INSTITUTO POLITÉCNICO DE BRAGANÇA
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AQUACULTURE CAGES FROM DECOMISSIONED WIND TURBINE BLADES: AN UPCYCLING STUDY

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RESUMO

Este trabalho aborda a prática inovadora de reutilizar as pás de aerogeradores no fim de sua vida útil para criar jaulas de aquacultura sustentáveis utilizando o processo de *upcycling*. O estudo apresenta quatro modelos de jaulas diferentes, cada um baseado na reutilização das pás de aerogeradores. Foram realizadas simulações usando o software *SolidWorks*, contribuindo para o desenvolvimento e aprimoramento dos modelos de gaiolas de aquacultura para avaliar o desempenho de alguns desses modelos. Além disso, o trabalho fornece uma visão geral da aquacultura para os próximos anos, destacando a crescente demanda por sistemas de cultivo de aquacultura. Um ponto importante é a análise da quantidade de pás de aerogeradores que serão descartadas nos próximos 20 anos, demonstrando assim a possibilidade de reutilizar esses recursos para atender de forma sustentável à demanda de aquacultura. A tese também inclui uma matriz SWOT que identifica os detalhes essenciais deste projeto, analisando suas forças, fraquezas, oportunidades e ameaças. Em resumo, esta tese enfatiza a importância da economia circular e da sustentabilidade na aquacultura, apresentando uma abordagem inovadora para reutilizar as pás dos aerogeradores descartadas e integrá-las estruturalmente aos sistemas de cultivo de aquacultura, contribuindo para o avanço da indústria neste setor.

Palavras-chave: *upcycling*, pás de aerogeradores, aquacultura e sustentabilidade.

ABSTRACT

This work addresses the innovative practice of reusing wind turbine blades at the end of their lifespan to create sustainable aquaculture cages using the upcycling process. The study presents four different cage models, each based on the repurposing of wind turbine blades. Simulations were conducted using SolidWorks software, contributing to the development and improvement of the aquaculture cage models to evaluate the performance of some of these models. Additionally, the work provides an overview of aquaculture for the upcoming years, highlighting the increasing demand for aquaculture cultivation systems. An important point is the analysis of the quantity of wind turbine blades that will be discarded in the next 20 years, thus demonstrating the possibility of reusing these resources to meet the aquaculture demand sustainably. The thesis also includes a SWOT matrix that identifies the essential details of this project, analyzing its strengths, weaknesses, opportunities, and threats. In summary, this thesis emphasizes the importance of the circular economy and sustainability in aquaculture, presenting an innovative approach to repurpose discarded wind turbine blades and structurally integrate them into aquaculture cultivation systems, contributing to the advancement of the aquaculture industry.

Keywords: upcycling, wind turbine blades, aquaculture, sustainability.

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1. Introduction

The growing recognition of global environmental challenges and the pursuit of sustainable solutions have driven research and innovation across diverse fields. One of these areas of increasing interest is the search for efficient ways to reuse discarded materials, minimizing environmental impact and contributing to the circular economy. In this context, this work presents an innovative approach to repurpose discarded wind turbine materials creating an efficient aquaculture cultivation system. Through the process of upcycling, wind turbine blades are transformed into sustainable aquaculture cage models, contributing to the circular economy, and reducing the environmental impact caused by disposing of these blades in landfills or through incineration.

Wind energy has a crucial role in the transition to renewable energy sources, with wind turbines becoming an essential part of it. However, as wind farms keep growing, the quantity of wind turbine blades reaching the end of their operational life also increases. The reuse of these materials is crucial to prevent waste accumulation and promote more sustainable practices. This study explores the technical feasibility of transforming wind turbine blades into aquaculture cages and highlights the potential of this process to make a significant contribution to the circular economy and reduce environmental impact. Creating efficient aquaculture cultivation systems from these discarded materials not only reduces waste but also opens new possibilities for the aquaculture industry, which faces constant challenges in meeting the growing global demand for food.

Therefore, the aim of this work is to contribute to the advancement of the aquaculture industry by providing an environmentally responsible and economically viable solution for food production. This research represents a step towards a more sustainable future, where the reuse of discarded materials becomes a key component in the quest for a greener and balanced world.

2. Theory and state of art

2.1. Upcycling

The process of upcycling involves repurposing, repairing, upgrading, and remanufacturing products and materials that are no longer in use or are slated for disposal, thereby increasing their value. This approach differs from recycling, where value is often lost to some extent. It involves transforming existing materials into new products, and often requires high energy consumption, making it the least preferred option among the 3 R's (reduce, reuse, and recycle) [10].

The context in which upcycling activities take place has an influence on them, including social, economic, and political factors. Upcycling can serve basic human needs, such as constructing shelters using waste materials, and can also be used for artistic or crafting purposes. Moreover, the availability of raw materials, the intended outcome, and the creative skills involved in manipulating and redefining materials differ according to the cultural and geographic circumstances of the area [11].

Upcycling falls under the sustainability umbrella since it involves reusing resources that would otherwise be thrown away, thereby prolonging their usefulness, and reducing the need for new natural resources. It is important to note that upcycling also involves a different process from downcycling (recycling), as upcycling assigns value to discarded products and offers the potential to reduce negative environmental impacts without the need for energy or chemical inputs [12].

A slight difference between the terms recycling and upcycling is that when we recycle, the material goes to stage of raw and in upcycling we don't have this step. Figure 1 shows the steps among each process.

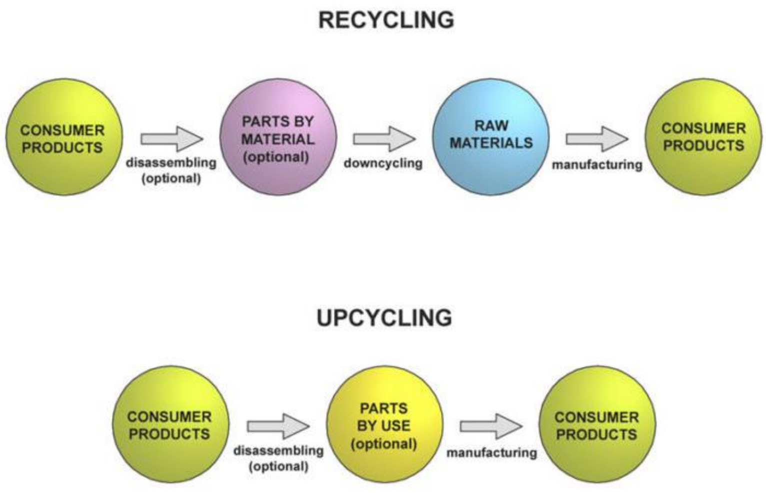

Figure 1 - Difference between Recycling and Upcycling.

Upcycling is a relevant practice of sustainability-oriented innovation, contributing to waste reduction and efficient use of resources. One of its advantages is its ability to minimize energy resources, valorize existing materials, create unique products, and select the best process from an environmental and socio-ethical perspective, while also being more readily accepted by consumers when the environmental benefits are emphasized in product communication [13].

About using upcycling methods for wind turbine blades, this practice aims to maintain the original physical shape and properties. One example of upcycling is the Re-Wind project, which repurposed wind turbine blades to create an 8,5 m pedestrian bridge. Upcycling methods can contribute to circular urban regeneration by using the composite materials of the blades to create new products for urban regeneration projects [23].

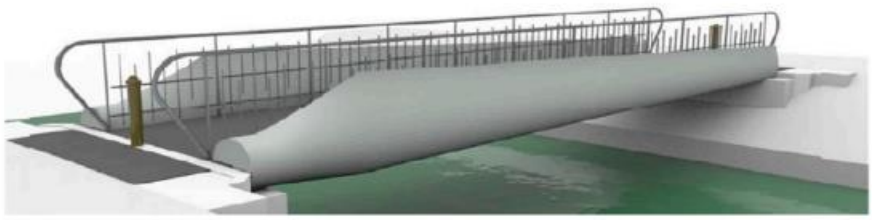

Figure 2 - A conceptual design of a pedestrian bridge using part of A26 wind blades [24].

The importance of upcycling wind turbine blades spans various aspects:

- ✓ Environmental Advantages: it reduces landfill waste, preserves resources, and lessens the need for new materials [25].
- ✓ Circular Economy: Embracing upcycling aligns perfectly with the principles of the circular economy, as it extends the lifespan of wind turbine blades and fosters a closed-loop system. Instead of discarding the blades, they are transformed into new products [25].
- ✓ Economic Opportunities: The upcycling of wind turbine blades opens economic prospects, particularly in the manufacturing and construction sectors, developing new industries and creating job opportunities [25].
- ✓ Sustainable Urban Regeneration: Utilizing upcycled wind turbine blades can play a vital role in sustainable urban regeneration projects. These blades can be repurposed to construct new structures such as pedestrian bridges, bike sheds, and even housing components [25].

In the next figures we can see other projects of upcycling wind turbine blades:

Figure 3 - A bike shed in Denmark made from wind turbine blades [26].

Figure 4 - Wikado playground [27].

2.2. Aquaculture

Aquaculture or farming in water is the aquatic equivalent of agriculture or farming on land. Defined broadly, agriculture includes farming both animals (animal husbandry) and plants (agronomy, horticulture, and forestry in part). Similarly, aquaculture covers the farming of both animals (including crustaceans, finfish, and mollusks) and plants (including seaweeds and freshwater macrophytes). While agriculture is predominantly based on use of freshwater, aquaculture occurs in both inland (freshwater) and coastal (brackish water, seawater) areas [3]. Aquaculture, which is the aquatic equivalent of agriculture, has been in existence for approximately 4000 years. Nonetheless, in contrast to agriculture, its contribution to global fish and shellfish production has been relatively minor in recent times [4].

There are various factors that explain the distinct development of agriculture and aquaculture. Historically, lakes and oceans have been a plentiful source of food, and the use of fishing techniques and technology were adequate to satisfy increasing demand. Thus, the incentive to learn farming methods was minimal. Additionally, the aquatic environment was considered challenging and intimidating, making the idea of constructing a secure facility in the sea, able to withstand the forces of tides and waves, appear unfeasible [4]. However, since the end of World War II, there has been a consistent rise in the global demand for fish, as shown in Figure 5.

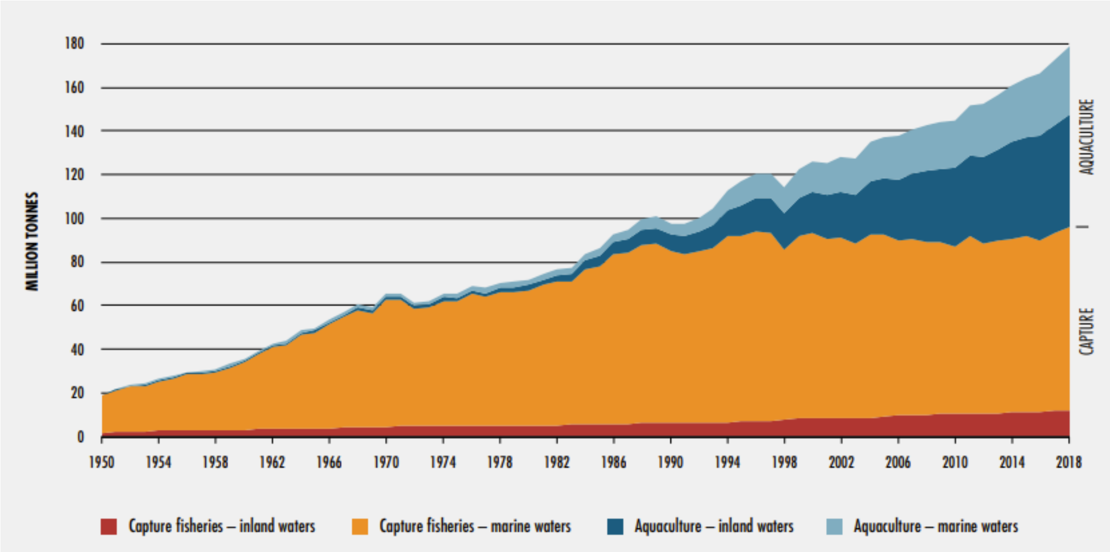

Figure 5 - World capture fisheries and aquaculture production [5].

2.3. Types of aquaculture

The practice of modern marine aquaculture has diversified significantly and includes complementary methods that are typically classified based on the production system as either extensive, semi-intensive, or intensive, as outlined in Table 1.

Table 1 - Types of aquaculture [7].

Extensive	The main goal of this approach is to manage the movement of organisms and prepare the environment for sedentary species. It is cost-effective and less demanding since it doesn't involve feeding or managing predators and diseases, but it is also less profitable. These systems are typically located near the coast, benefiting from tidal water and natural food replenishment, and require minimal intervention, resulting in organisms that closely resemble their wild counterparts.
Semi-intensive	The semi-intensive system involves a greater degree of production factor control, with higher densities used to raise a larger number of fish in a more limited area. The fish are provided with supplementary feed in addition to natural food sources, while predator and disease management is also implemented to prevent significant losses.
Intensive	The intensive production method involves strict environmental control to achieve maximum production with high densities in limited spaces. Almost all the feed is provided through rations, and disease prevention, monitoring, and treatment are crucial. Achieving maximum output requires strict management of various parameters, making this form of aquaculture costly due to the significant investment required in materials, equipment, and labor.

Marine locations are generally divided into two simple discriminative descriptors: inshore and offshore, based on the generic consideration of exposure to adverse weather conditions of the sea, and particularly whether the location is subject to ocean waves or not. The following table shows a classification proposed by FAO in 2009 as part of its study on offshore cage aquaculture.

Table 2 - Site classification proposed by FAO in 2009 (6).

	Coastal	**Off the coast**	**Offshore**
Location / hydrography	<500 m from the coast	from 500 m to 3 km	>2 km, generally within continental shelf zones
	<10m depth; low tide	>10 m depth to 50 m	
	Within sight	Often within sight	depth > 50 m
	Usually sheltered	Somewhat sheltered	
Enviroment	Short period winds	Local coastal currents	Oceanic swells
	Local coastal currents	Tidal streams	Variable wind periods
	Strong tidal streams		Possibly less local current
Access	100% accessible	Accessible 90%, at least	Accessibility around 80%
	Landing possible all the time	Landing usually possible	Landing periodically
Operation	Most of the time manual operation	Some automated operations	Remote operations

2.4. Market overview

Global fish production is estimated to have reached about 179 million tons in 2018, with a total first sale value estimated at 360 billion EUR, of which 82 million tons, valued at 225 billion EUR, came from aquaculture production. Of the overall total, 156 million tons were used for human consumption, equivalent to an estimated annual supply of 20,5 kg per capita [5] .

Global food fish consumption increased at an average annual rate of 3.1 percent from 1961 to 2017, a rate almost twice that of annual world population growth (1.6 percent) for the same period, and higher than that of all other animal protein foods (meat, dairy, milk etc.), which increased by 2.1 percent per year. Per capita food fish consumption grew from 9,0 kg (live weight equivalent) in 1961 to 20,5 kg in 2018, by about 1.5 percent per year [5]. Table 3 shows the world aquaculture production and utilization during the last 28 years.

Table 3 - World and aquaculture production and utilization [5].

	Average per year *(million tons, live weight)*					
	1986-1995	1996-2005	2006-2015	2016	2017	2018
Capture						
Inland	6,4	8,3	10,6	11,4	11,9	12,0
Marine	80,5	83,0	79,3	78,3	81,2	84,4
Total Capture	**86,9**	**91,3**	**89,9**	**89,7**	**93,1**	**96,4**
Aquaculture						
Inland	8,6	19,8	36,8	48,0	49,6	51,3
Marine	6,3	14,4	22,8	28,5	30,0	30,8
Total aquaculture	14,9	34,2	59,6	76,5	79,6	82,1
Total world fisheries and aquaculture	**101,8**	**125,5**	**149,5**	**166,2**	**172,7**	**178,5**
Utilization						
Human consumption	71,8	98,5	129,2	148,2	152,9	156,4
Non-food uses	29,9	27,1	20,3	17,9	19,7	22,2
Per capita apparent consumption (kg)	13,4	15,9	18,4	19,9	20,3	20,5

2.5. Types of aquaculture cages

Aquaculture is a constantly evolving subject of study and investment, driven by technological advancements and high demand for aquatic products. The technology in this sector is expressed in a diverse market, offering various solutions to meet the specific demands of local farming conditions. Among the available equipment, aquaculture cages stand out, which can be made of different materials and sizes, allowing fish to be raised in a controlled and protected environment. In addition, support boats are essential for the transportation and maintenance of the cages, ensuring that the fish receive the necessary care to grow healthy. These advanced technological solutions are crucial for the sustainable production of aquatic food, which contributes to global food security and the conservation of natural resources [1].

In Table 4 we can see the types of cages present nowadays and its operational models.

Table 4 - Types of cages for aquaculture [2].

Structure	Operational model
Floating	Flexible
	Rigid
Semi-submersible	Flexible
	Rigid
Submersible	Rigid

2.5.1. Gravity cage (floating or submersible)

A gravity cage is a floating collar system attached to a net with weights underneath it to impose a vertical force, keeping the structure in the intended shape, which can be circular or square, as shown in Figure 6.

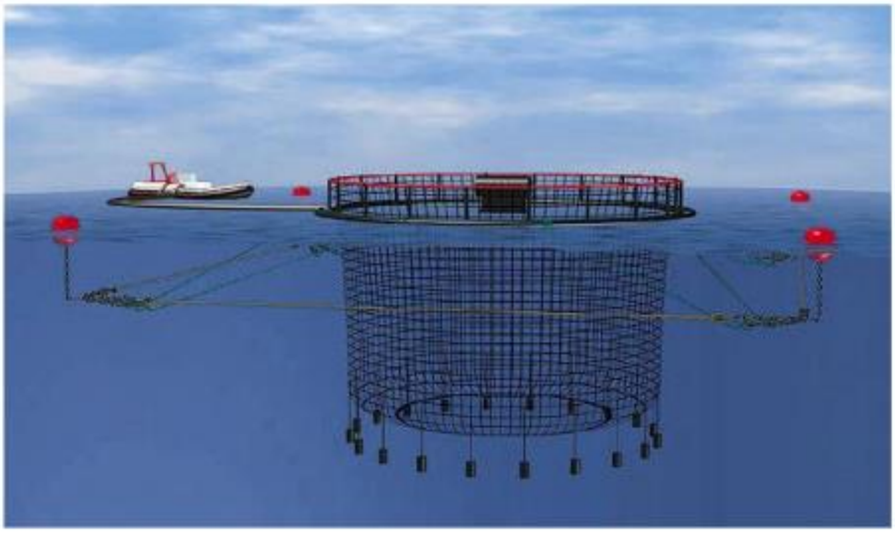

Figure 6 - Type of submersible cage [21].

In Figure 6, you can see floating collars made of wood, metal, and plastic/rubber, which are used to attach and suspend nets using weights at their base. These collars are specifically designed for supporting the nets rather than conducting operations from them, with interventions being performed from boats or support rafts. Table 5 shows advantages and disadvantages of this cage.

Table 5 - Advantages and disadvantages of gravity cage [2]

Advantages	Disadvantages
Great resilience to wave force, allowing for long periods of use.	Relatively expensive for small volumes.
Good impact resistance.	Service of large vessels required.
Variety of possible configurations.	Limited access to exits.

2.5.2. Cages fully submersible

This type of cage is capable to fully submerging. Its system is fully submersible and equipped with a feeding silo. Figure 7 represents one cage of this model:

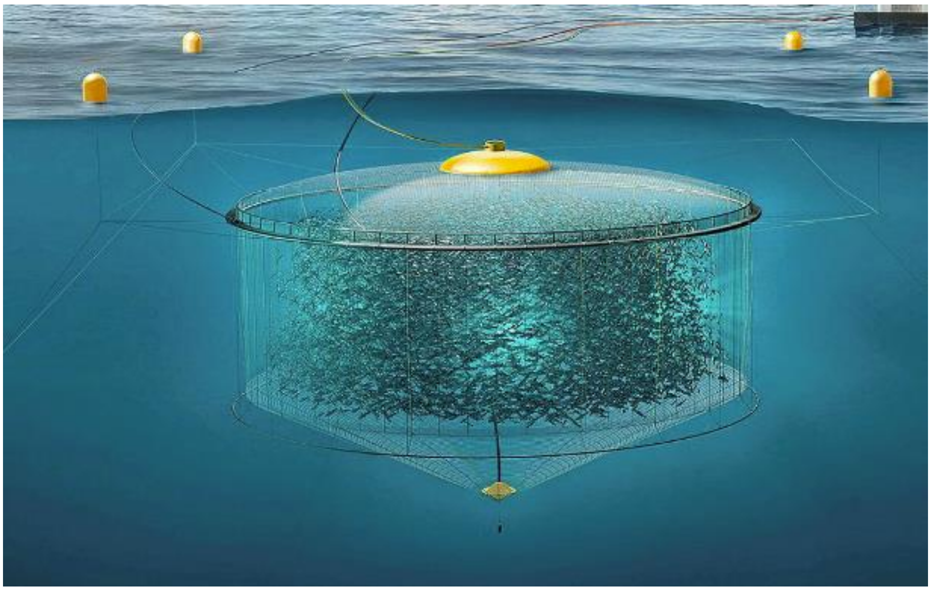

Figure 7 - Type of cage fully submersible [21].

The advantages and disadvantages of this cage are represented in Table 6.

Table 6 - Advangates and disadvatages of fully submersible cages [2].

Advantages	Disadvantages
Minimal visual impact	Low visibility in normal state
Avoids storm effects	Difficult to operate
Avoids ice, vessel traffic, and surface debris.	High cost

2.5.3. Semi-rigids cages

In the case of semi-rigids cages, the structure is held together by cables that connect the steel parts to each other.

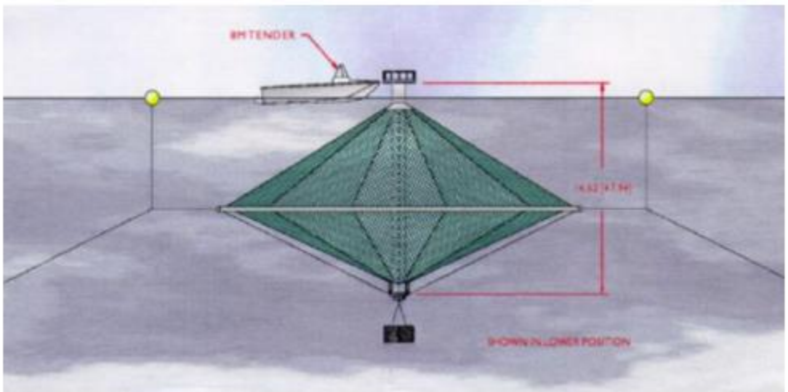

Figure 8 - Semi-rigid cage [2].

