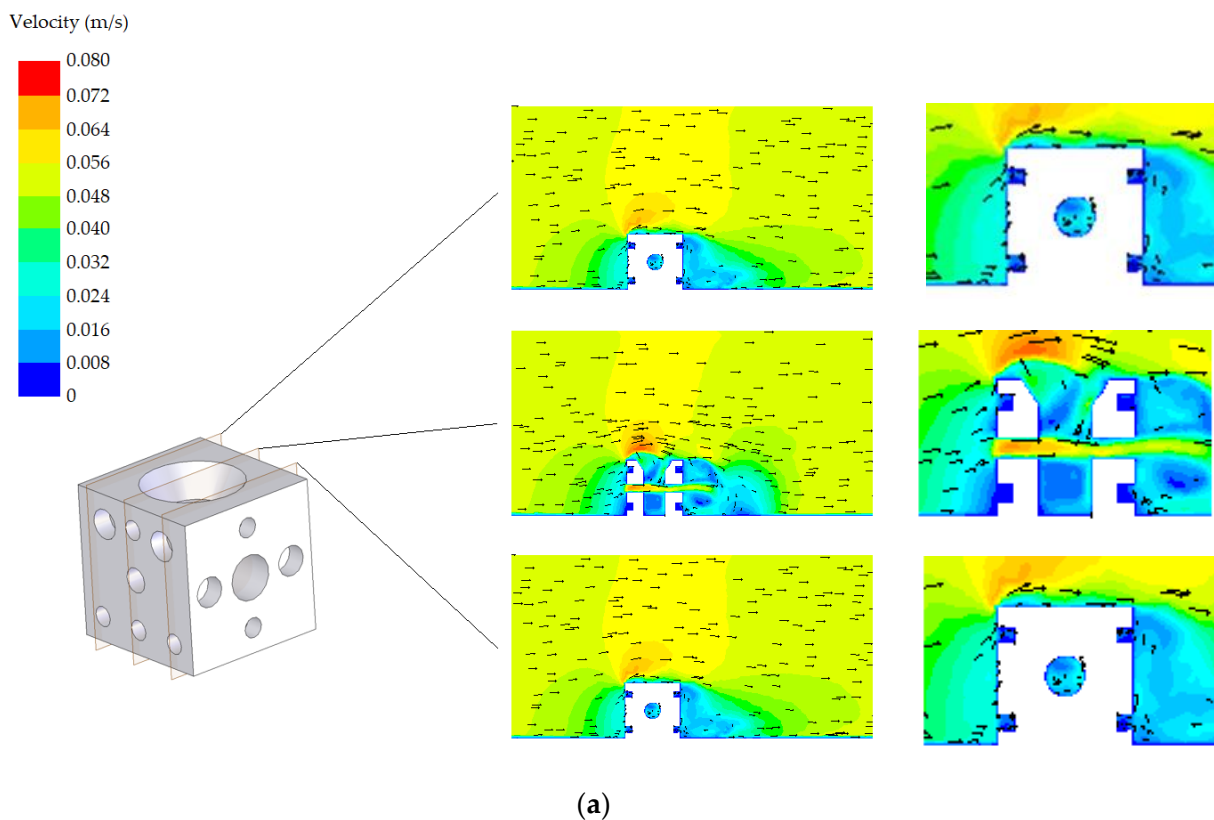
**Table 3.** General information and relevant parameters for the standard and modified AR unit designs.

Relevant Information and Main Parameters	Standard Model	Modified Model
Geometrical characteristics	12 nest cavities (20 cm diameter)	4 nest cavities (30 cm diameter)
	8 nest cavities (30 cm diameter)	12 nest cavities (20 cm diameter)
<i>EM</i>	1	1
<i>NM</i>	1	1
<i>HM</i>	1	0.7 <sup>a</sup>
<i>AREIT</i>	3	2.7

<sup>a</sup> This value is the result of dividing the area of the nest cavities for the modified model by the corresponding area for the standard one [12].

### 3.2. CFD Results

The velocity fields corresponding to both designs (standard and modified) with the two possible orientations (A and B) are shown in Figures 8 and 9, respectively. Three planes are represented in these figures. A detail in the zone around the AR is also included in these figures. Regarding the standard AR, two of the planes are similar due to symmetry. All proposals offer an adequate habitat for species, promoting the circulation of nutrients. It was found that the flow in the tube interiors provides a suitable environment for cephalopods. Circulation is produced, which guarantees nutrient renewal inside the tubes, as well as a favourable hydrodynamic effect, facilitating the continued presence of nutrients around the AR. Both designs present appropriate results in terms of the circulation. However, from Figures 8 and 9, it is clear that there are small differences, also reflected in the NCC index presented in the following subsection.