The enclosure's volume is upheld through tension on the structure, comprising a central steel beam encased in a circular steel collar connected by non-stretchable tensioned cables. A vertical steel tube beam provides buoyancy and evenly distributes loads to both the net and the circular tubular edge through radial framing lines. Table 7 represents its advantages and disadvantages.

Table 7 - Advantages and disadvantages of semi-rigids cages [2].

Advantages	**Disadvantages**
Semi-submersible or fully submersible	Not yet fully proven and commercially validated
Minimal structural distortion with currents	Efficient feeding and easy net changing are a challenge for this model.
Easily towable.	-

2.6. Relevant parameters for the cage

To ensure successful installation of the cage, barges, and marine beacons, it is crucial to evaluate all parameters that can affect them. When choosing the cage model, designing, and constructing the anchoring system, as well as selecting the service vessel, it is necessary to consider the local bathymetry or depth, wind, direction and speed of currents, waves, seabed, and the incidence of storms and hurricanes.

2.6.1. Bathymetry

Bathymetry refers to the process of measuring the depth of water in oceans, rivers, or lakes. Bathymetric maps bear a resemblance to topographic maps, utilizing lines to depict the shape and elevation of underwater features.

Cages are typically designed to handle pressures up to 15 meters of depth without factoring in this variable in the calculations. However, in the case of extreme occurrences like larger waves, it may become necessary to submerge the cages to depths between 30 and 50 meters [9].

Depth has significant impacts on the practice of aquaculture. The depth influences the choice of materials, equipment, and dimensions in the design of the anchoring system. Regarding the depth of the cage, it should not be deeper than one-third of the local depth, depending on the current velocity. Additionally, at least 15 meters should be left between the seabed and the bottom of the cage in open water [8].

To prevent potential abrasion, it is recommended that the water depth be twice the total depth of the net and measured from the lowest point of the largest waves during low tide, as shown in figure 5 [6].

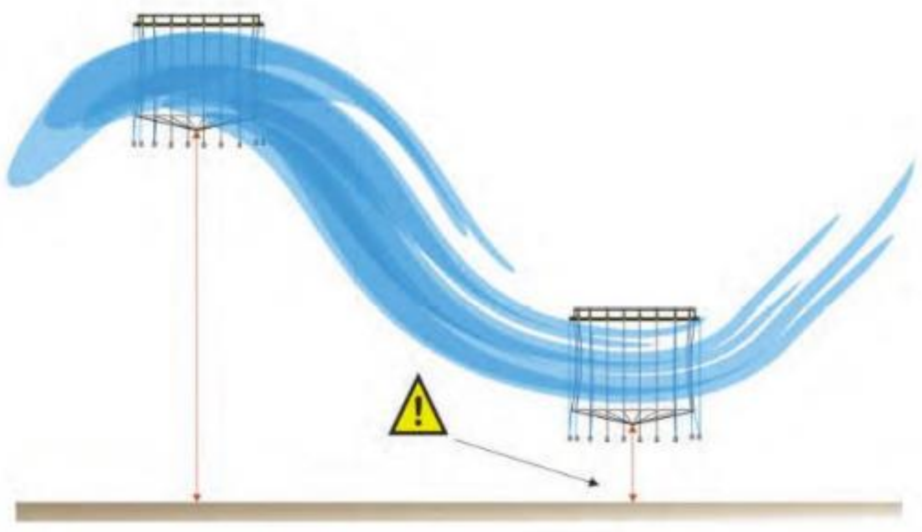

Figure 9 - Distance from the base of the net to the seabed as a function of wave height [6].

2.6.2. Waves

Waves represent approximately 20% to 25% of the total forces affecting mooring systems and aquaculture equipment. Accordingly, the diameter of the cage should be appropriately sized according to the wave height and period. In locations with high waves, it is generally recommended to have larger cage diameters. However, in locations with lower wave heights but with a very short period, material wear increases significantly. In this case, although the waves do not transfer a high amount of energy to the structures, they are much more solicited due to the higher frequency of waves that hit the structure.

Wave prediction, regarding their amplitudes, periods, and frequencies, becomes extremely important when placing an aquaculture structure offshore. Obtaining information such as long-term frequency and wind direction is necessary.

Longer period waves produce larger loads on moorings and greater cage drift, while shorter period waves produce higher angular displacement of joints. Concerning wave forces, dynamic vertical forces imposed by waves tend to be the most important, as they exert bending and torsion forces. Bending forces are maximum at wavelengths like the cage's dimensions. Therefore, coastal locations can be vulnerable to forces, as well as offshore locations. Cyclical stresses imposed by the periodicity of waves can cause fatigue in the structure's members, which can be more significant than occasional very large waves [7].

2.6.3. Characteristics of maritime currents

Currents are important for determining the necessary weights to keep the net stretched and in the correct position, causing the movement of the cage, as well as fish transfer, affecting the shape of the net, compromising maintenance operations that require diving and responsible for dispersing solid waste.

When designing the cage mooring system, it is necessary to consider the current speed. The compensating buoys are sized according to the expected current speed recorded at the site, as well as the dimensions of each component that makes up an anchoring system. The net generates very strong drag forces due to its large area, which is exponentially exacerbated when a net is full of fouling. In this case, it becomes almost a solid barrier, increasing the load supported by the anchoring system and potentially exceeding its discharge limit. The currents impose an additional drag force on the mooring system, in addition to the wave force already present on the anchor components. This load can generate an impact effect on both the anchors and concrete blocks, especially when the seabed is particularly hard, and the anchor remains there rather than in sediment.

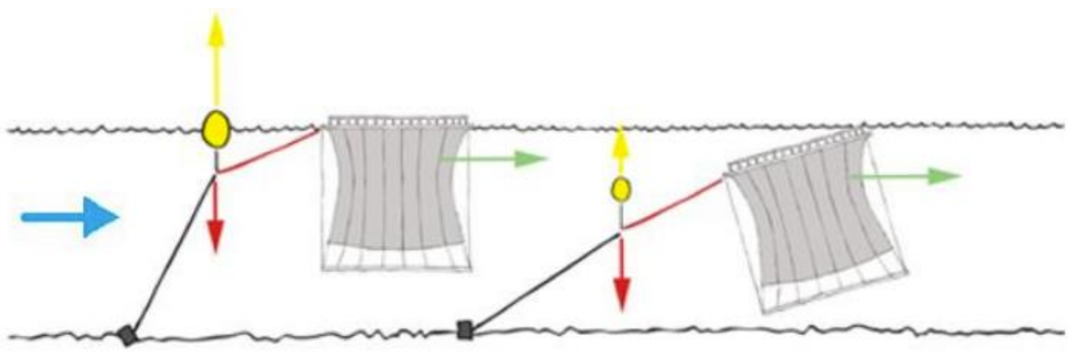

Figure 10 - Currents effects when submersing the cages [8].

When a cage is under a current (blue arrow), the net generates a drag force (green arrow), and the buoys of the mooring system are subjected to a downward tension (red arrows). This downward load is countered by the buoyancy (yellow arrows). If the buoys are too small, as seen on the right side of Figure 3, the buoyancy will be less than the downward load, resulting in the submersion of the buoy and the collar of the cage in strong current conditions.

2.6.4. Fouling

One of the most critical problems in mariculture is fouling, which has the potential to cause significant issues with the structure and production of fish. This issue is identified by encrustations that consist of a mixture of various marine flora and fauna organisms, that attach themselves to both the net and all submerged structures.

When organisms attach themselves to the net, they can cause blockage of the mesh, which prevents water from flowing through the cage and leads to insufficient exchange between the internal and external areas. This lack of exchange results in a reduced exchange of dissolved oxygen, which has negative effects on the growth and health of the fish. Additionally, when the net is covered with organisms that have hard shells, the fish may experience cuts and lacerations that increase the risk of infections and diseases, potentially resulting in higher mortality rates.

Figure 11 - Demonstration of nets with and without fouling on it.

Antifouling

The problem of biofouling has been a standing issue, throughout history different approaches have been utilized to tackle this problem. Various methods have been employed to safeguard ships against biofouling including the use of mixtures and metals such as copper and lead. As the shipping industry continues to expand there is a growing demand for ecologically friendly techniques to prevent biofouling. Below you will find a list of methods that can help prevent fouling along, with their characteristics:

- Tributyltin (TBT): The use of tributyltin (TBT) as an antifouling agent has led to the development of more effective paints for protecting ship hulls, but it’s a potent pesticide that harms marine fauna and flora. To address this problem, there is a growing and urgent need to seek antifouling paint solutions that are biodegradable [15];
- Low-adhesion coating: The use of low adhesion coatings, such as those based on polytetrafluoroethylene (PTFE) or siloxanes, has been a promising solution to reduce biofouling on marine structures. Siloxane-based coatings, in the other hand, have shown promising results but are more expensive and fragile compared to conventional coatings [15];
- Natural anti-fouling: The use of natural anti-fouling substances produced by sessile marine organisms, such as algae, corals, and sponges, represents a promising strategy for preventing marine fouling and mitigating the environmental impact of anthropogenic anti-fouling agents [15];
- Biomimetic surfaces: The use of biomimetic surfaces represents a promising strategy for developing antifouling materials, and recent advances in nanotechnology have made it possible to reproduce these micro topographies in synthetic materials at a large scale for coating applications [15].

2.6.5. Pollution

A wide range of pollutants can damage the cages and negatively affect the farmed fish stock, causing death or contamination that may render the fish unsuitable for human consumption. To minimize the risks, it is advisable to avoid highly industrialized areas, although pollution may also occur because of maritime traffic. Rivers may contain debris or large floating objects that can damage the net or even the structure in case of impact [7].

2.6.6. Wind

The wind accounts for approximately 5% to 10% of the total forces acting on the cage anchoring system. It can have a direct impact on the cages and their activity by exerting traction forces on the net, disturbing boats moving around it, or even dispersing feed outside the cages. Information about wind can usually be obtained from weather authorities and summarized in a wind rose chart, which provides information on wind speed, direction, and occurrence at a given location [8].

2.7. Submersion of cages

Submerged cages represent a promising approach to sustainable aquaculture in exposed and unprotected marine environments, offering advantages such as increased production potential, improved fish quality, and reduced risks of biomass loss and structural damage. This approach enables aqua culturists to better control fish metabolism by taking advantage of the cooler water temperatures at deeper depths, while also promoting environmental sustainability using submerged cultivation sites. Further research is needed to optimize the design and operation of submerged cages and to assess their long-term impact on the marine ecosystem.

2.7.1. Oceanics 1

This type of submersion has a best combination with typical features of floating cages since it has easy access and management for farming activities. Oceanics 1 has the following characteristics:

- Clearing chamber in HDPE aisle pipes (alternatively floodable or filled with air) located above the cage network and in the water line.
- A ballast (submersion tube) located under the cage net, formed by an HDPE tube with chains. The total weight is less than the total buoyancy of the pipe.

When the air and water valves are opened, the cage submerges as water pressure expels air from the pipes with the aid of ballast. Conversely, to achieve floating, the process is reversed: the air intake through the valves expels the water from the pipes. The cage remains afloat when all the air valves are closed [18].

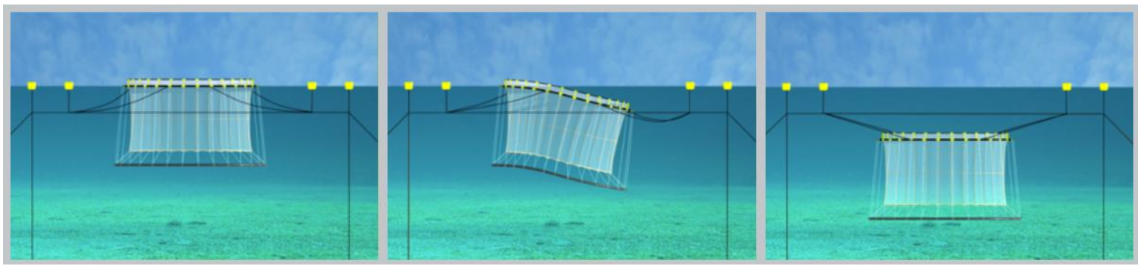

Figure 12 – Demonstration of process of submersion Oceanics 1 [18].

The anchoring system is the same as that used by floating cages: a grid anchoring system. The lattice system is one of the most cost-effective arrangements among all those used in the cage culture market. The difference is in the double float line: the main anchor floats resist the forces of the anchors, and the grid anchor floats maintain the weight of the cage while submerged [18].

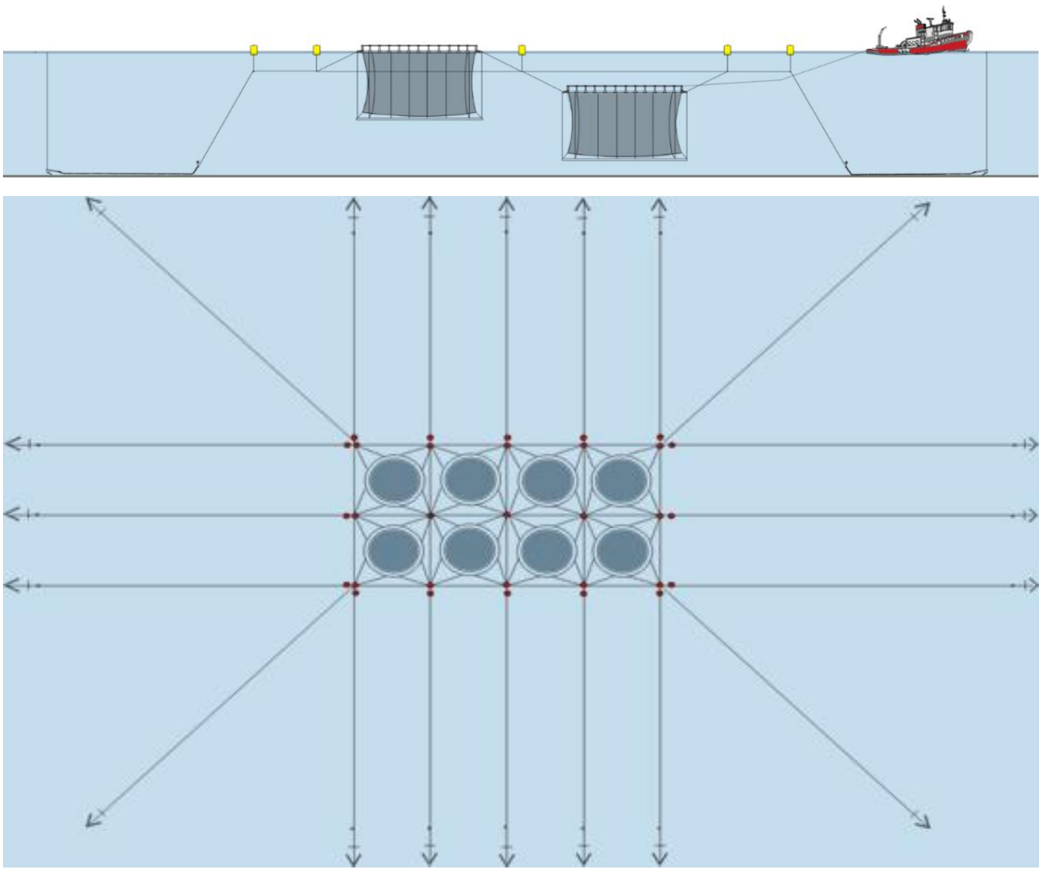

Figure 13 - Mooring system Oceanics 1 [18].

2.7.2. Oceanics 2

The technology utilized in this type of cage incorporates high-density polyethylene tubes that are consistently filled with air, enabling the buoyancy to surpass the weight of the structure. These cages are equipped with a compensation chamber positioned beneath the net, containing weights, specifically chains, or ballasts, which collectively outweigh the buoyancy of the upper tubes of the cage, as depicted in Figure 14 [18].

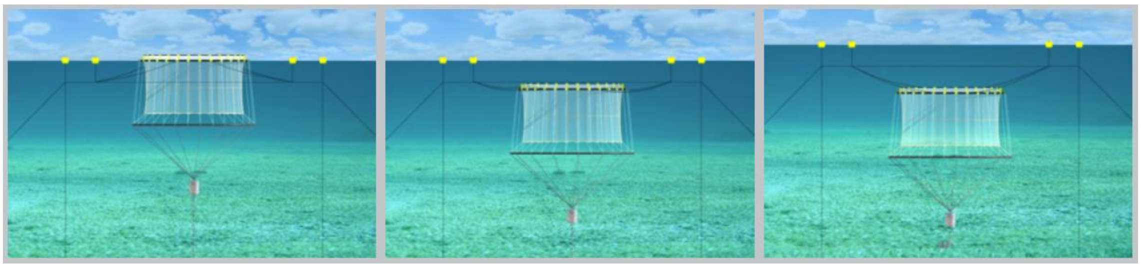

Figure 14 - Submersion process Oceanics 2 [18].

Generally, the cage's maximum sinking depth is twice the depth of the grid system. In such instances, the clearing chamber resembles a "diving bell," featuring a hot-dip galvanized steel cylinder that remains open only at the top. The combined volume of the diving hood and pipes must provide sufficient buoyancy to lift an adequate length of chains used as ballast, allowing the cage to float. The filling and emptying procedures of the hood are controlled from the surface through a flexible air pipe and a shut-off valve. With the Oceanics 2, to simplify handling operations, the cage net is furnished with a "removable" net cover at the top.

2.7.3. Aquapod

Aquapod represents a distinctive marine aquaculture containment system designed to thrive in open ocean environments and accommodate a variety of species. Constructed with interconnected triangle net panels forming a spheroid shape, the Aquapod offers the flexibility of operating partially surfaced for convenient operations or fully submerged for storm safety. Additionally, the cage can rotate 360 degrees in any direction, facilitating easy access to all sections of it. Moreover, the Aquapod retains its shape and volume even in the face of strong currents or when under tow [19].

Figure 15 - Aquapod cage [18].

The Aquapod's anchoring options encompass grid systems, single and multi-point mooring systems. Generally, the preferred depths for Aquapod installations range from 35m to 100m. The deployment of Aquapod net is strategically coordinated to align with the existing infrastructure [19]. Figure 16 shows this system from the sea.

Figure 16 - Ocean view of aquapod cage [18].

2.8. Disposal of wind turbines in Europe

Effective and sustainable management of waste from aging wind turbines is crucial for the continued use of wind energy as an environmentally friendly energy source. The rapid expansion of the wind energy market poses a potential challenge, as the decommissioning of turbines could generate significant amounts of waste that require proper handling and disposal. Without proper preparation by the industry, this waste management issue could become a significant obstacle to the long-term sustainability of wind energy [14].

A wind turbine is exposed to two forms of aging: loss of performance because of physical wear and tear, and relative aging compared to the newest technology on the market. Sooner or later every plant will either be taken down since it is no longer worth repairing, or simply be replaced with newer more efficient technology. A lifetime of 20 years is by far the most common used for all types of wind power plants. As the wind power technology is still relatively young, few countries have markets that have been well developed for more than 20 years, and hence there is not yet much empirical data on turbine lifetime [14].

The dataset for offshore wind farms in Europe comprises a total of 6132 wind turbines and 128 wind farms. These were commissioned between 1995 and

2023, in twelve European countries. The information presented in Table 8 can be accessed on the Wind Europe website. The table presents the quantity of offshore turbines in all Europe by country. The historical data provided within this dataset includes the first recorded offshore wind farm in Europe, located in Denmark in 1995, up to the most recent one in the United Kingdom in 2023.

Table 8 - Offshore wind turbines in Europe.

Country	Turbines connected
United Kingdom	2708
Germany	1501
Denmark	630
Netherlands	627
Belgium	399
France	143
Sweden	80
Finland	19
Norway	13
Ireland	7
Portugal	3
Spain	2

Considering this information, we might have 6132 blades to be decommissioned in the next 20 years from offshore wind farms. If we include the onshore wind turbine blades, this number increases potentially, giving an opportunity to the market of aquaculture cages developed using partially wind turbine blades.

2.9. Swot analysis

SWOT, which stands for Strengths, Weaknesses, Opportunities and Threats is a commonly used tool for analyzing internal and external environments to attain a systematic approach and support for decision making. When conducting a SWOT analysis, it involves evaluating the organizations strengths and weaknesses based on its resources and capabilities. Moreover, opportunities and threats arise from actions or inaction, within the marketplace. Also, it's important to mention that SWOT analysis should be viewed as a tool integrated into the management and business development process than just being used as a static listing device [38]. Figure 17 shows the description of each parameter inside a SWOT matrix.

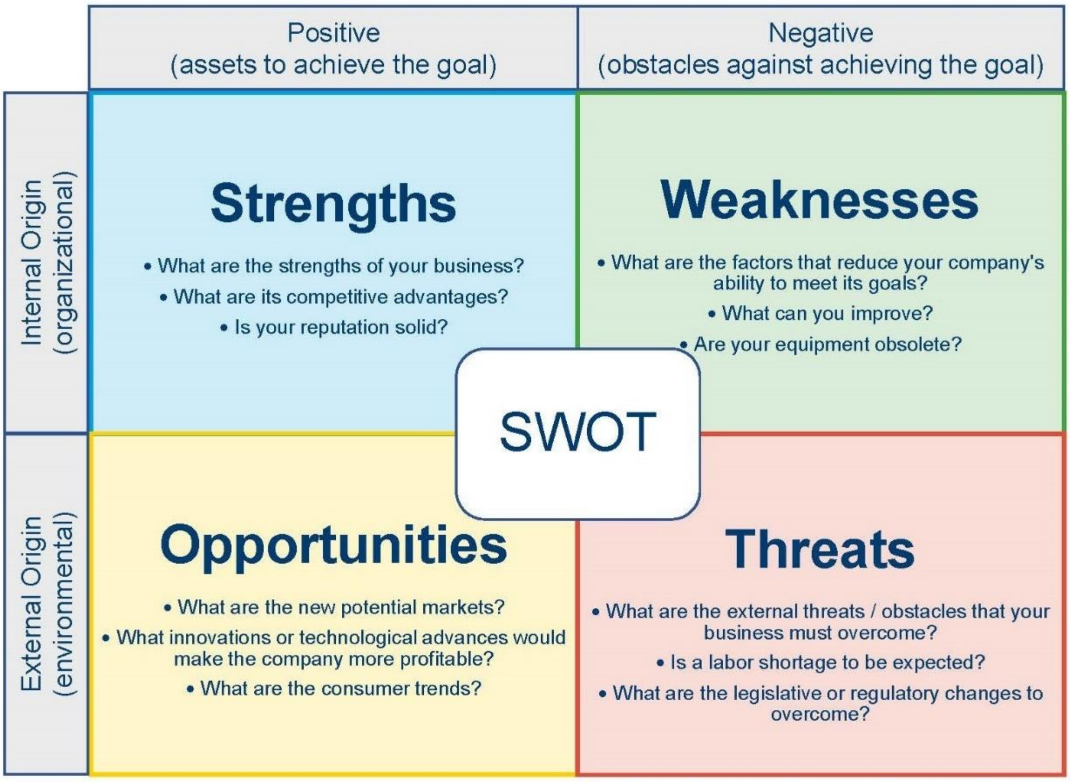

Figure 17 - SWOT analysis description [31].

A SWOT matrix will be presented in the results and discussion chapter, informing the strengths, weaknesses, opportunities, and threats of the idea rooted in this project.

3. Materials and methods

In today's context, wind turbine blades are often either incinerated or buried in empty lands when they reach the end of their operational life. To mitigate the environmental impact of this disposal method, the concept of upcycling wind turbine blades has been explored, aiming to reduce the need for landfills and incineration by repurposing the blades for alternative functions once their initial lifecycle concludes, such as incorporating them into functional roles within wind turbines.

Consequently, models of aquaculture cages integrating these repurposed wind turbine blades into their structures will be introduced. Four distinct design models have been developed for presentation and potential market assessment. The process of bringing a new product to fruition involves a series of steps culminating in its launch. These stages encompass:

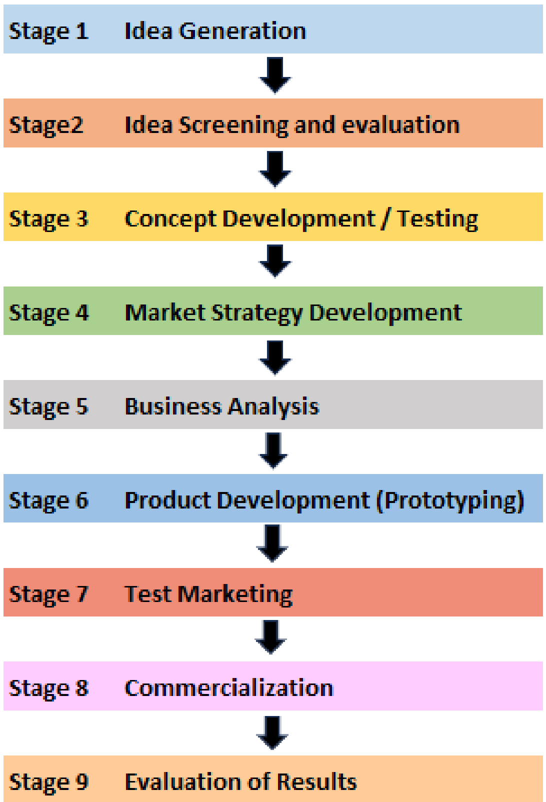

Figure 18 - Steps of project development [29].

The stages encompassed in the process of developing a new product are outlined as follows:

Idea Generation: This initial phase revolves around generating a multitude of ideas for potential new products. Considerations span from identifying market gaps and customer needs to drawing from internal or external sources of inspiration.

Idea Screening and Evaluation: During this stage, ideas are meticulously sifted through and evaluated to ascertain the most promising prospects for profitability. Factors considered includes the product's market potential, technical feasibility, and alignment with the company's overarching goals.

Concept Development and Testing: Product concepts are meticulously fashioned, considering elements such as the intended target audience, advantages, and conceivable usage scenarios. Subsequently, these concepts are subjected to consumer testing, aiming to gather feedback that refines and hones the original ideas.

Market Strategy Development: A comprehensive marketing strategy is devised to effectively position the new product in the market. Elements like market segmentation, positioning, and pricing strategy are meticulously contemplated.

Business Analysis: A financial evaluation of the potential product is conducted, weighing factors such as costs, sales forecasts, and projected profitability. This stage plays a pivotal role in gauging the product's overall viability.

Product Development: The potential product goes through a developmental stage that includes activities such as creating prototypes and testing to ensure functionality and quality. This process also encompasses aspects related to design, manufacturing procedures, and technical specifications.

Test Marketing: The emerging product is introduced within a limited market scope, allowing for further feedback collection and performance assessment. Evaluation factors span market reactions, consumer adoption, and potential areas for refinement.

Commercialization: The product is officially launched for production, distribution channels, advertising campaigns, and sales promotions. Components such as marketing communication strategies and distribution networks are all considered.

Evaluation of results: Following a period of market presence, the product's performance is meticulously appraised. Metrics includes sales figures, customer responses, and overall profitability.

It´s important to understand that in this work, we will consider only the idea generation and idea screening and evaluation, since no real tests were developed, and the models created and presented here are only theorical.

3.1. Project requirements

The main premise of the project was to create an aquaculture cage that could utilize wind turbine blades as structural reinforcement, thereby providing a reuse purpose for the wind turbine blades and reducing the environmental impact associated with their disposal and incineration at the end of their lifecycle.

Regarding the site characteristics for implementing this cage, it was considered that the location should not exceed a marine current of 3 knots, that is approximately 1,54 m/s. And the deep, for model 1, should be between 30 and 33 meters. For the other models, in the range of 12-15 meters. Table 9 shows the oceanics characteristics accepted to the local.

Table 9 - Oceanic characteristics to be considered for the models.

OCEANIC CHARACTERISTICS	
Maximum current speed	1,5 m/s
Maximum wave height	5,0 m
Average wage height	2,0 m
Depth	>=10 x <= 33 m

The selected fish for cultivation is the gilt-head bream, characterized by its oval and compressed body shape, with a prevailing silvery-gray color. This type of fish is commonly found in habitats with sandy and rocky bottoms adorned with algae, typically near the coast and at depths ranging from 10 to 30 meters [34].

In Portugal, the number of tons of gilt-head bream cultivated through aquaculture in the year 2021 amounted to 3091 tons. The tonnage of this fish's cultivation has seen substantial growth in recent years, especially when compared to the 1038 tons cultivated in 2017 [34]. Figure 19 shows the Gilt-head bream and Table 10 shows its characteristics.

Figure 19 - Picture of Sparus Auratus (Gilt-head bream) [35].

Table 10 - Characteristics of Gilt-head bream [35].

Characteristics of Golden fish	
Scientific name	Sparus Auratus
Family	Sparidae
Temperature	5 to 32ºC
Longevity	11 years
Length	35 cm to 70 cm
Depth	1 to 30 m

3.2. Design thinking

This chapter will describe how the blade was created in CAD software, so it would be used to construct the models thought for this project that will be presented in following topics. The chosen airfoil was the NACA 63-212 to create the blade profile. The design of this airfoil is presented in Figure 20.

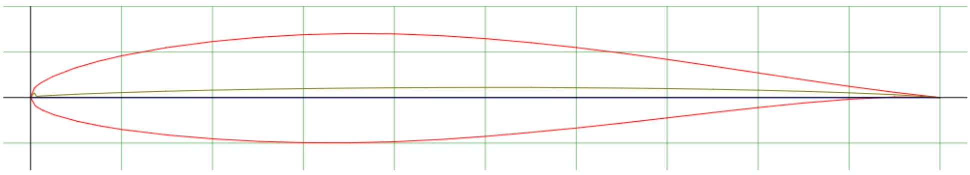

Figure 20 - Airfoil NACA 63-212 [16].

After choosing the airfoil, it was necessary to consider three important parameters, which will be described below: the chord, the radius, and the twist angle.

- ✓ Chord: It is an imaginary line that runs through the blade from the leading edge to the trailing edge. You can see it described as “c” in the next figure:

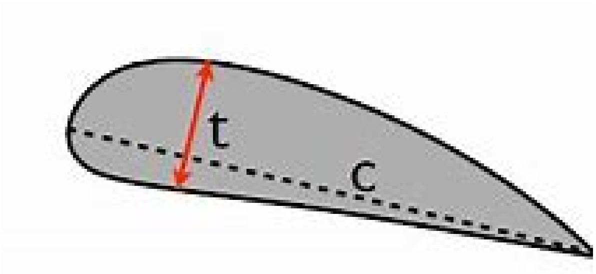

Figure 21 - Representation of the chord.

- ✓ Radius: In this case, can be considered as the lenght of the blade.

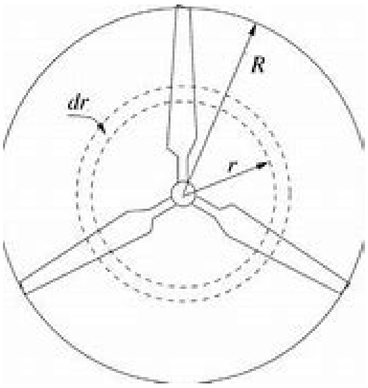

Figure 22 - Representation of the radius, which is "R".

- ✓ Twist angle: Succinctly, the angle of twist is the relative rotation of one face of a shaft with respect to another face when a torque is applied to that shaft.

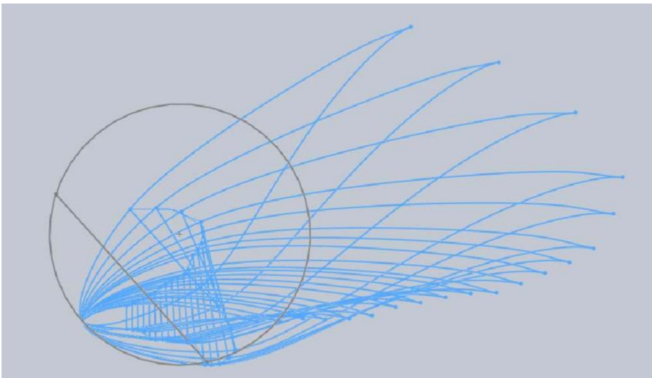

Figure 23 - Representation of the twist angle.

All the definition of these parameters were summarized just to understand the idea of the concept on how the blade was created for this project. Table 11 presents all the data required for constructing the blade, which will be utilized in developing the models examined within this project. These parameters were the chord, the radius and twist angle.

Table 11 - Parameters used to create the blade in Solidworks.

Chord (m)	Radius (m)	Twist angle (º)
4,145	3,4	20,0
4,054	4,0	19,0
3,992	4,6	18,0
3,902	5,2	17,0
3,795	5,8	16,0
3,678	6,4	15,0
3,549	7,0	14,0
3,428	7,6	13,0
3,300	8,2	12,0
3,173	8,8	11,0
3,047	9,4	10,0
2,925	10,0	9,0
2,575	12,0	8,0
2,386	14,0	7,5
2,208	16,0	7,0
2,109	18,0	6,5
2,002	20,0	6,0
1,895	22,0	5,5
1,792	24,0	5,0
1,665	26,0	4,5
1,531	28,0	4,0
1,329	30,0	3,5
1,240	32,0	3,0
1,034	34,0	2,5

An important note is that the twist angle considered for this project is just to emphasize the necessity of it. This criterion was not certainly calculated, since it’s just for evaluation and the data to create this was confidential. The same happens to the chord and radius parameters.

With this data, a draft of the blade was created. In Figure 24, it shows the sketch of the blade. It’s observed the twist angle of the blade along its length, as well as the variation in chord.

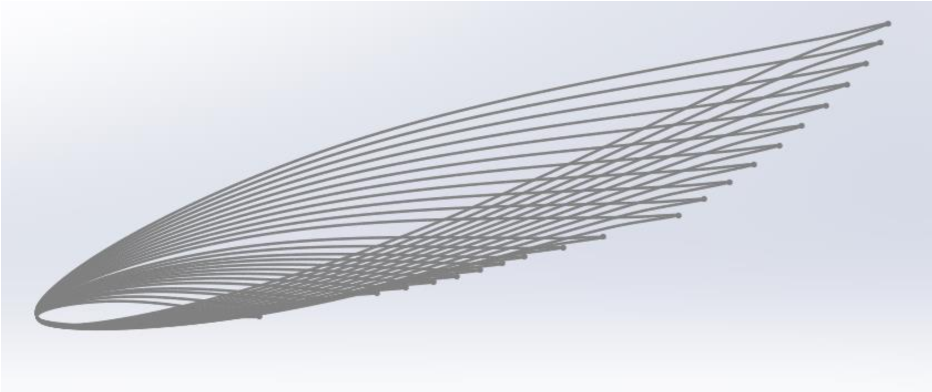

Figure 24 - Front view of the blade's draft.

Figure 25 and Figure 26 shows the isometric view and the side view of the blade, respectively.

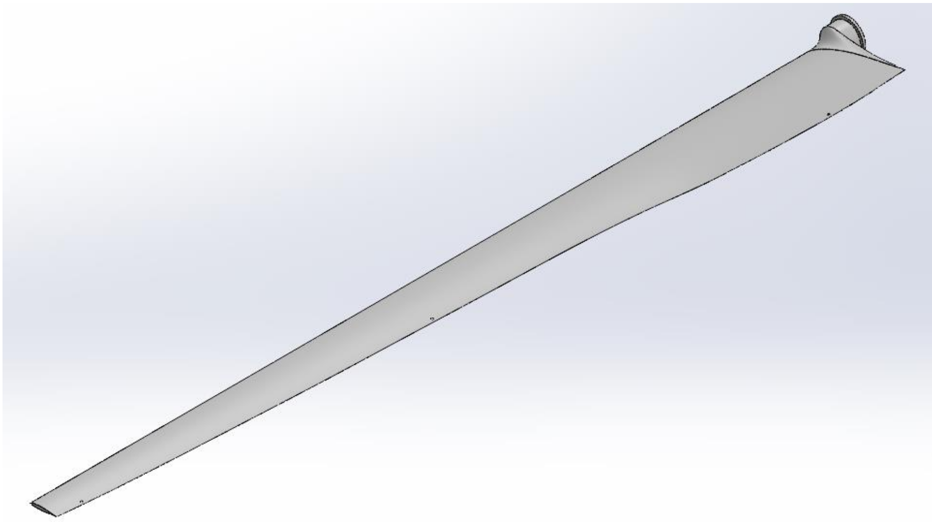

Figure 25 - Isometric view of the blade.

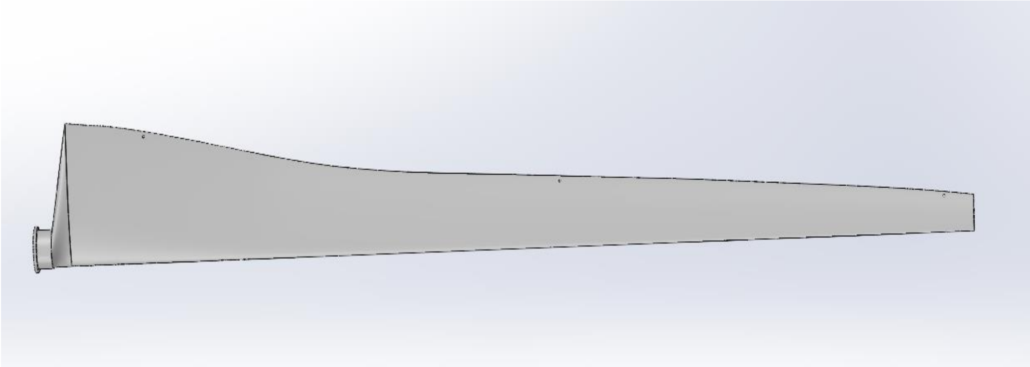

Figure 26 - Side view of the blade.

The material used for the wind turbine blade was E-Glass Fiber. The information in Table 12 was taken from software SolidWorks and shows the mechanical properties of this material. It’s important to know that the fiber glass properties may vary due to it way of being manufactured and developed, such as the concentration of components and alloys used.

Table 12 - Mechanical properties for E-glass fiber.

Property	Value	Unit of measure
Elastic Modulus	72500,00	N/mm²
Poisson's Ratio	0,23	N/A
Shear Modulus	318,90	N/mm²
Mass Density	2630,00	kg/m³
Tensile Strength	2050,00	N/mm²
Compressive Strength	5,00	N/mm²
Yield Strength	2875,00	N/mm²
Thermal Conductivity	0,23	W/(m·K)
Specific Heat	1386,00	J/(kg·K)

Four models will be presented during this chapter. Each model has its own characteristics and will be exhibited in detail for a better understanding of the proposals. Having this in mind, below is shown the representation for each one.

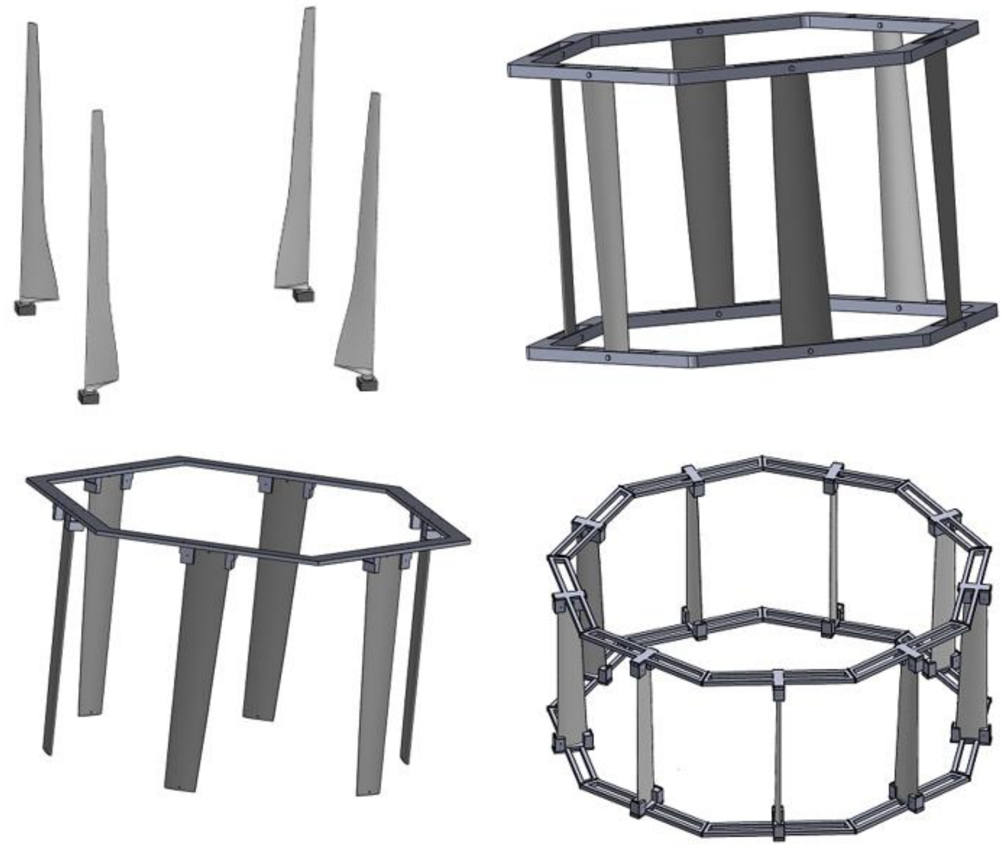

Figure 27 - Showcase of all models presented in this work.

3.3. Model 1

In this topic will be presented the model 1 proposed for this work. Figure 28 shows the design of this model in an isometric view:

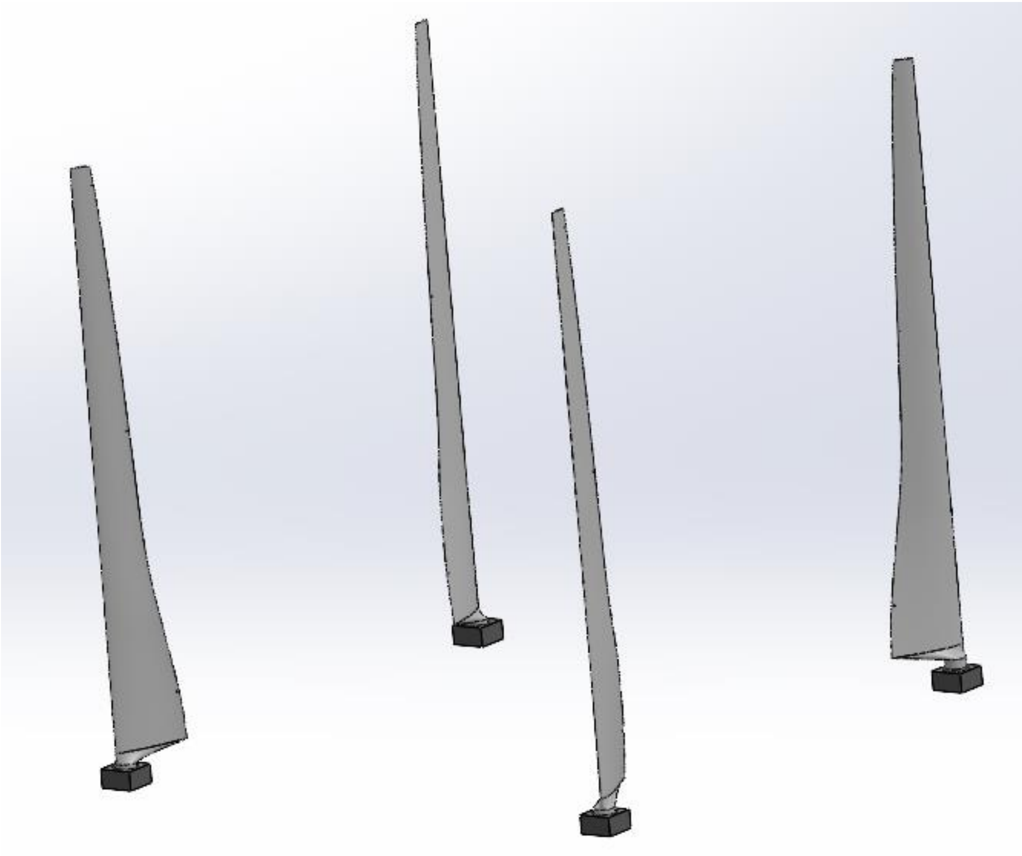

Figure 28 - Assembly model 1.