**Figure 8.** Cont.

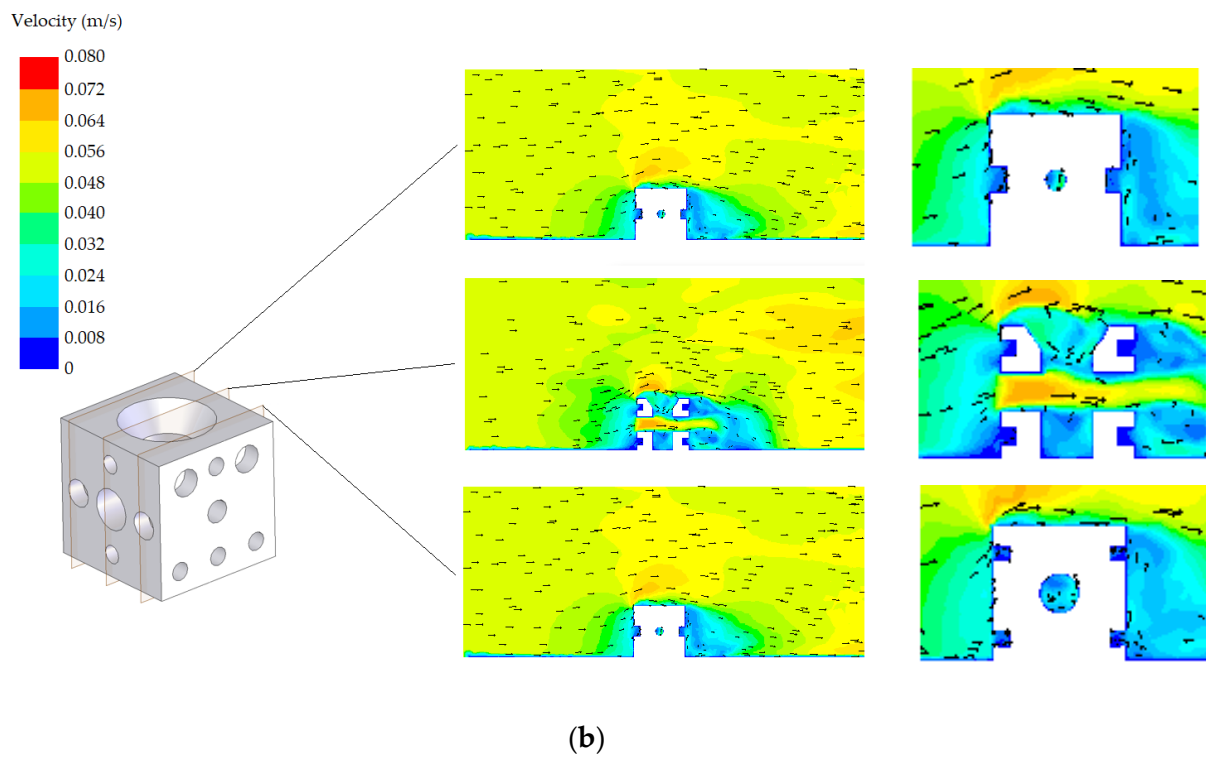


Figure 8. Velocity field corresponding to the standard design: (a) orientation A and (b) orientation B.