To create the model 1, the entire blade will be used to construct the layout. The concept behind this model is to have the blade connected to a support at the seabed, with the net secured to the edge opposite the leading edge of the blade.

A concrete box was envisioned for this purpose, which will be deployed at the seabed and serve as a fixed support for the blade. Figure 29 represents the box created in an isometric view.

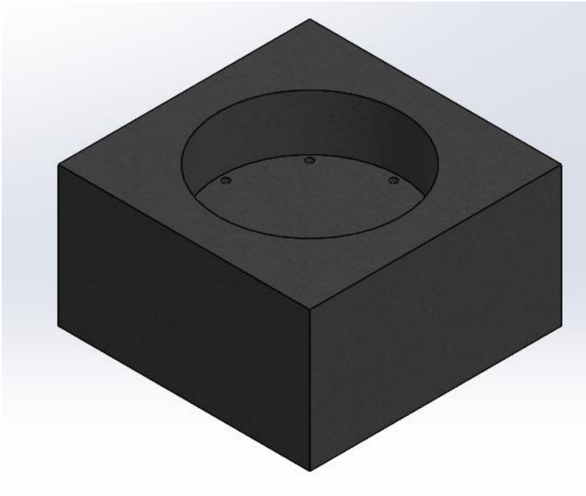

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Figure 29 - Concrete box for assembly of the whole blade.

Figure 30 shows the top view of the box, along with its respective dimensions, which are also displayed in Table 13.

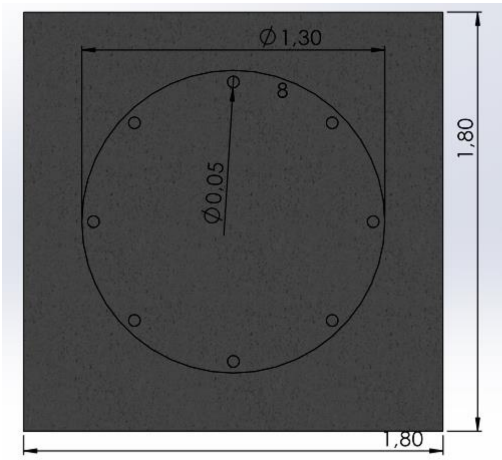

Figure 30 - Top view of concrete box

Table 13 - Dimension for the concrete box used in model 1.

Dimension	
Height	1,0 m
Lenght	1,8 m
Width	1,8 m
Depth of the holes	0,5 m
Diameter of the hole	1,3 m

Since a simulation were also done to check if this concrete box would handle the compressive load on it due to the weight of the blade, it’s important to mention the mechanical properties of it. Table 14 shows the properties of the concrete used in SolidWorks.

Table 14 - Properties of the “Normal weight concrete” in SolidWorks.

Property	**Value**	**Units**
Elastic Modulus	1,70 E+10	N/m²
Poisson's Ratio	2,00 E-01	N/A
Shear Modulus	1,00 E+07	N/m²
Mass Density	2,24 E+03	kg/m³
Tensile Strength	3,50 E+06	N/m²
Compressive Strength	3,00 E+07	N/m²
Yield Strength	2,00 E+07	N/m²
Thermal Expansion Coefficient	1,00 E-05	/K
Thermal Conductivity	5,00 E-01	W/(m·K)
Specific Heat	7,50 E+02	J/(kg·K)
Material Damping Ratio	5,00 E-02	N/A

The blade will be fastened to the concrete box using screws in the following manner. These screws will help on supporting the blade and have it fixed.

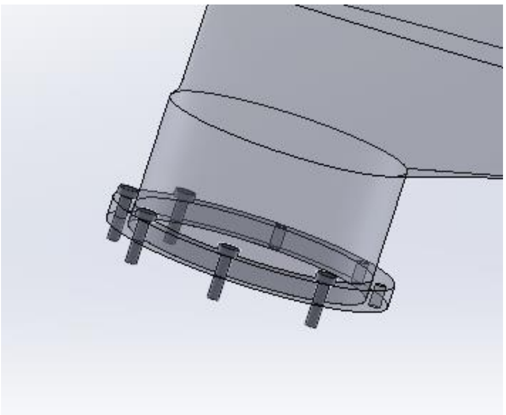

Figure 31 - Fastening of the blade to the box.

The final design intended to this model is represented in Figure 32.

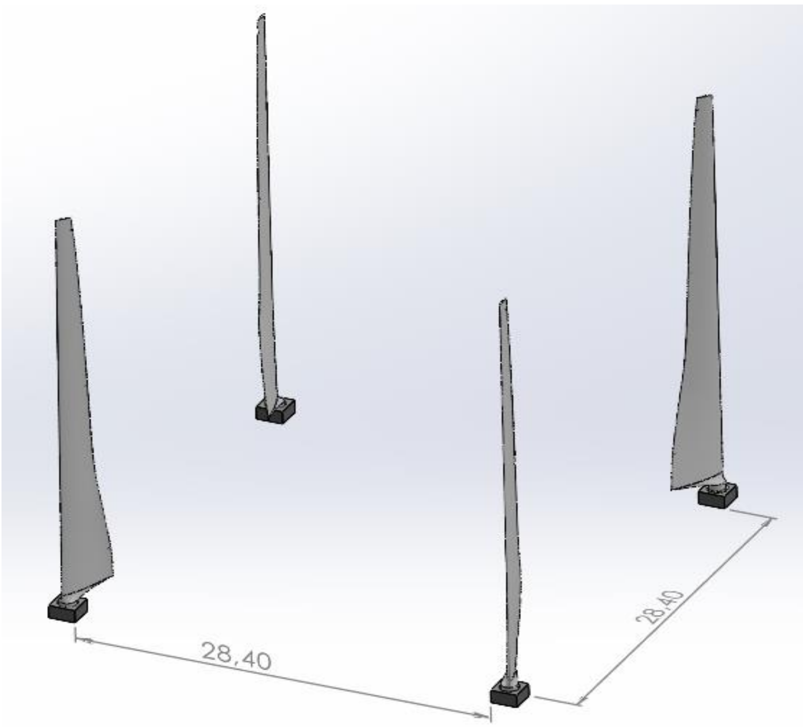

Figure 32 - Final assembly of the cage model 1.

This model must be placed in locations with the flattest possible surface, ensuring stability for it. In the presented design, we have 28,4 meters between the boxes, arranged in a square pattern.

Six holes have been created in the blade, which will serve as attachment points for the net for the cage. The holes have 5 mm, and their location are shown in Figure 33.

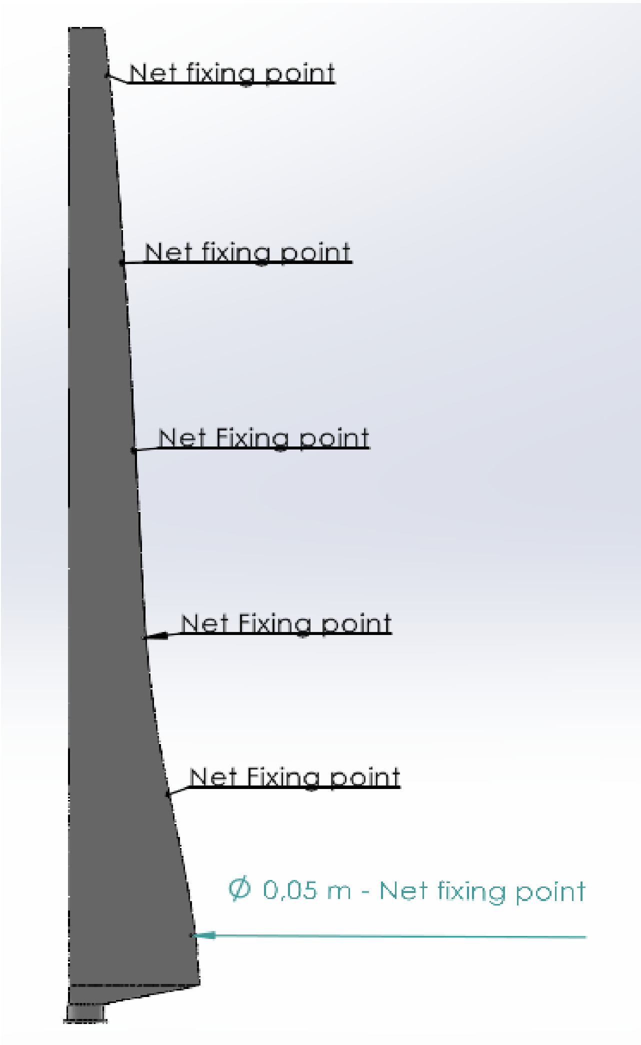

Figure 33 - Hole to fix the net.

The advantages and disadvantages of this model is presented in Table 15. The biggest issue for this model may be the size of the blade. Since it has 34 meters, the logistics to do the transportation of the part is hard and needs special transport.

Table 15 - Advantages and disadvantages of model 1.

Advantages	Disadvantages
Cage layout in any format.	Blade size.
Variability of the cage diameter.	Logistical challenge due to the size of the blade.
	Assembly of the cage on-site.

Table 16 shows the characteristics of the model 1. Some of the characteristics are quantity of blades needed for the proposed model and the type of cage that it will be.

Table 16 - Characteristics for model 1.

Characteristics of model 1	
Quantity of blades	4
Location	Off the coast
Type of cage	Submersible

For this model, a simulation was conducted to verify whether the developed assembly would withstand the drag force and determine the maximum and minimum stresses at focal points. The result of this simulation will be presented in a future topic.

The drag coefficient is an important variable to be considered for this model, as the blade has a length of 34 m and will be used almost entirely. With this, the parameters considered for calculating the drag force and how it was done will be shown.

In physics, drag force is the force that opposes the relative motion between an object and a fluid. A fluid is anything that flows, such as a liquid or a gas. When the fluid is air, drag force is represents air resistance. The object might move through the fluid, or the fluid might move around the object, but in both cases the drag force acts in the opposite direction of the relative movement [32].

The formula that expresses the drag force is:

$$F = C_d * \rho * V^2 * A \tag{1}$$

Where:

F = drag force;

C_d = drag coefficient;

ρ = density of the fluid;

V = velocity of the body or of the fluid;

A = cross section area.

Figure 34 shows some elliptical profiles that can be used to consider the drag coefficient.

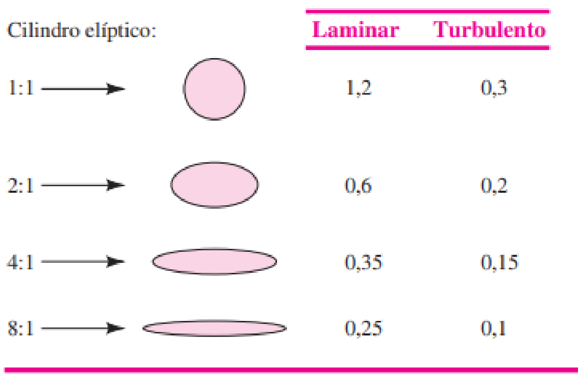

Figure 34 - Cross section area for coefficient drag force.

The profile considered was the 4:1, as it is the one that most closely represents the Naca profile chosen to develop the blade in this project, which is presented in Figure 20. The higher the drag coefficient, the greater the drag force. In this case, the drag coefficient of the laminar profile, 0,35, will be considered. It is worth noting that the drag coefficient can vary based on the Reynolds number of the flow.

Two criteria will be used to analyze the drag force. One in which the current is in contact with the leading edge of the blade, and the other where the current will be in contact with the larger side of the blade. The first situation is represented in Figure 35 and the second situation in Figure 36.

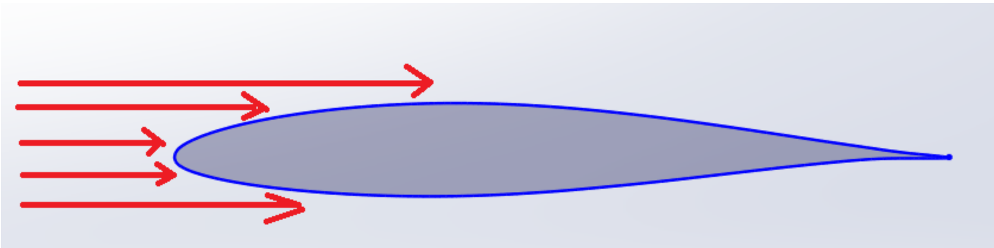

Figure 35 - The current direction against the leading edge of the blade.

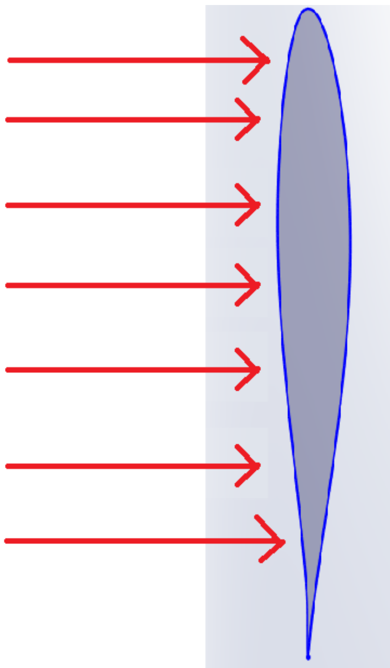

Figure 36 - The current direction against the larger side of the blade.

Providing further details of the simulation, starting with the fixation points considered. The blade will be fastened to the concrete box using 8 stainless steel bolts. The bolts have the following mechanical properties, as shown in the Table 17.

Table 17 - Mechanical properties of AISI 316 stainless steel in SolidWorks.

Property	**Value**	**Units**
Elastic Modulus	1,93E+11	N/m²
Poisson's Ratio	2,70E-01	N/A
Tensile Strength	5,80E+08	N/m²
Yield Strength	1,72E+08	N/m²
Thermal Expansion Coefficient	1,60E-05	/K
Mass Density	8,00E+03	kg/m³
Hardening Factor	8,50E-01	N/A

Figure 37 shows the points where the blade will be fastened to the concrete box using bolts.

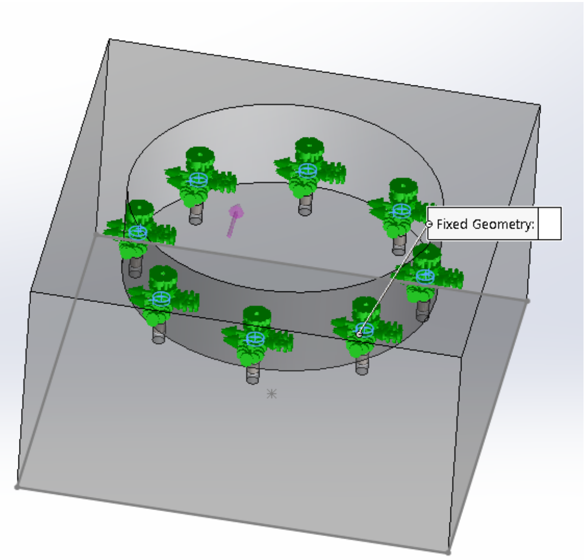

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Figure 37 - Fixing points of simulation for model 1.

The mesh created for the simulation has 16 Jacobian points, with a total of 19509 nodes and 11232 elements. All these mesh parameters are described in Table 18.

Table 18 - Mesh parameters used to simulate drag force.

Jacobian points	16 points
Max Element Size	0,698 m
Min Element Size	0,034 m
Total nodes	19509
Total elements	11232
Mesh quality	High

Regarding the last step of the simulation, which is the area and type of force applied to the assembly, due to the blade having a shape like an ellipse, it becomes challenging to apply the force in the required region. It was established that the contact area of the fluid with the assembly be rectangular. This way, obtaining the results would be simpler, as the elliptical contact zone is more limited in the software used.

As mentioned earlier, two simulations will be conducted, one at the leading edge of the blade, and the other in contact with the region of greater area, perpendicular to the blade. As a result, the rectangular dimensions that were considered in the force setup step will be presented. Figure 38 shows the rectangular area for L = 2.6 m, which would be the average value for the blade chord length, with the arrows representing the direction of the current.

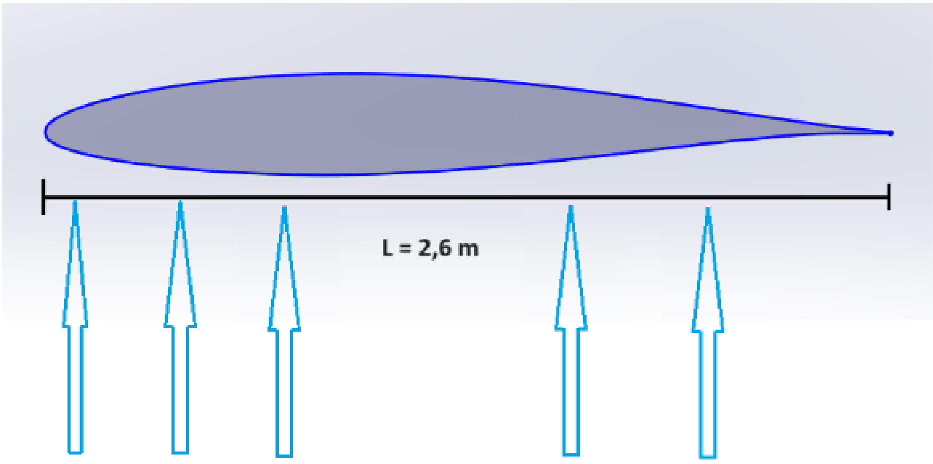

Figure 38 – Size of the larger side of the blade in contact with fluid.

Figure 39 shows the dimension "L" considered, which was 0,8 m and the direction of the current in this regard, represented by the blue arrows.

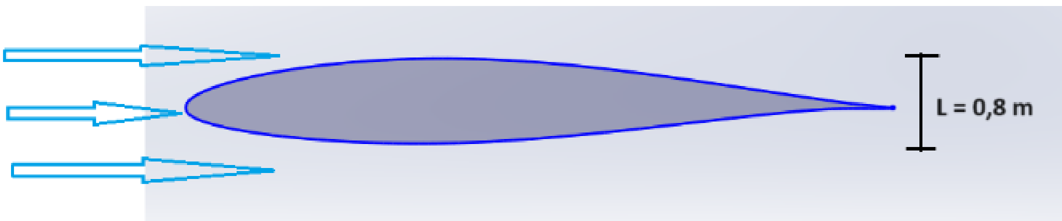

Figure 39 - Size of the leading edge of the blade in contact with fluid.

Figure 40 and Figure 41 show the cross-section area considered to calculate the drag force.

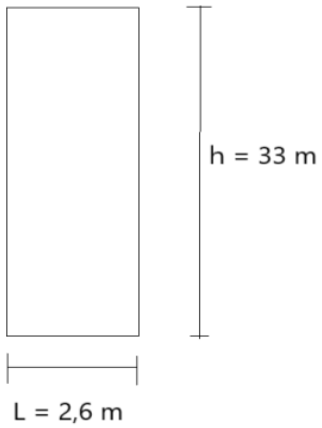

Figure 40 - Cross section considered to calculate the drag force, average chord for L dimension.

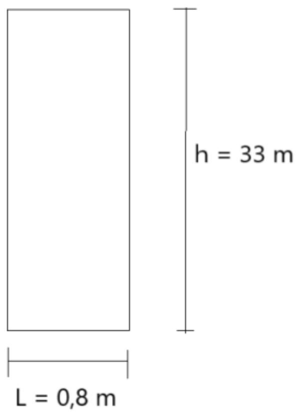

Figure 41 - Cross section considered to calculate the drag force, leading edge.

Figure 42 shows the model developed in SolidWorks and the location where the force is applied for the simulation in the software. This force application location is the same as represented in the Figure 39.

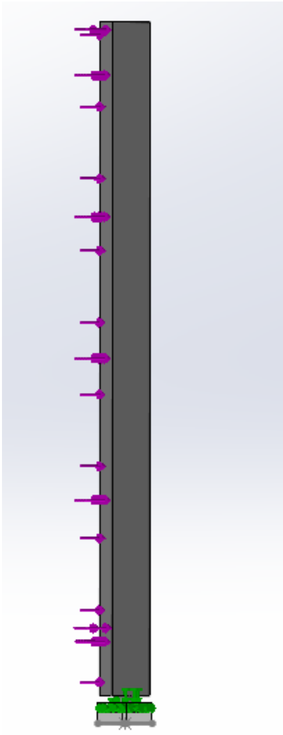

Figure 42 - Smaller side of the blade to applicate drag force.

Figure 43 displays the location where the force is applied for the simulation in the software, highlighting the same from the Figure 38.

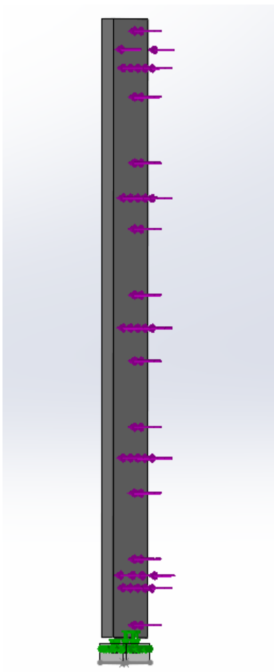

Figure 43 - Larger side of the blade to applicate drag force.

However, these were the materials and methods used for the CAD development of model 1, as well as for conducting the static simulation study.

The volume of this cage, considering that it is assembled in a square format with distances of 28.4 meters between its sides, will be 25,800 m³. The volume in this model is much greater compared to the others that will be presented. However, the distance between the blades is a parameter that can be modified according to the project's requirements, so this volume can be adjusted as needed.

3.4. Model 2

In this topic will be presented the model 2 proposed in this work. Figure 44 shows the design of this model:

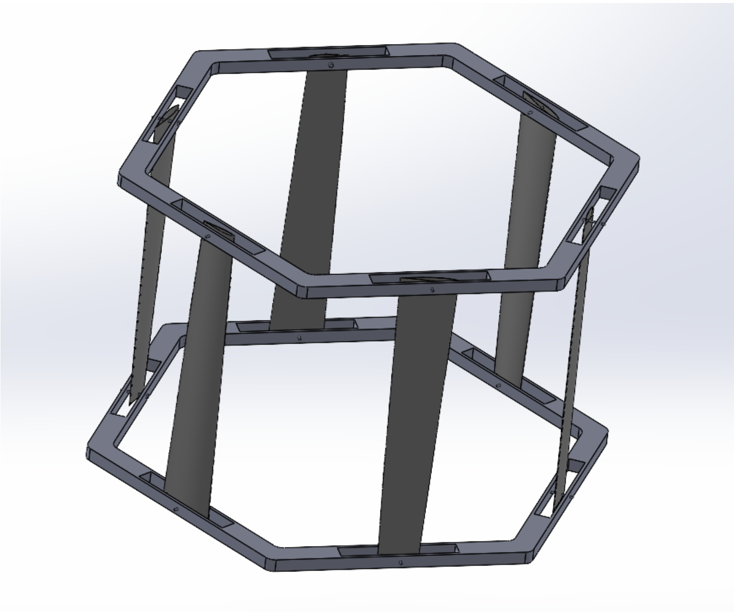

Figure 44 - Assembly model 2.

For the creation of model 2, only a part of the blade will be used. It was taken into consideration that for this model, the use of special transportation would not be necessary. Therefore, according to the regulations for special traffic permits, Decree No. 472/2007, machines that are not registered and do not exceed the gross weight of 40 tons or the following dimensions are exempt from special traffic permits:

- 12 meters in length;
- 2,55 meters in width;
- 4 meters in height from the ground.

In Decree-Law No. 133/2014, the maximum dimensions of vehicles for the purpose of regular circulation without special transportation are as follow:

- ✓ Motor vehicle-trailer combination - 18.75 meters;
- ✓ Motor vehicles with two or more axles (excluding heavy passenger cars) - 12 meters;
- ✓ Trailers with one or more axles - 12 meters;
- ✓ Heavy passenger cars with two axles - 13.5 meters;
- ✓ Heavy passenger cars with three or more axles - 15 meters;
- ✓ Articulated heavy passenger cars - 18.75 meters;
- ✓ Motor vehicle-tractor unit with three or more axles - 16.5 meters;
- ✓ Motor vehicle-trailer combination - 18.75 meters;
- ✓ Tourist trains - 18.75 meters;
- ✓ Motor-driven or towed machines - 20 meters.

Considering the presented decrees, only 12 meters of the blade were considered, so there is no need for special transportation in this project. The size of the rope and the length used to make up the part of the blade that is used are shown in the following table:

Table 19 - Parameters of the blade taken from original one to create the 12m model.

Radius (m)	Chord (m)
16	2,208
18	2,109
20	2,002
22	1,895
24	1,792
26	1,665
28	1,531

In the following image, we see the profile of the part that after been cut:

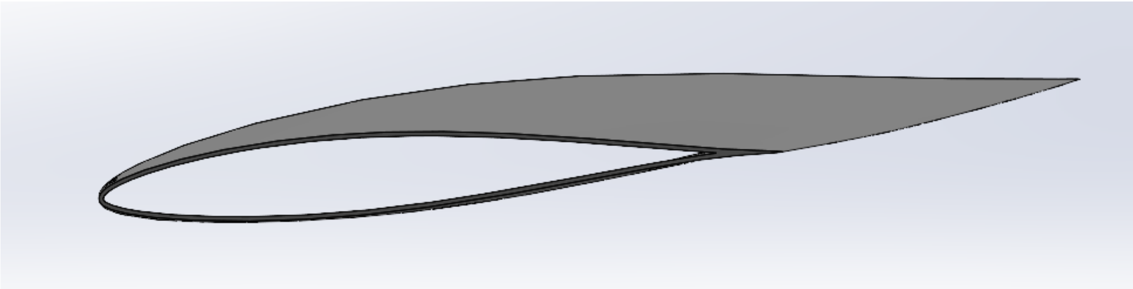

Figure 45 - Front view of 12 m blade.

The draft of the isometric view and the completed design are presented in the following images.

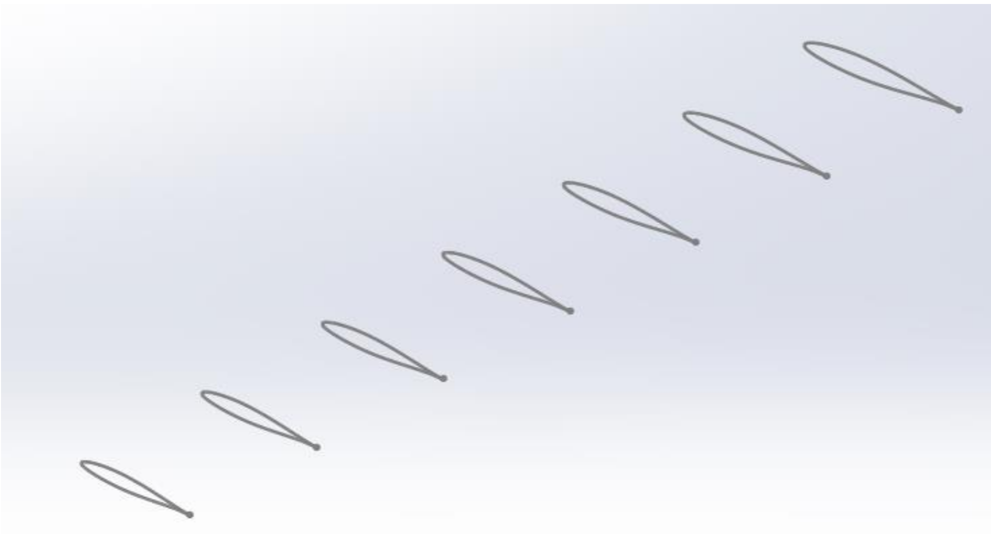

Figure 46 - Isometric view of the sketch Naca profile in their respective planes.

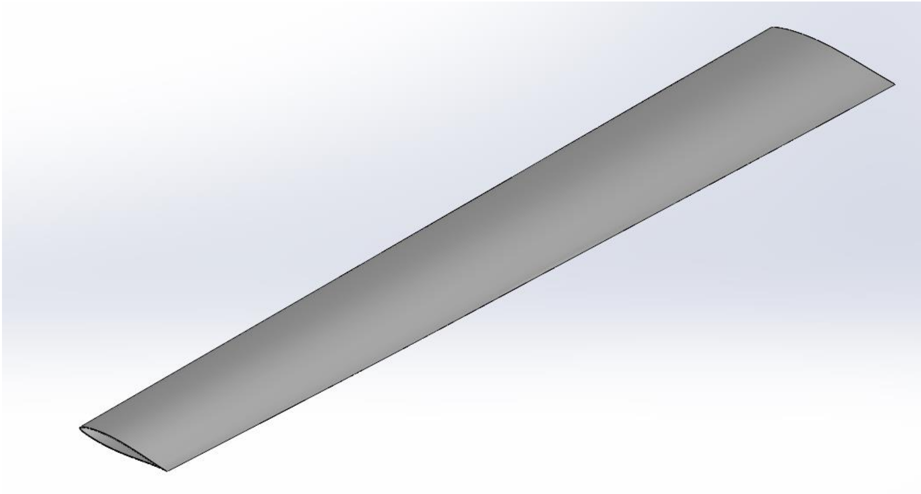

Figure 47 - Completed design of 12m blade.

A hole was created in the center of the blade to fix it in the structure, as shown in Figure 48.

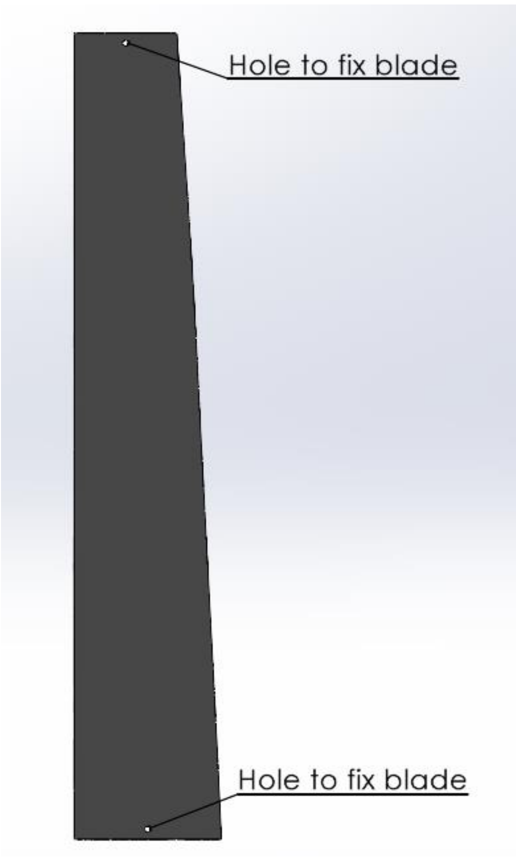

Figure 48 - Hole to fix the blade in structure.

This hole has a diameter of 8 cm, and its center is located 15 cm from the beginning of the blade. The hole is present both on the upper and lower sides. Both the top and bottom structure has the same dimension and specifications. It has 6 sides, and it is presented in Figure 49.

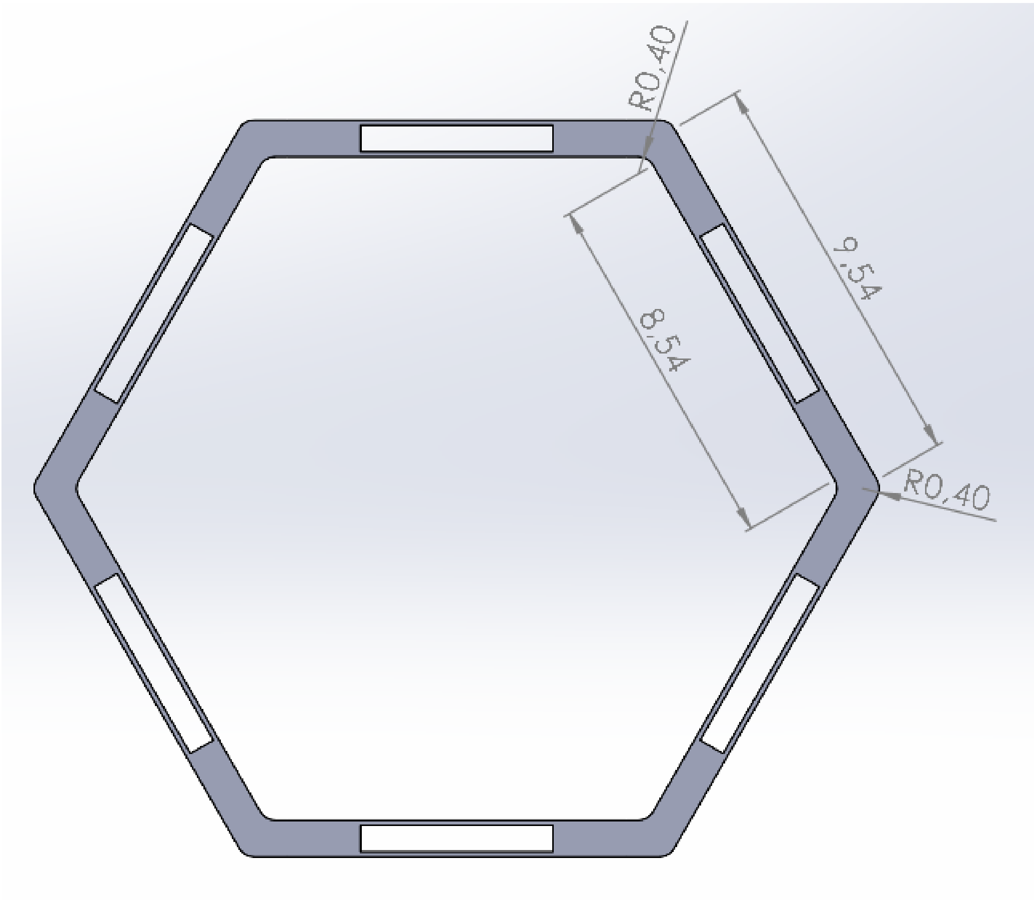

Figure 49 - Upper and bottom structure of model 2.

With these parts presented, after they been assembled, the result can be presented in Figure 50, described as frontal view.

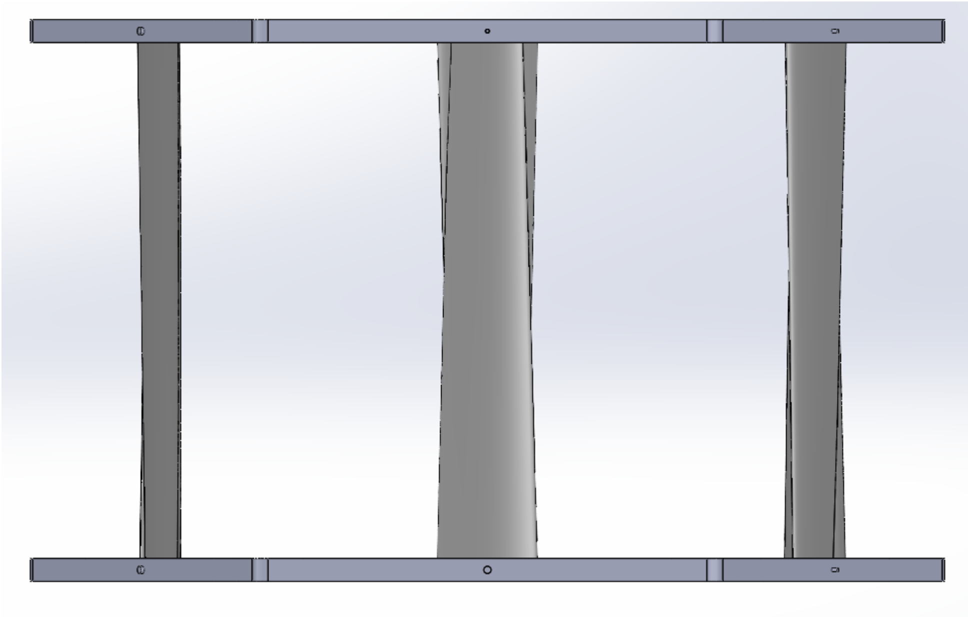

Figure 50 - Frontal view of the cage model 2.

In the next figures, the top view and isometric view are highlighted, respectively:

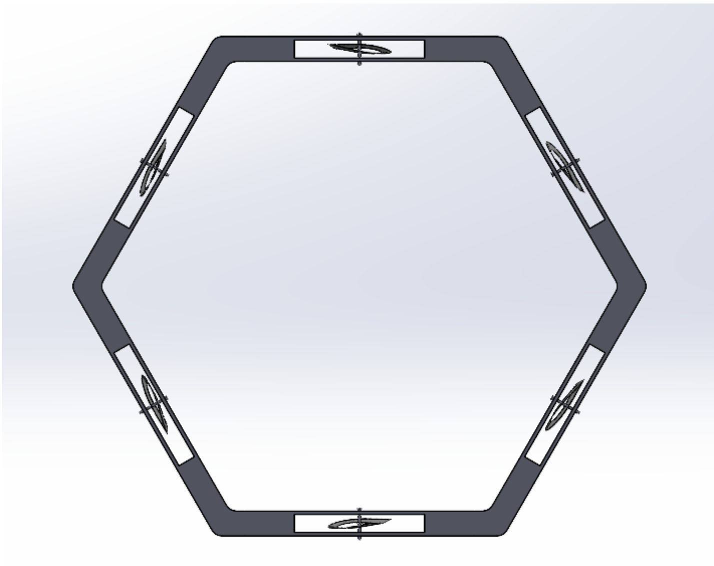

Figure 51 - Top view model 2.

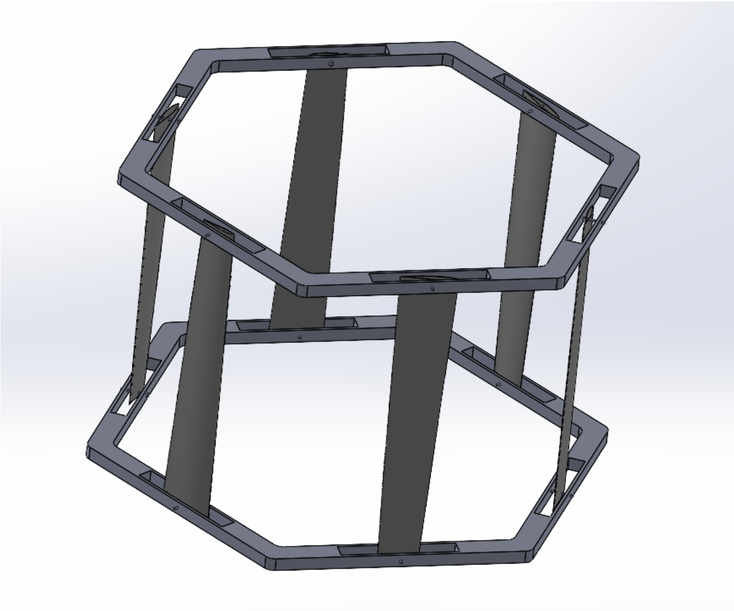

Figure 52 - Isometric view model 2.

The cage is fastened with screws that have a diameter of 8 cm, which will secure the blades to the upper and lower supports. In Figure 53 we can see how it is fastened.

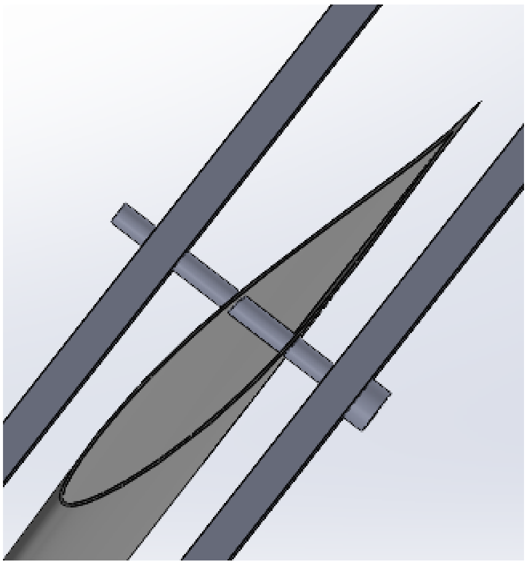

Figure 53 – Fastening of the structure and blade.

The screw is made of stainless steel and its properties were described previously in Table 17. The screw is an important part of this assembly, since it will hold the weight of the blade. The simulation of load will be shown in chapter of results and discussions.

Considering that the inner circumference of the polygon measures 9 meters and the height is 12 meters, we have an estimated volume of 763 m³. Since the complete portion of the hexagon will not be used, only 90% of this volume will be considered, resulting in a final volume of 686,7 m³.

About the fixation of the net, for this model was created 12 fixing points, 6 each side, to fix the net. The hole has 3 cm and is spaced 2 meters to each other.

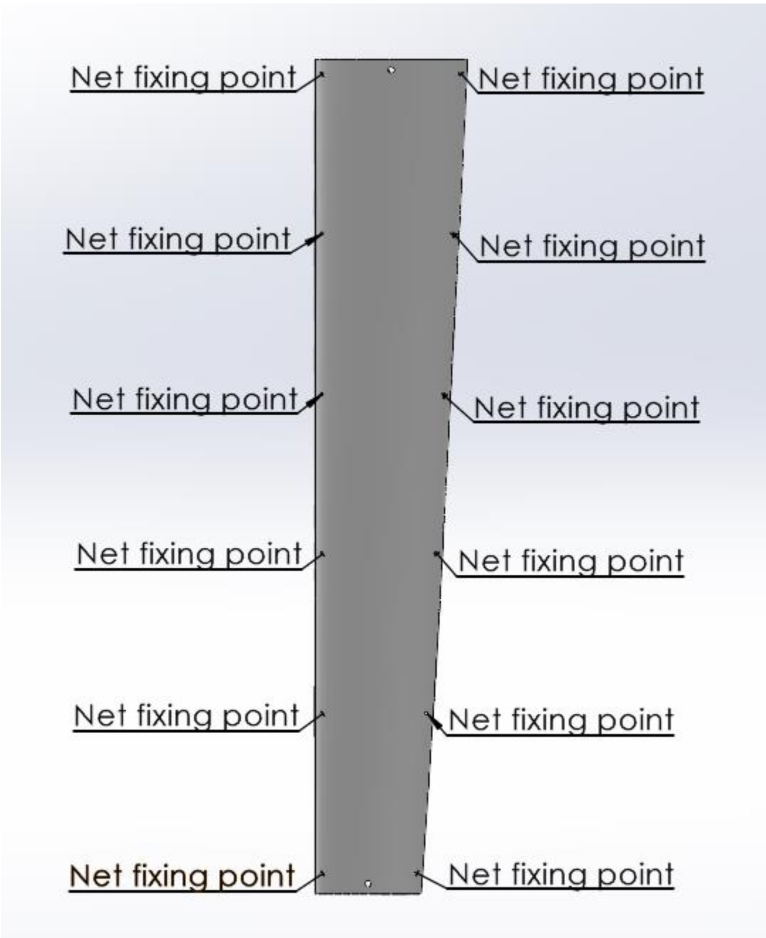

Figure 54 - Fixing points for the net in cage model 2.

The advantages and disadvantages of model 2 are presented in Table 20.

Table 20 - Advantages and disadvantages of model 2.

Advantages	Disadvantages
It can be fully submersible or adapted for floating.	More complex fixation.
It has a smaller size compared to model 1.	Structural weight for whole cage.
More versatile.	Assistance in the flotation of the cage.

Table 21 shows the general characteristics for this model, as the quantity of blades used and the type of cage it will be.

Table 21 - General characteristics of model 2.

Characteristics of model 2	
Quantity of blades	6
Location	Off coast
Type of cage	Floating / Submersible

This cage has two types to be proposed, floating and fully submersible. To this cage to be floating, it will need some particularity to be studied, which will be discussed in chapter of results and discussion. Another situation is the points of fixation for the net.

Another important parameter to be shown in this topic are the steps followed to do the simulation of load for the screw that holds the blade. The fixing points used to do the simulation are the anchor points in extremities of the screw, which will meet the structure. These parts are highlighted in blue in the following image.