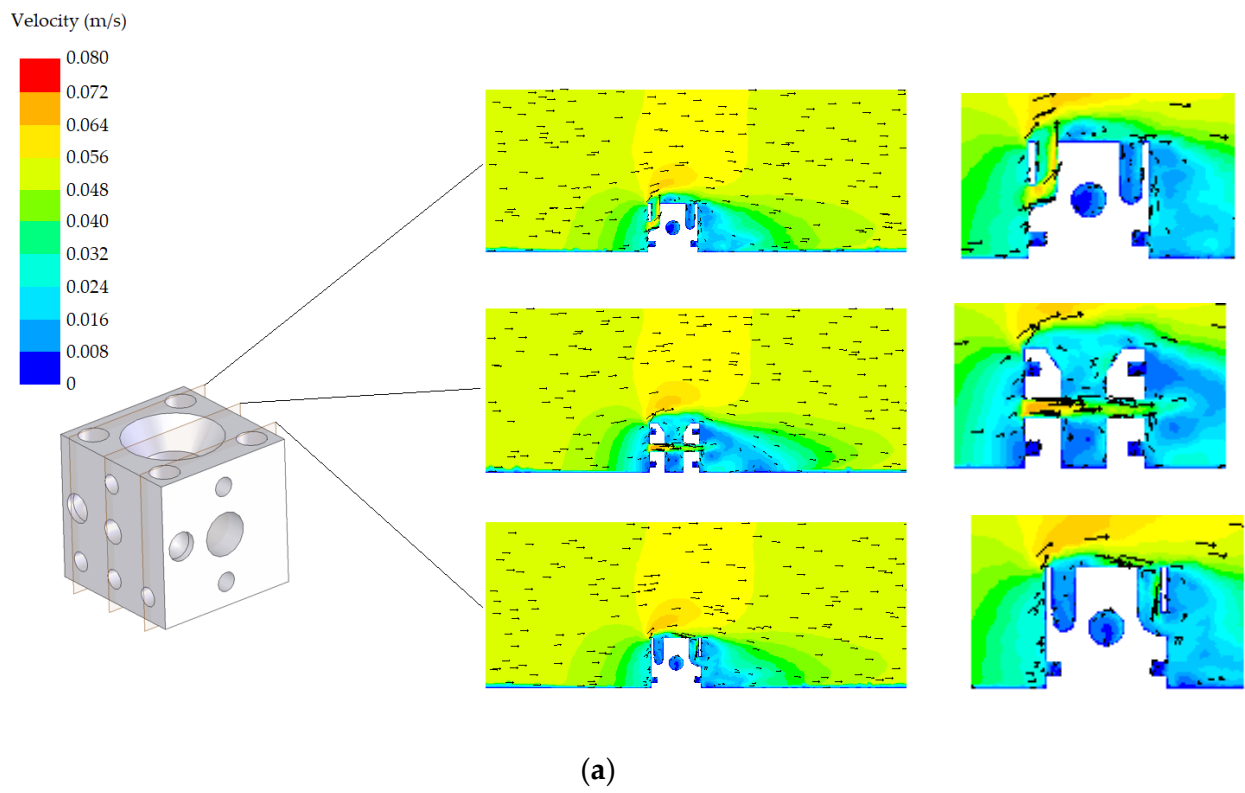
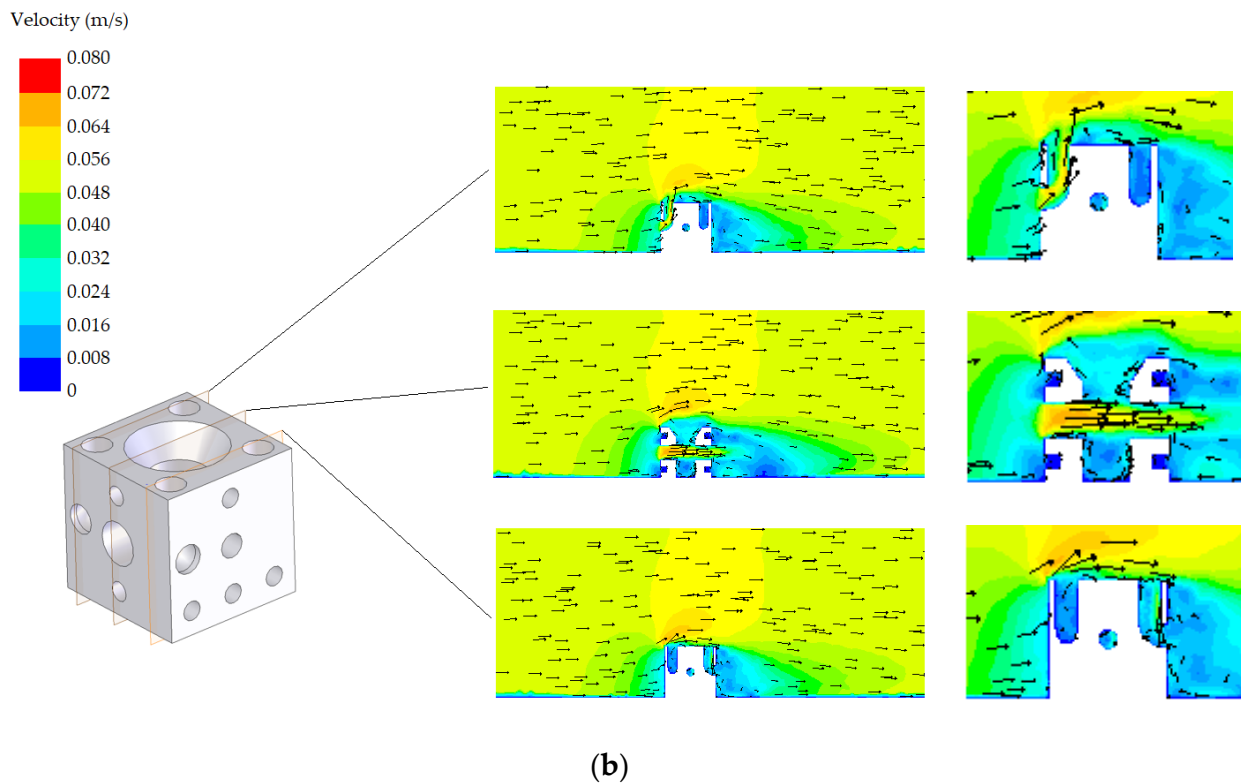