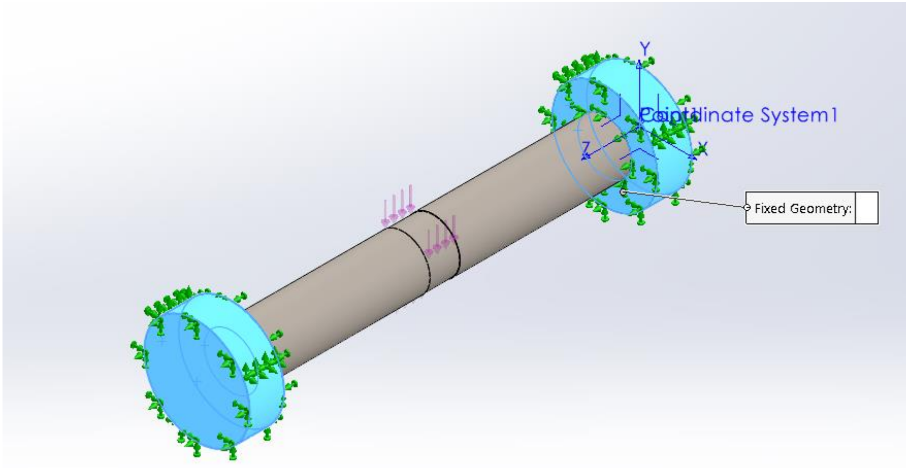

Figure 55 - Fixing points to simulate a static analysis for pin used in model 2.

The load used was calculated based on the weight of the blade. The mass of the blade is approximately 1200 kg, within the 12 meters. Therefore, the weight used in this stage was 12 kN, with the load direction being negative along the y-axis as shown in the coordinate system in Figure 56.

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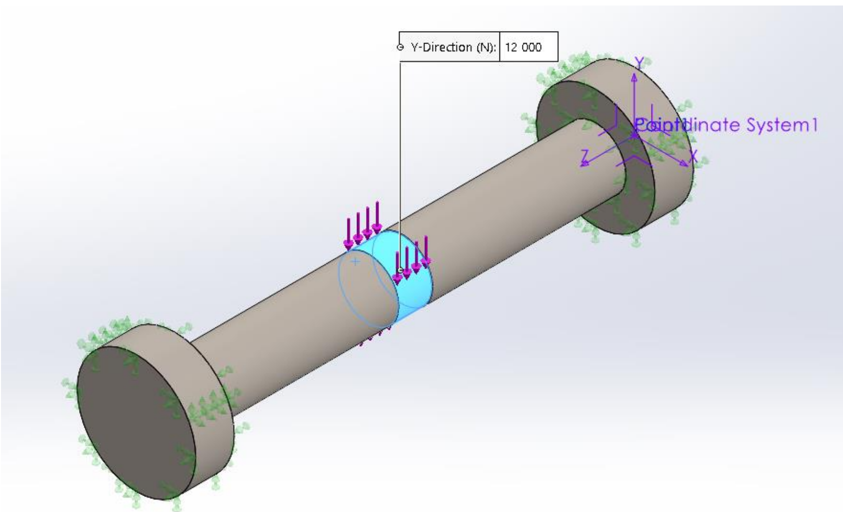

Figure 56 - Load steps in simulation for Model 2.

The mesh created for this simulation have 16 Jacobian points and a total node of 19777 elements. Other parameters of this mesh are shown in Table 22.

Table 22 - Mesh parameters used to simulate the load on screw of model 2.

Jacobian points	16 points
Max Element Size	0,03 m
Min Element Size	0,02 m
Total nodes	19777
Total elements	12686
Mesh quality	High

Another analysis that will be described is the parameter to have this cage floating. All the data will be presented and discussed in the results and discussions section.

3.5. Model 3

In this topic will be presented the model 3 proposed in this work. Figure 57 shows the design of this model:

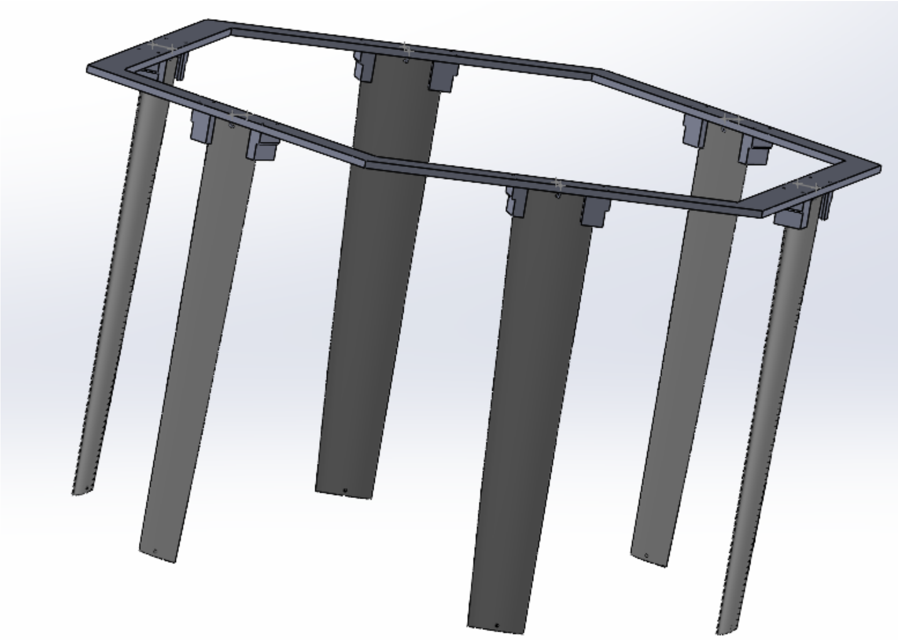

Figure 57 - Assembly model 3.

In model 3, the cage will have only the upper support for holding the blades. The other edge of the blade will have limited movement since the idea is for the other end to be tied to a rope, which will be anchored to the seabed. It will have 6 points that will be used to hold the support fitting, used as wedge to the blades.

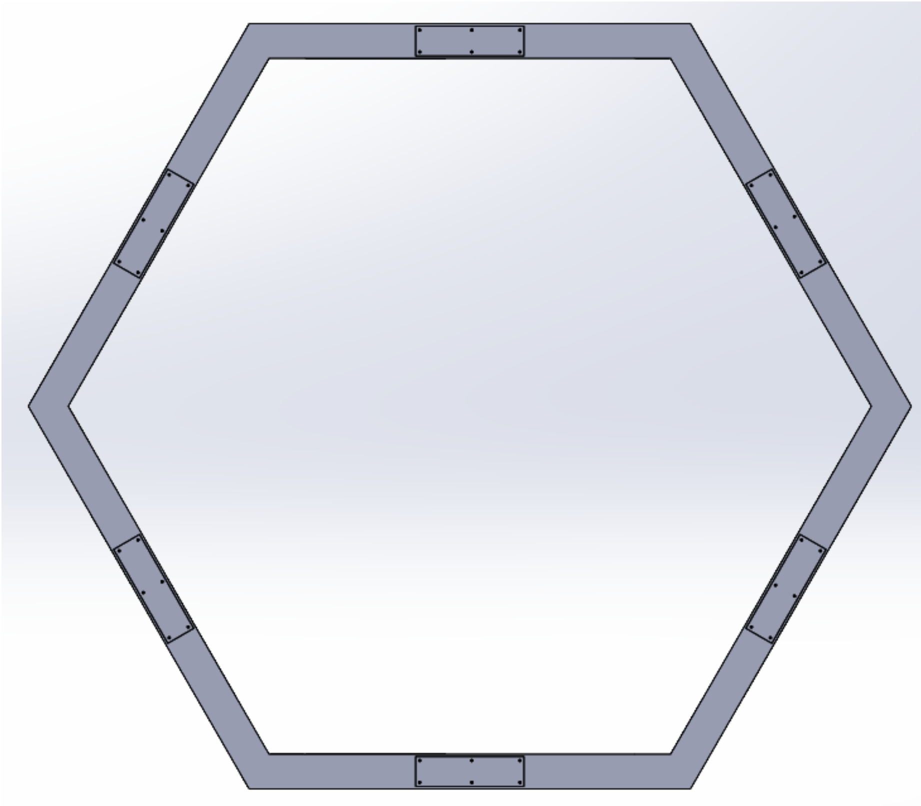

Figure 58 - Top view of model 3 to present the dimension of the cage.

The following table shows the dimension of the hexagonal support of the cage. The internal and external side are the inner circumference of the polygon and the cut for support fitting is the place to attach the wedge to link blade and structure.

Table 23 - Dimensions of the hexagonal support of model 3.

Dimension	
Internal side	10 m
External side	11 m
Cut for support fitting	2,7 m x 0,75 m

In this design, there are holes that will be used for fastening the screws to the blade support. In Figure 59 is shown the wedge to link the blade to the structure.

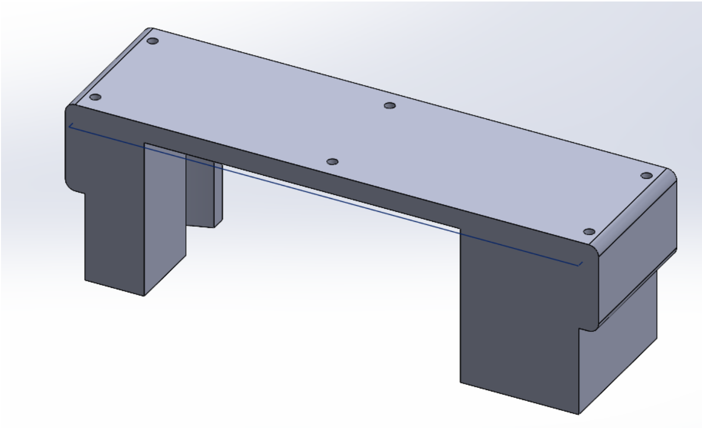

Figure 59 - Wedge to link blade and structure.

Figure 60 shows the dimension of the wedge link created to this model to attach the blade to the top support.

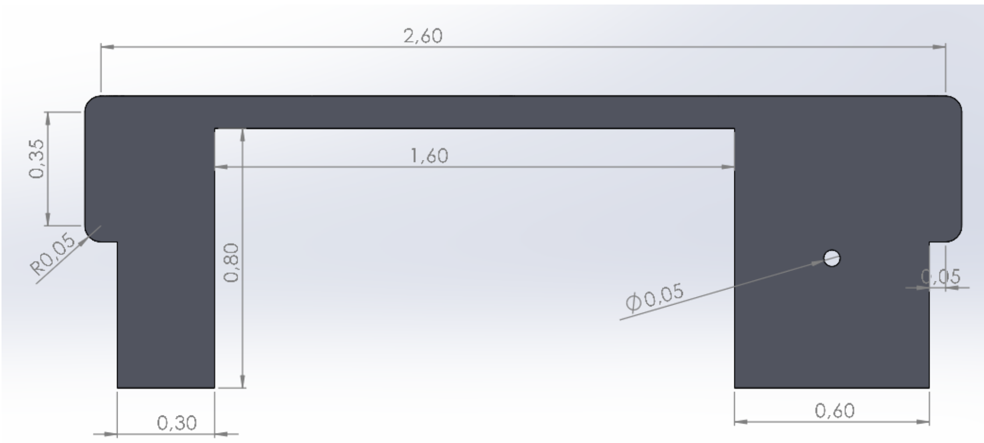

Figure 60 - Dimension of the wedge link.

This part will be attached to the upper base as well as the blade. The four holes at the end will be used to secure the screws to the upper base. The two central holes will be used to hold the blade in place using chains. This idea to use chains is to facilitate the assembly and reduce the weight of the cage. For better visualization of what has been said, Figure 61 shows the assembly of the parts.

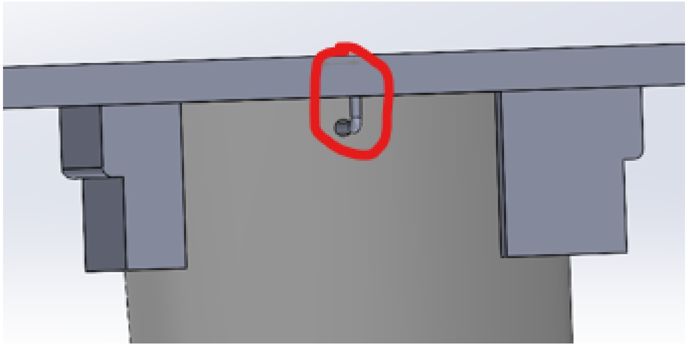

Figure 61 - Assembly blade and wedge.

The chain is represented by the red circle indicating where it goes. That part was used to indicate the chain. It is better visualized in Figure 62.

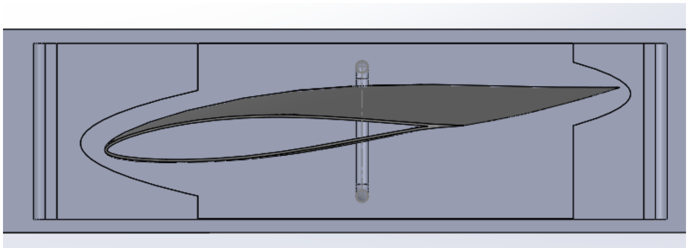

Figure 62 – Bottom view of assembly blade and wedge.

The complete cage has the following appearance:

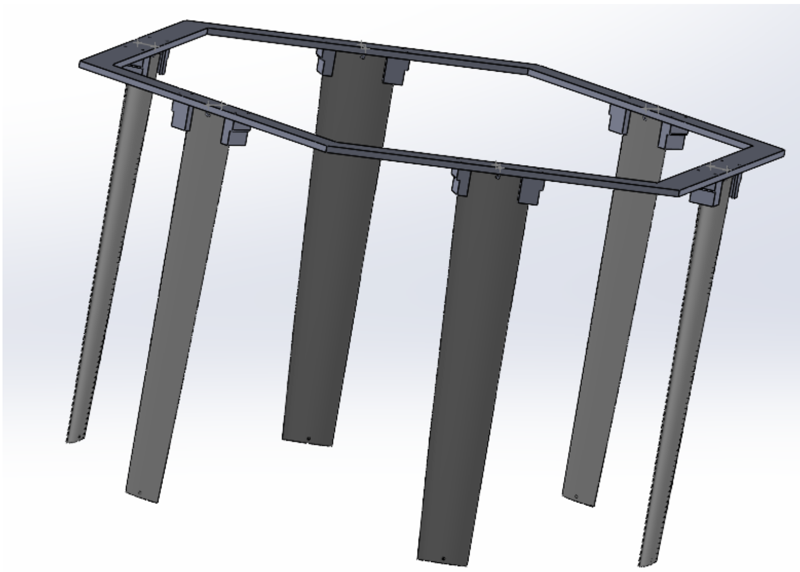

Figure 63 - Final assembly model 3.

Considering that the inner circumference of the polygon measures 10 meters and the height is 12 meters, we have an estimated volume of 942 m³. Since the complete portion of the hexagon will not be used, only 90% of this volume will be considered, resulting in a final volume of 847,8 m³.

Since this model has just one part of the blade fixed to a support and the other part will be loose, Figure 64 represents the idea expressed for this model. For this case, the structure would be floating and would also need to have a floating system to support its weight. The steps to better inform the parameters to develop this system will be shown in results and discussion chapter.

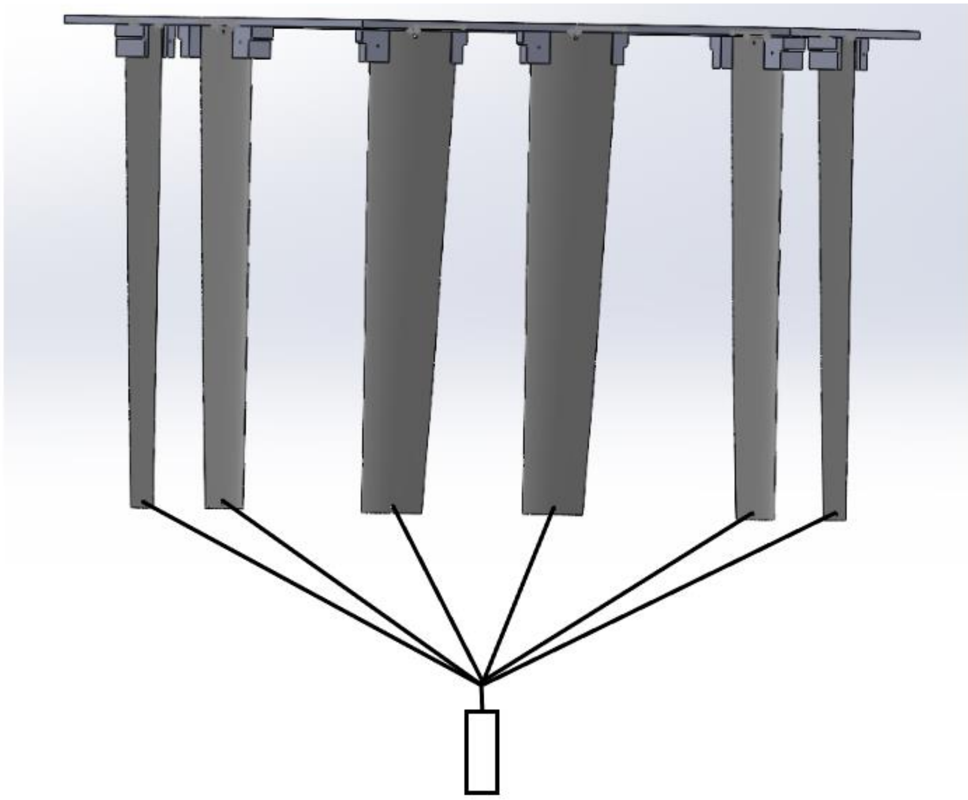

Figure 64 – Anchoring of the blades to help fixation.

About the fixation of the net, it will be the same as presented in model 2, as shown in Figure 54. Since the blade and geometry of the cage is pretty similar, no change was considered for the net fixing points. The advantages and disadvantages of this cage are presented in Table 24.

Table 24 - advantages and disadvantages of model 3.

Advantages	Disadvantages
It has less weight compared to the other models.	Limited to one scenario, as floating
The blades are not entirely structurally rigid.	Necessity of floating system.
Semi-submersible or fully submersible	Strong marine currents can affect the structure

Some of the characteristics of this model is that it has 6 blades, as in model 2 and the application site for this model must be at least 14 meters deep. The characteristics presented for the model 3 is shown in Table 25.

Table 25 - Characteristics of model 3.

Characteristics model 3	
Quantity of blades	6
Location	Off the coast
Type of cage	Floating

3.6. Model 4

In this topic will be presented the model 4 proposed in this work. Figure 65 shows the design of this model:

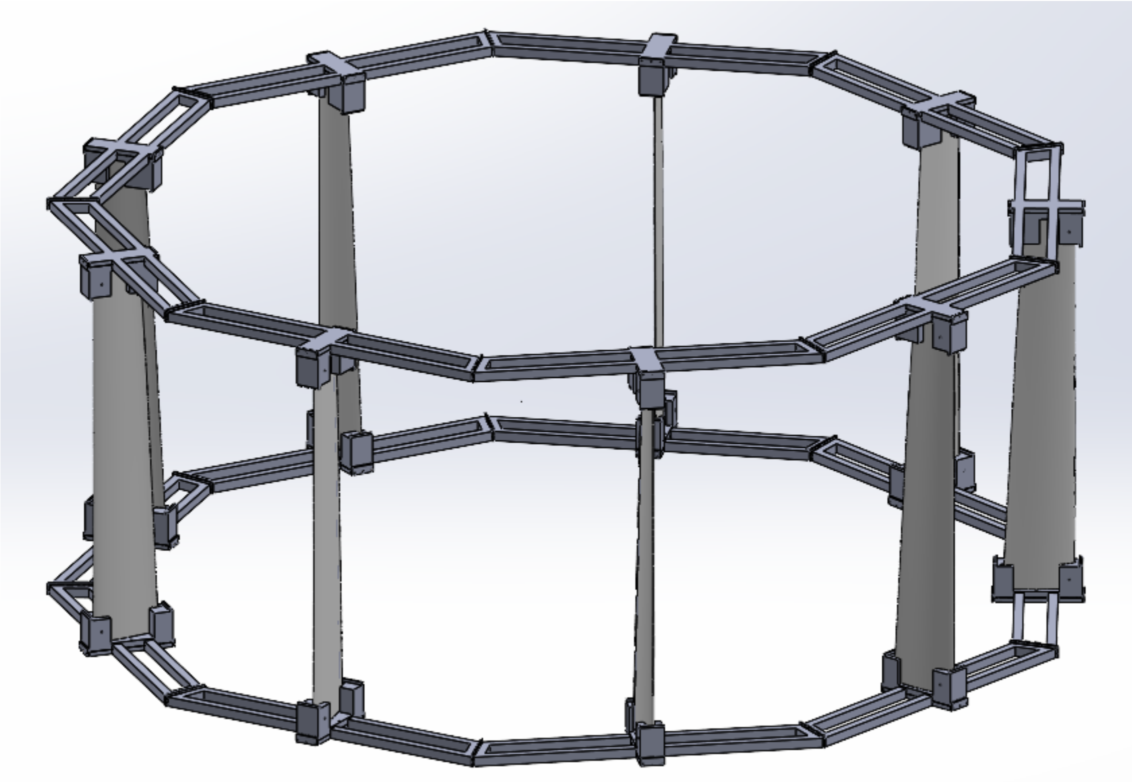

Figure 65 - Assembly model 4.

Model 4 will have a structure like model 2, but the idea is to have it on the seabed, meaning that this cage will be fully submersible. Another difference is that this model goes with nine 12m section blade. In consideration of this concept, the optimal deployment location for this model should possess a depth ranging from 10 to 14 meters, thereby maximizing the utility of the proposed design without the need of additional fixation supports or immersion and emersion systems.

The bottom part of the cage has an inner circumference of 28,36 m, as shown in Figure 66.

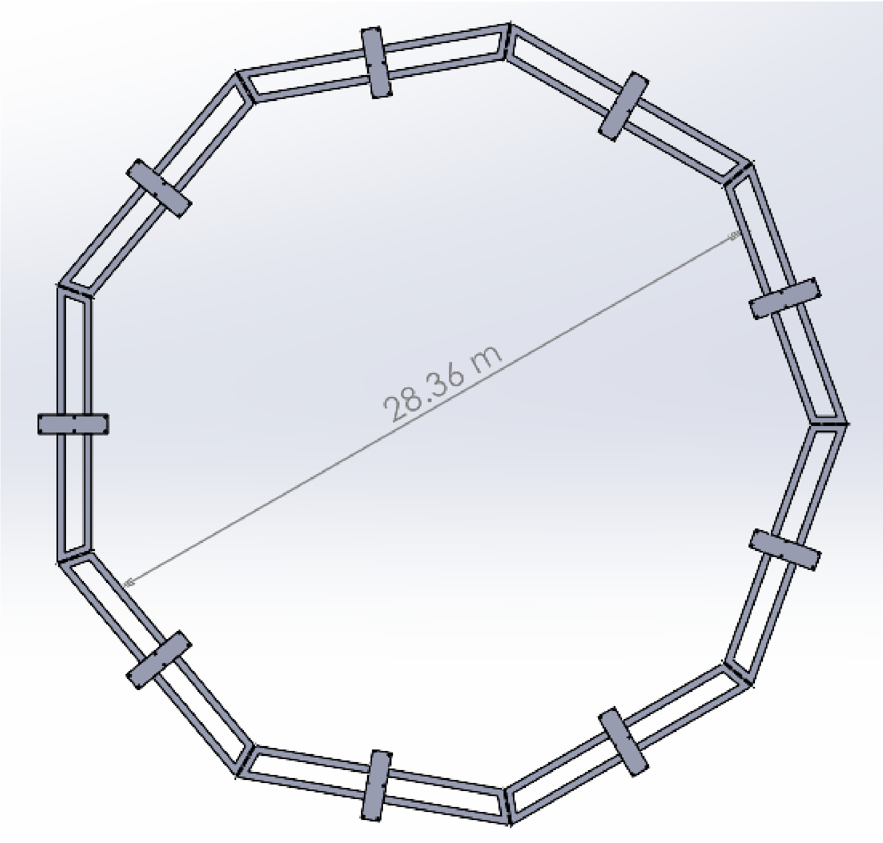

Figure 66 - Bottom part for cage model 4.

The bottom structure of this model is connected among 9 parts. Figure 67 shows the dimension of the part that is assembled to form the support which goes in seabed. It's important to mention that the dimensions of this model presented in the figures are all in meters.

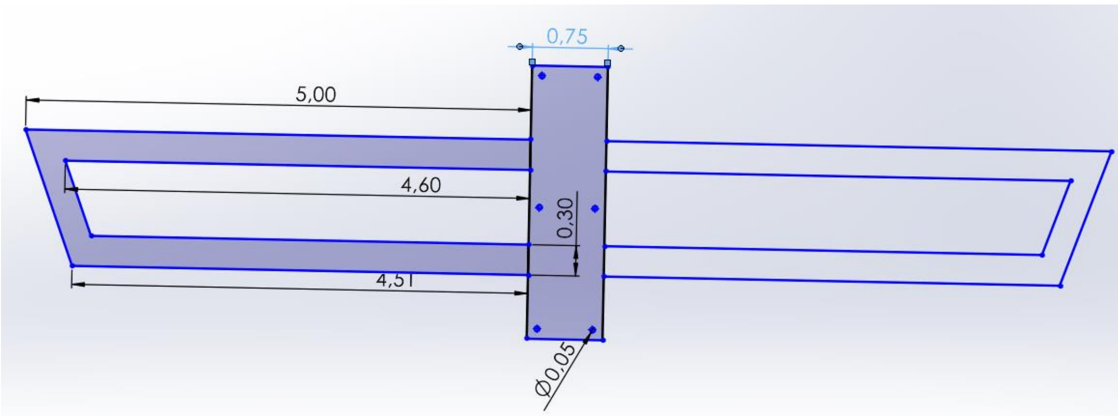

Figure 67 – Dimension of the support to create the structure that goes on seabed.

The model has the following design.

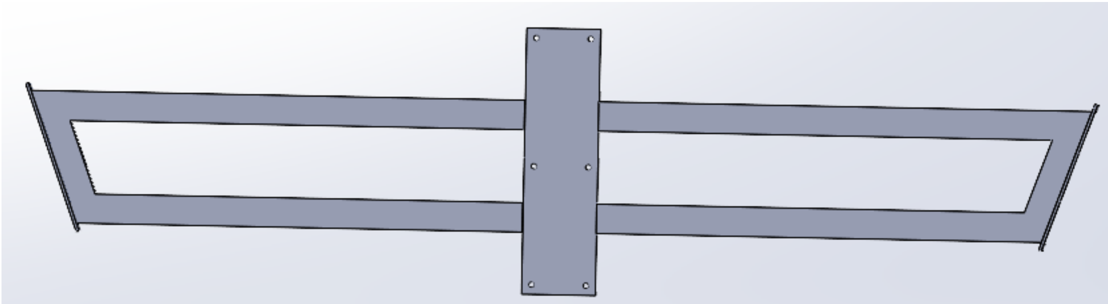

Figure 68 – Final design of the support that goes on seabed.

The lateral part of this piece will have a design that represents a flange. The idea is to connect the pieces to have it fixed and stabilized. Figure 69 demonstrate the dimensions of the flange connection.

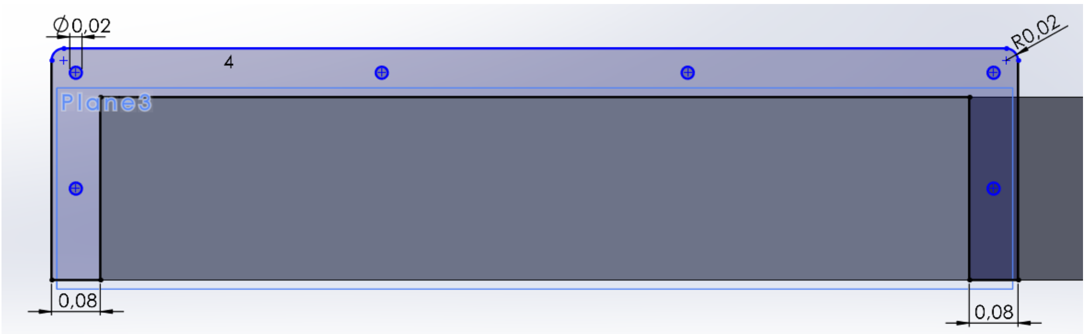

Figure 69 – Flange dimension to attach seabed supports.

The idea to have the parts connected as flanges is because it reduces the stress on the connection parts. The assembly is done with six stainless steel bolts and nuts and has the following results:

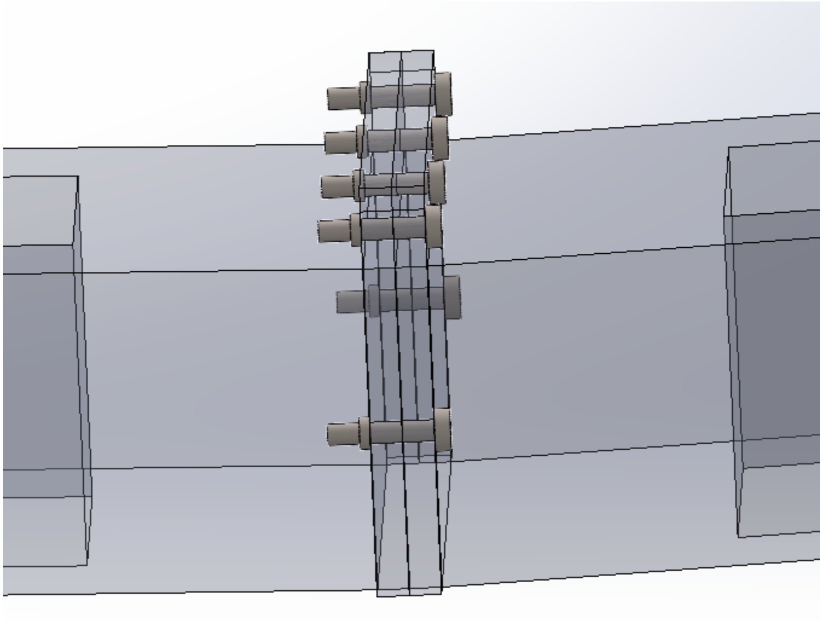

Figure 70 – Assembly of the parts with bolts and nuts.

After off all the connection of the parts, the assembly of the structure that goes on seabed resumes itself in Figure 71.

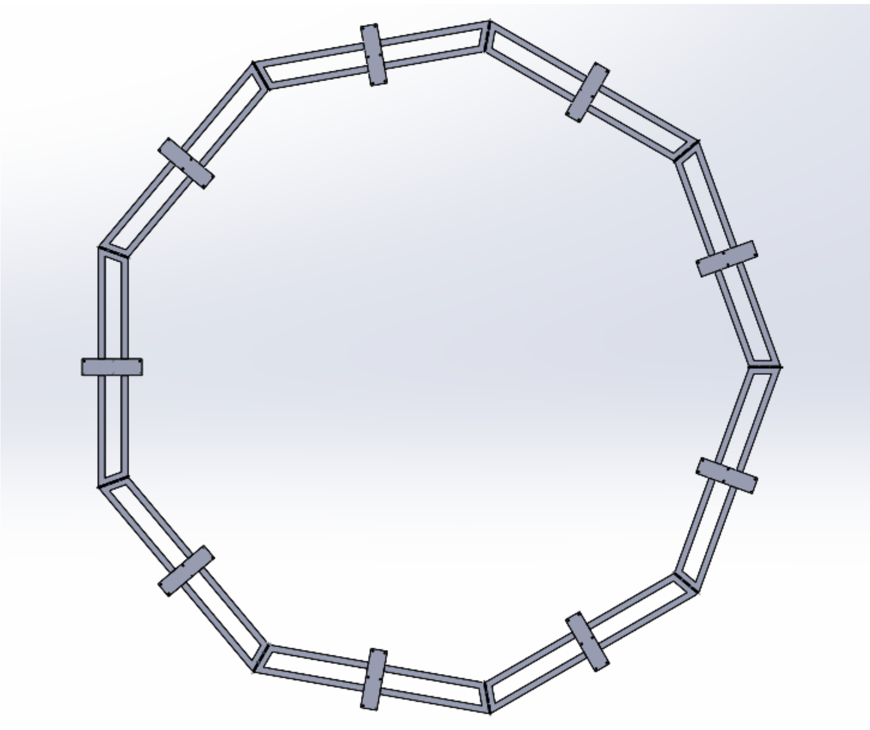

Figure 71 – Final assembly of the seabed support.

Then we must connect the bottom part to the "couplings" of the blades. These couplings have the following design. All the measures are in meters.

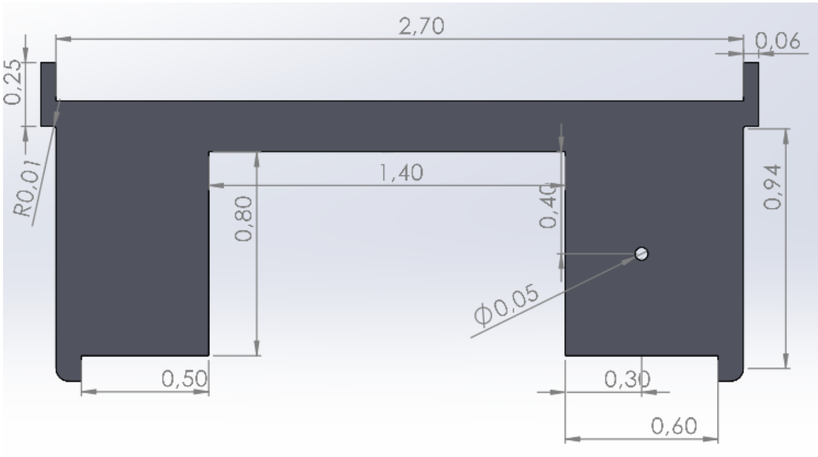

Figure 72 - Coupling dimension that connects blade and seabed structure.

The next figure shows the holes where the bolts go to fasten with the cage's base. It's important to mention that the dimensions in the figure are in meters.

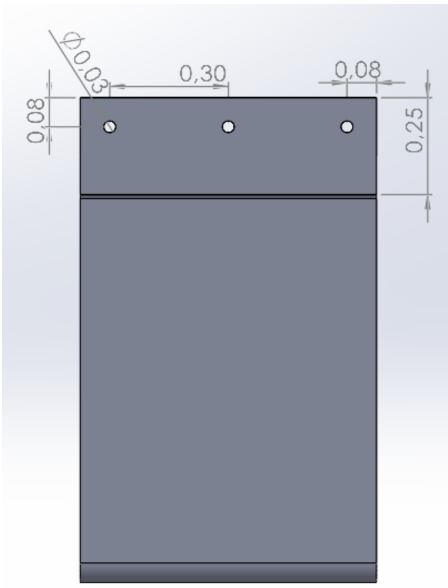

Figure 73 – Dimension of holes that fix coupling and seabed structure.

These parts will be fastened with bolts on the side, as shown in the image. Figure 74. All the bolts in this model are made of stainless steel.

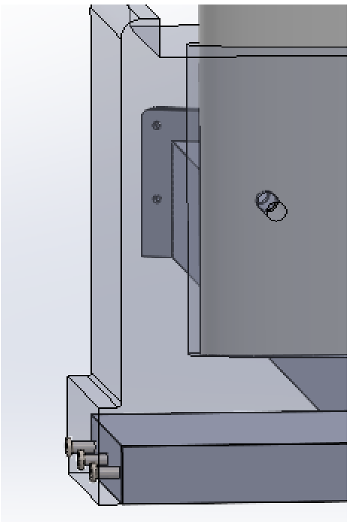

Figure 74 – Fixing of the bolts to the coupling.

After this step, we have a screw going through the blade and couplings. The intention of it is to help fixing the parts together, giving more stability. This screw is M60 x 800. It has a huge dimension, but due to the difficulty of the assembly, it needs to have special measures. Figure 75 shows the assembly of this part, in top view.

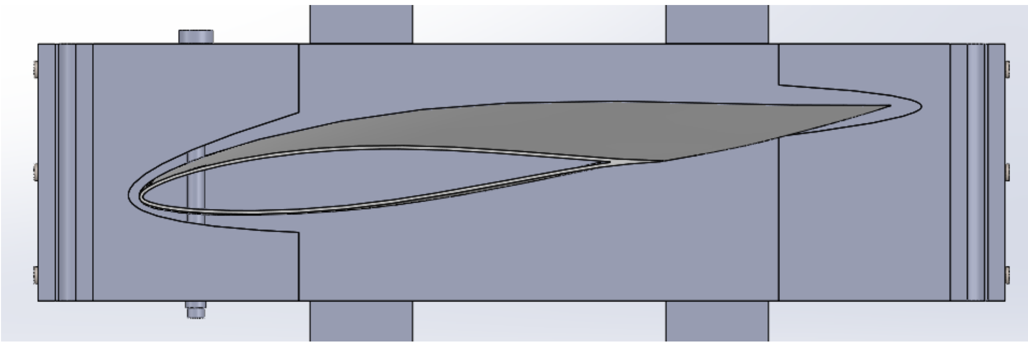

Figure 75 - Top view for assembly (cage-coupling-seabed support).

The top structure has the same design as the bottom structure, but the part that connects the blade to the top is smaller, due to the chord of the blade. Dimensions are shown in meters in Figure 76.

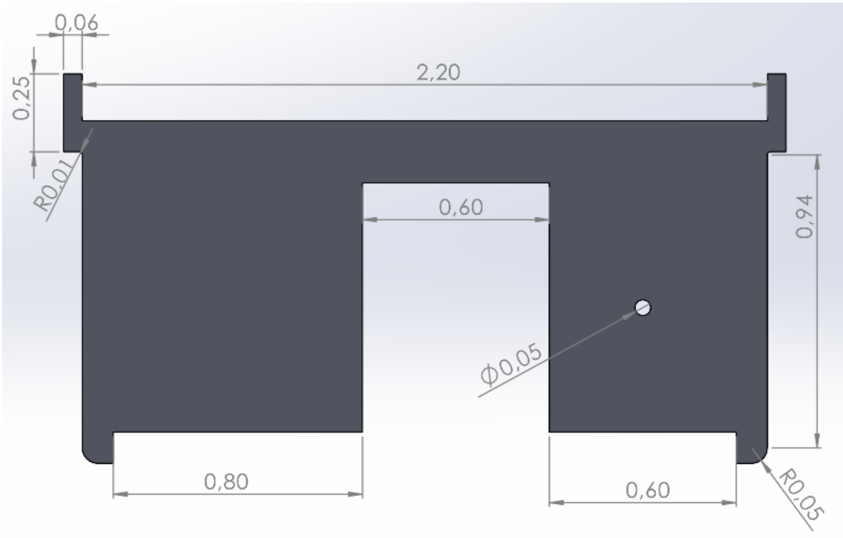

Figure 76 - Dimension of the blade support for the top structure.

There´s also a hole in one side of the part, to fix the blade using a screw with same dimension of the one for inferior support. Figure 77 shows the assembly of the parts.

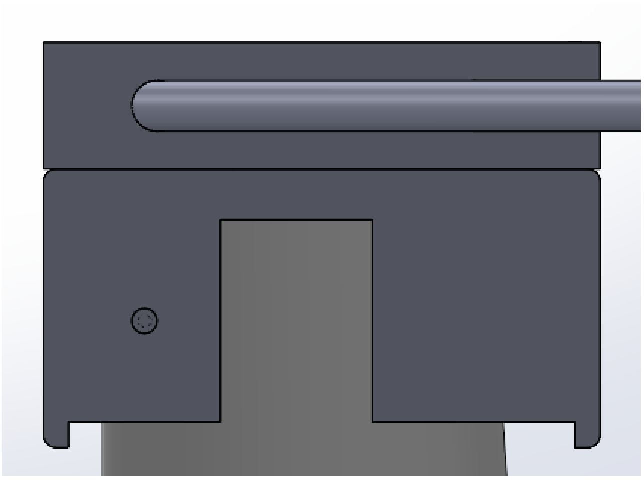

Figure 77 - Assembly of the blade, top structure, and pin.

In Figure 78 we can see the final structural assembly of cage model 4. This design is bigger than models 2 and 3. With this, it can meet a higher demand for fish farming.

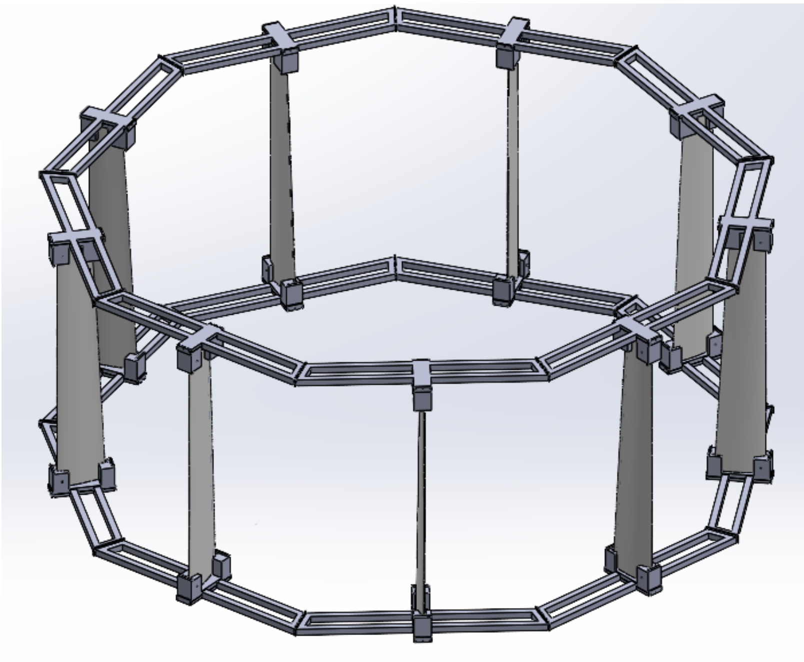

Figure 78 - Trimetric view for final assembly of model 4.

Due to the fact it has a higher internal diameter than the other cages, with an internal circumference of 28,3 meters, the estimated volume of this model is around 7580 m³. The quantity of blades for this model is higher than all others, since it has 9 blades, and the idea is that the model will be submersible. Table 26 shows some characteristics of this model.

Table 26 - Characteristics of model 4.

Characteristics	
Quantity of blades	9
Location	Off the coast
Type of cage	Submersible

The advantages and disadvantages of this model are shown in Table 27.

Table 27 - Advantages and disadvantages of model 4.

Advantages	Disadvantages
More volume compared to Model 2 and 3	Assembly may be more complex due to connections.
Minimal visual impact	Maintenance more complex if needed.
Good impact resistance	Low visibility

4. Results and discussion

For the evaluation of the proposed models, simulations were conducted to assess the conditions that each one can offer and the materials that can be used in structural manufacturing. Also, some important considerations were done to the models proposed, as a table that summarize the main characteristics of each model, to compare them.

4.1. Model 1

For model 1, a drag force study was conducted due to the size of the blade used, and a load study on its base was performed to determine whether it can support the weight of the blade or not. All the results obtained in the simulations will be discussed throughout this topic.

4.1.1. Drag force simulation

Starting with the simulation of the drag force, it is necessary to show the parameters used for the calculation and how they were obtained. The first parameter is the fluid velocity. In this case, the considered velocity was 3 knots, which is equivalent to 1,54 m/s. The average velocity in most of the Portuguese regions may not be at this value in areas where aquaculture systems are applied. It's worth noting that the regime considered for the analysis was laminar.

Taking this into consideration, the next parameter is the contact area. For the calculation where the contact is at the leading edge, the following rectangular dimension was considered, as shown in Figure 79:

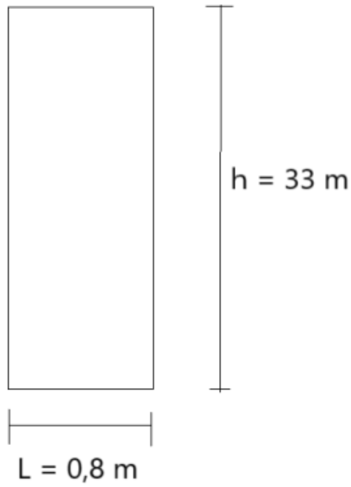

Figure 79 - Cross area for simulation of drag force.