Figure 9. Cont.



**Figure 9.** Velocity field corresponding to the modified design: (a) orientation A and (b) orientation B.

### 3.3. NCC Index Results

The NCC index values for the two designs and orientations are summarised in Table 4. For the volume of the upwelling ( $V_{upwelling}$ ) region, similar values were adopted for both designs and orientations (standard design and orientation A:  $0.189 \text{ m}^3$ , standard design and orientation B:  $0.152 \text{ m}^3$ , modified design and orientation A:  $0.206 \text{ m}^3$ , modified design and orientation B:  $0.165 \text{ m}^3$ ). They represent between 4.5 and 6.1% of the total volume ( $V_{AR} = 3.375 \text{ m}^3$ ). Consequently, only values of 1 and 2 were achieved. When the same orientation was considered, the volume of the upwelling ( $V_{upwelling}$ ) region was always higher in the modified design than in the standard one. Therefore, it is possible to say that the modified AR module is more conducive to this phenomenon, although the differences are small. In terms of the orientation, for the same design, option A always obtained higher values of  $V_{upwelling}$  than orientation B. The reason for this is that orientation A corresponds to the smaller main hole (250 mm) parallel to the current velocity. This promotes a higher proportion of the incoming water to be directed upwards, propitiating the upwelling effect. On the other hand, orientation B corresponds to the larger main hole (450 mm) parallel to the current velocity, and thus, a lower proportion of the upcoming water is directed upwards because it easily enters inside the AR. As for the back eddy effect, similar volumes were also obtained for both designs and orientations (standard design and orientation A:  $V_{backeddy} = 0.619 \text{ m}^3$ , standard design and orientation B:  $V_{backeddy} = 0.492 \text{ m}^3$ , modified design and orientation A:  $V_{backeddy} = 0.652 \text{ m}^3$ , modified design and orientation B:  $V_{backeddy} = 0.546 \text{ m}^3$ ). These values represent between 14.58 and 19.32% of the total volume. Therefore, values of 2 and 3 were assigned according to the rules defined in Section 2.3. In this case, the trend is the same as that already discussed for the upwelling phenomenon: the modified design performs better than the standard one for a given orientation and, orientation A is more conducive to back eddy phenomenon, once a design is selected. Regarding the circulation in the interior cavities, the modified design with orientation B is the alternative with the highest average flow velocity inside the module ( $v_a = 0.031 \text{ m/s}$ , that is, 0.62 times the current velocity). Consequently, its  $I_{effect}$  subindex adopts a value of 3. If orientation A is considered, the average



flow velocity decreases, taking a value of 0.022 m/s, slightly below 0.5 times the current velocity. The same trend is true for the standard design: circulation in the interior cavities is favoured when orientation B is considered, in contrast to the  $U_{effect}$  and  $B_{effect}$  subindices. Since orientation B corresponds to the larger main hole (450 mm) parallel to the current velocity, more water enters the interior of the AR, which is expelled, mainly to the back part. This creates very intense circulation, and a high proportion of the interior of the AR has high velocities. Consequently, it is clear that the orientation with respect to the direction of the current velocity affects the nutrient circulation inside the module. Under the same orientation, the modified design always obtains higher average flow velocities than those achieved by the standard one and, consequently, better circulation exists in the interior of the module. The reason for this is that open holes promote higher velocities since they provide an inlet and an outlet. Closed holes lead to very low velocities since there is no outlet for the water to flow. On the other hand, it is important to note that the standard design with orientation B obtained a slightly higher average flow velocity than the modified design under orientation A (0.024 and 0.014 m/s, respectively). Nevertheless, these two values are so close to each other that there should not be differences in the assigned scores (both velocities are slightly below 0.5 times the current velocity, adopting a dimensionless value of 2). Consequently, the NCM index adopts a value of 7 for the modified design (orientations A and B) and for the standard module with orientation A. Nevertheless, the standard design with orientation B was the worst alternative according to this parameter.

Regarding the HCM subindex, both modules meet the conditions to obtain the best possible value (3) for the  $N_{NC}$  indicator. Furthermore, all the cavities present a suitable size for cephalopod molluscs, obtaining a value of 3 for  $S_{NC}$ . However, the standard design has no open cavities ( $T_{NC} = 1$ ), whereas one out of four cavities in the modified design is open ( $T_{NC} = 2$ ). Therefore, the modified design slightly outperforms the standard one for the HCM subindex (7 and 8 points, respectively). In this case, the orientation has no influence on the HCM subindex, since this metric assesses the impact on the habitat instead of quantifying the nutrient circulation.

If the NCC index is analysed, it is possible to say that both AR designs obtain remarkable results, since they present values close to the maximum (18) and far from the worst possible result (6). Nevertheless, in contrast to the AREIT index, in this case, the modified design was found to be slightly superior to the standard module. The selection between orientations A and B for the modified design will depend on whether the aim is to promote the circulation in the interior cavities (orientation B,  $I_{effect} = 3$ ) or the upwelling phenomenon (orientation A,  $U_{effect} = 2$ ).

Finally, it should be noted that the NCC results showed no significant differences for the two designs. This is a reasonable outcome, as the two modules differ only in the number and type of cavities. Nevertheless, the NCC appears to be sensitive enough to quantify such small differences. Greater differences would be obtained when comparing more disparate designs (for example, the proposed AR modules and a cylindrical one).

**Table 4.** NCC index results for the standard and modified designs.

Results	AR Design			
	Standard		Modified	
	Orientation A	Orientation B	Orientation A	Orientation B
$U_{effect}$	2	1	2	1
$B_{effect}$	3	2	3	3
$I_{effect}$	2	2	2	3
<b>NCM</b>	<b>7</b>	<b>5</b>	<b>7</b>	<b>7</b>
$N_{NC}$	3	3	3	3
$S_{NC}$	3	3	3	3
$T_{NC}$	1	1	2	2
<b>HCM</b>	<b>7</b>	<b>7</b>	<b>8</b>	<b>8</b>
<b>NCC</b>	<b>14</b>	<b>12</b>	<b>15</b>	<b>15</b>

#### 4. Conclusions

An analysis of the landings of cephalopod molluscs in Galicia showed the decline in catches in recent years. This is the reason why, after analysing the evolution of artisanal fishing in the last five years, the installation of ARs was proposed. Two different AR designs were considered in this work with the objective of imitating certain natural characteristics of the reproductive habitat for cephalopod mollusc species.

The starting point was the basic geometry of the AR module, which was based on the principles contained in ecosystem ecology and developed in Ref. [16]. From this cubic module, two AR modules were proposed: the so-called standard and the one designed under the consideration of multiplying the open-type vertical cavities.

Both designs were compared according to the existing *AREIT* index. This indicator served to estimate the potential positive transformation of the ecosystem once the modules had been installed. The results obtained show that both designs lead to the same level of positive impact on the ecosystem in terms of energy (*EM*) and nutrients (*NM*). Furthermore, both designs also achieved notable results in terms of habitat modification. However, in this case, the impact was not exactly the same, since their values for the *HM* subindex were not equal (different number of nest cavities).

Nutrient circulation was also analysed in both AR designs in all cavity types. A CFD model was applied for such a purpose. Finally, a new index was proposed and applied. In particular, it was the *NCC* (nest cavity circulation) indicator, which overcomes the main limitations of the *AREIT*.

According to the results obtained, the two proposed modules—the standard and modified ones—could ensure the development and growth of cephalopod molluscs in Galicia and specifically in the Ares-Betanzos estuary, since they act in a similar way. The first of the possibilities, the standard module, leads to a higher number of cavities, with a higher *AREIT* index, while the modified design favours circulation within cavities, with a higher *NCC* index.

Finally, this study presents some limitations that are linked to possible future developments. One option is to repeat this study varying water currents and tidal conditions. Other possibility is to analyse other parameters that also condition the habitats of the cephalopod mollusc in Galicia, such as the pH of the reef base material.

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