The fluid density considered was 1025 kg/m³, and as discussed earlier, the drag coefficient used will be 0,35, as it aligns with the Naca profile used for the blade's design. Taking these parameters and applying them to the drag force formula, we have:

$$F = \frac{Cd * \rho * A * V^2}{2} = \frac{0{,}35 * 1025 * (33 * 0{,}8) * (1{,}57)^2}{2} = 11{,}67\ kN \qquad (2)$$

A safety factor of 2 was considered for this project, so in this case, the force used in the simulation was 23,34 kN. Using this force value, considering the parameters described in the materials and methods, we have the results for maximum stress and maximum displacement shown in Figure 80 e Figure 81.

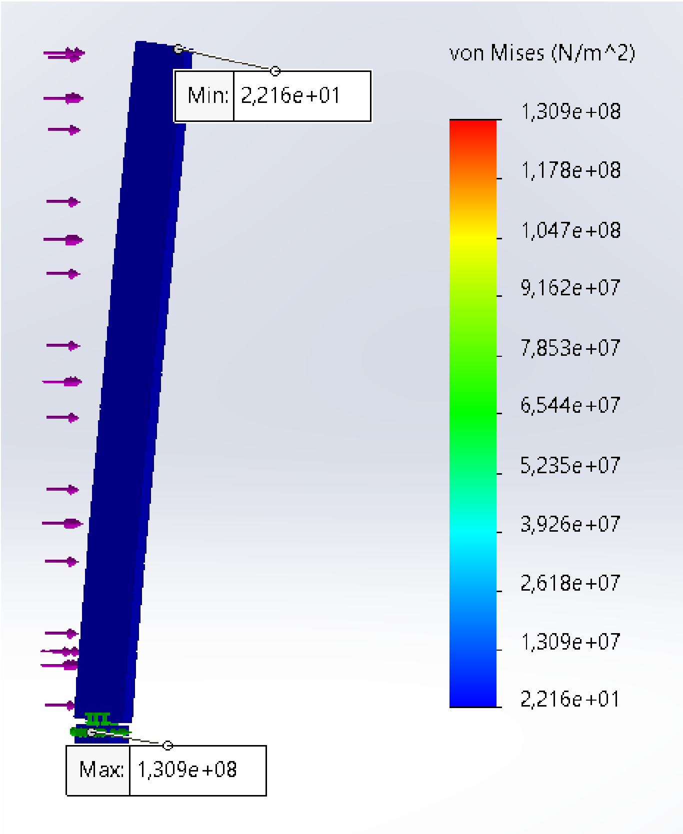

Figure 80 - von Mises stress for L=0,8m.

We can see that the maximum stress is 130,9 MPa at the attachment point between the blade and the concrete base. In other words, the highest stress will be on the bolts. Considering that the screw is made of stainless steel and its shear stress is 172 MPa, this stress would be supported.

In Figure 81, it is shown that the maximum displacement would be 4,86 mm. Therefore, this displacement does not have a significant structural impact on the project. It is also worth noting that the situation with a current of 3 knots is not common; it was studied only to assess how it would be supported if the event occurs.

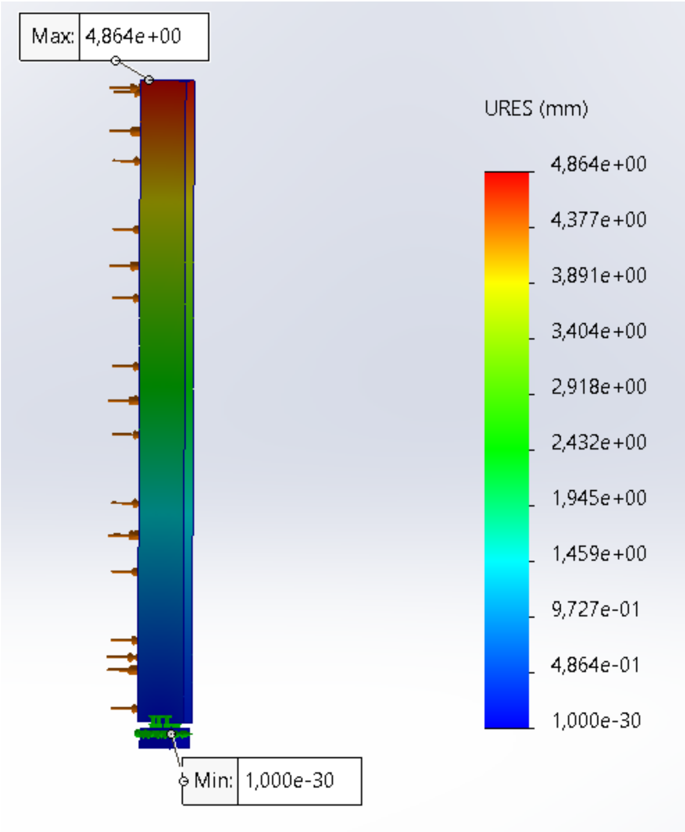

Figure 81 - Displacement for L = 0,8m.

For the condition of current flowing perpendicular to the blade, as shown in the Figure 38, it was considering the following rectangular dimension:

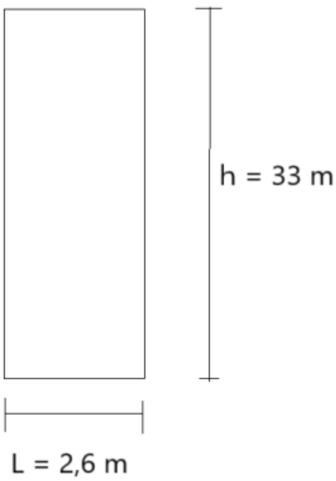

Figure 82 - Cross area for simulation of drag force considering L = 2,6m.

Considering the same density and drag coefficient, we have:

$$F = \frac{Cd * \rho * A * V^2}{2} = \frac{0{,}35 * 1025 * (33 * 2{,}6) * (1{,}57)^2}{2} = 37{,}94\ kN \quad (3)$$

We can see that the drag force will be much higher in this situation since the contact area is larger. However, applying the methods described before and the same security factor, the force considered for simulation was 75880 N. Afterwards, we have the result of a von Mises stress equal to 344 MPA, as shown in Figure 83. This stress is higher than the maximum stress supported by the bolt. Therefore, some solutions need to be discussed.

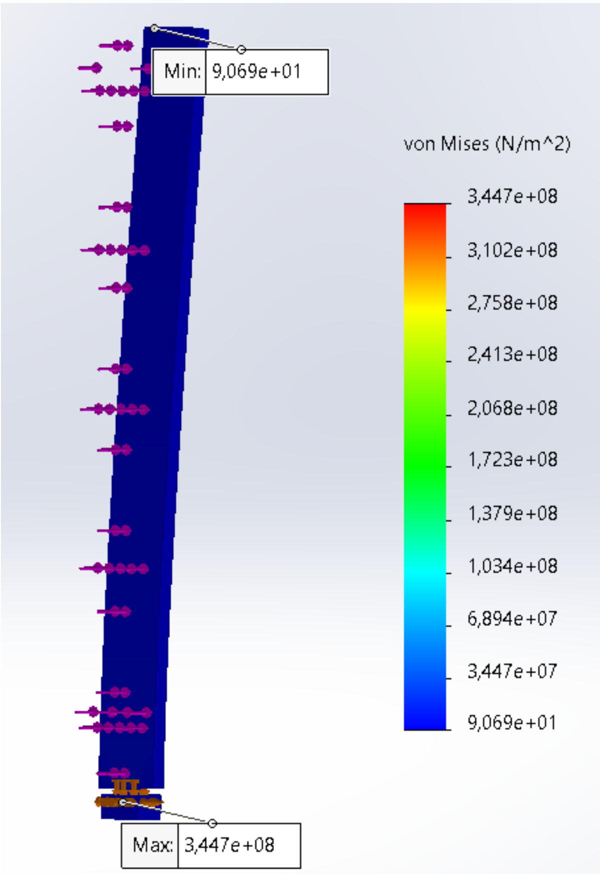

Figure 83 - von Mises stress for L=2,6 m.

One factor that can help reduce the stress on the bolts is to create anchoring points for the blade. These points would help decrease the stresses at the attachment points by distributing the load more effectively. Figure 84 shows the anchoring concept to help support the drag force.

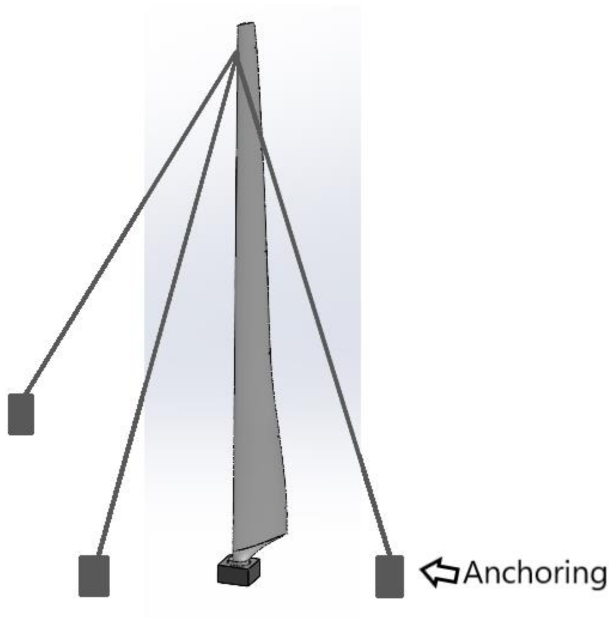

Figure 84 – Anchoring to help on supporting load.

Another option is to increase the number of fixing points. For the simulation, it was fixed by eight bolts. Then, this number was increased to sixteen points and a revaluation was done to see if this quantity of bolts could support the stress created by the drag force. Figure 85 shows the new quantity of bolts evaluated to fix the blade and solve the stress problem.

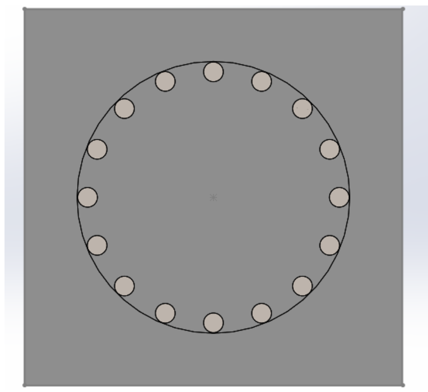

Figure 85 - 16 bolts for revaluation of the stress.

Doing the simulation again considering those fixing points, the maximum stress was 57,14 MPa. The stress now is far from the shear stress of 172 MPa from the bolt material and is easier supported. Figure 86 shows the results of the simulation. Concluding, increasing the number of fixing points can be a great resolution for the stress issue.

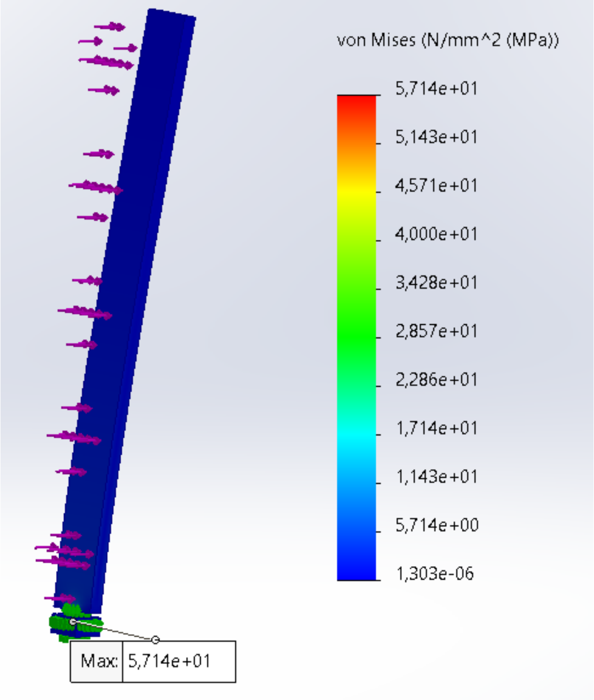

Figure 86 - von Mises stress from simulation with 16 fixing points.

A simulation was also conducted to verify if the concrete box where the blade would be attached could support the weight of the blade. The load used was calculated based on the weight of the blade. The blade, in its initial 34-meter form, has an approximate weight of 6 tons. Therefore, the weight used in this stage was 58,86 kN, Figure 87 shows the local where the compressive load was applicated.

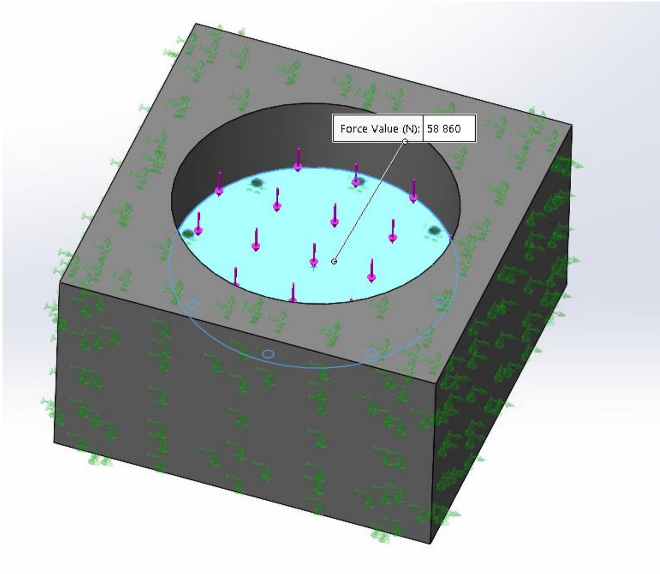

Figure 87 - Local of the load application.

As a result, the following outcomes were obtained for von Mises stress presented in Figure 88. The maximum stress was 0,38 MPa and the maximum displacement was 0,001 mm. The final stress is much far from the yield strength of 20 MPa.

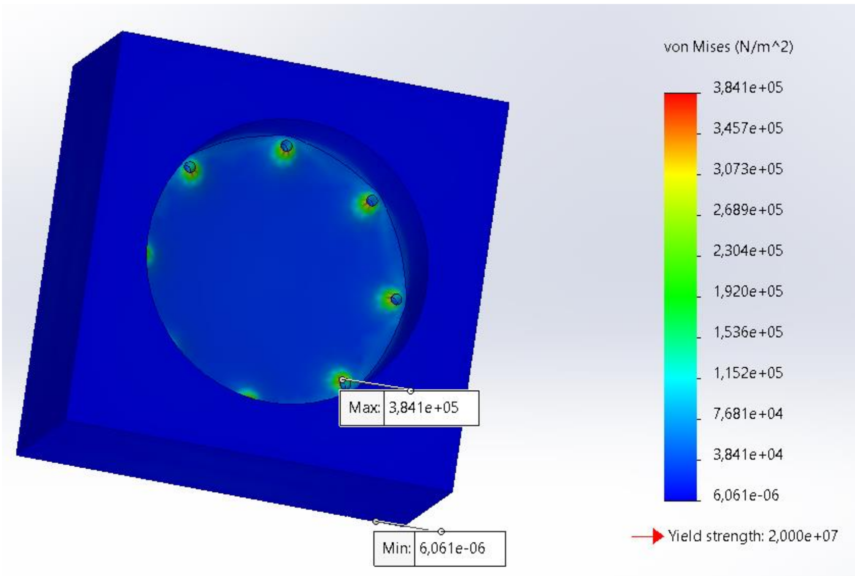

Figure 88 - von Mises result for concrete box simulation.

A representation of the cage with the net was created using software Blender. Figure 89 shows the idea of it.

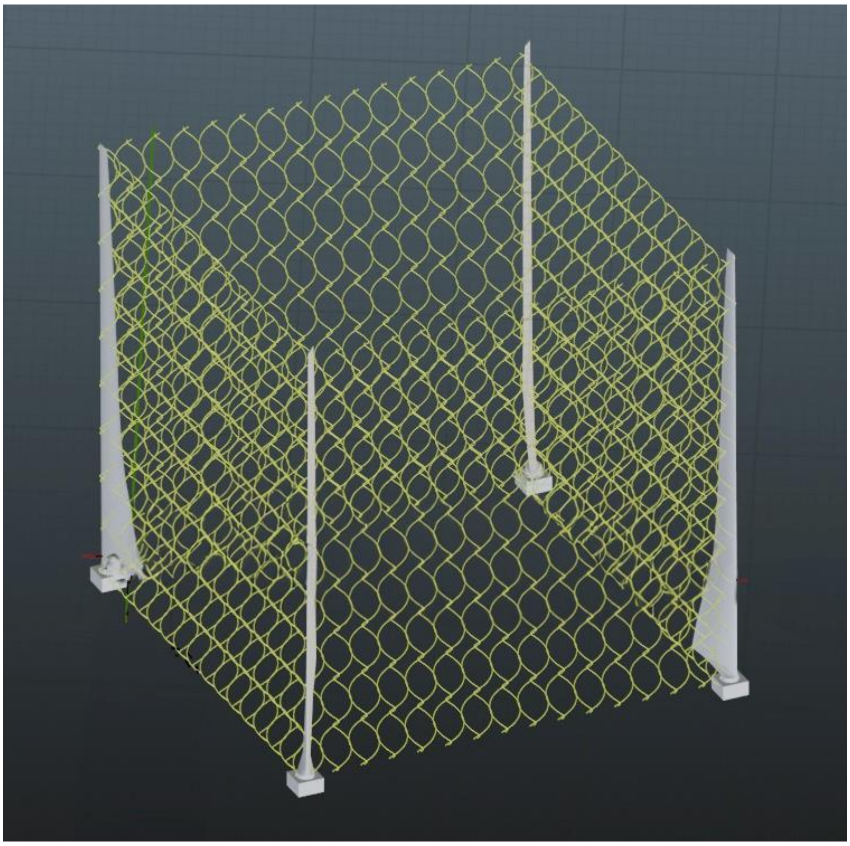

Figure 89 - Representation of cage model 1 with the net.

4.2. Model 2

The idea for this model is that it would be either floating or fully submerged. In the case of it being floating, it will be necessary to assess the weight of the cage and determine whether the buoyancy force is greater or less than the weight of the structure. The 12-meter blade has a mass of 1160 kilograms. With this, the following evaluation needs to be performed:

$$Fe \geq P$$

Where Fe is the buoyancy force and P is the weight of the structure. In the scenario where the buoyancy force is greater or equal to the weight of the structure, the cage will float. In the reverse situation, the cage will sink. On the left, in Figure 90, the object's weight is the same or greater than the buoyant force acting on it, so the object floats. On the right, the object's weight is greater than the buoyant force acting on it, so the object sinks.

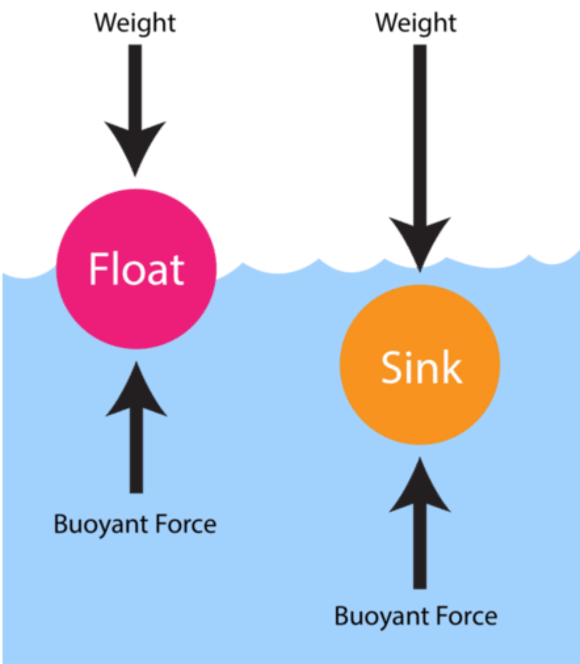

Figure 90 - Weight and buoyancy force.

So, it's first important to understand the meaning of buoyancy. Buoyancy is the tendency of an object to float or to rise in a fluid when submerged. This fluid can be either a liquid or a gas. The formula to express the force described before is:

$$F_e = V * \rho * g \tag{4}$$

Where:

F_e = buoyancy force;

V = volume of the object;

ρ = fluid density;

g = gravity.

Having this stated and knowing that the volume of the blade is 0.44 m³, using formula (4) considering fluid density equal to 1025 km/m³, the buoyancy force is 4424,3 N. Considering the weight of the blade as previously mentioned, which is 1160 kilograms, its weight force would be 11380 N. With this, the blade would sink.

In addition, in case where the blade is filled with water, with an internal volume of approximately 3,26 m³, the buoyancy force is 32780,1 N. The weight force exerted by the blade plus the weight of the water inside it would be greater than the buoyancy force. Therefore, the blade would sink too. Taking this analysis into account for blade only, we can see that for the floating cage model, an anchoring system or balloons is needed to make the cage floating, or the cage could be considered as submersible, which is also an option. For the flotation of the cage, it will be necessary to define the material of the blade support structure more precisely to make a more accurate estimation of the total weight of the cage. This will enable a better dimensioning and definition of the flotation system.

In the market, there are currently numerous applications that operate based on the concept of Archimedes' principle, such as submarines, submersibles, lifting bags, and flotation devices. When we talk about the need to submerge something, the most common thought relates to submarines, which are vehicles capable of navigating both on the surface and underwater, with their primary focus being the ability to stay submerged for extended periods.

Submarines have ballast tanks that, when filled with water during submersion, allow them to achieve neutral buoyancy. The more water in the ballast tanks, the heavier the submarine becomes, causing it to submerge [37].

A ballast tank is a compartment within the structure of ships, submarines, or a floating structure that contains water to maintain its stability. These components not only provide stability but also enable the submersion and resurfacing of submarines reliably. So, the idea is to use equipment like a ballast tank or something else that can assist in the flotation process of the cage or make it submersible.

Four types of ballast tanks will be summary defined, just to express the idea of each one and demonstrate that may be used or considered for this model. The types are flexible ballast tank, pressure ballast tank, piston ballast tank and compressed air ballast tank.

Flexible ballast tank

The adaptable ballast tank comprises a rubber balloon located within a sturdy tank. To fill the tank, open the valve and pump water into it. Close the valve to prevent water from escaping once the tank is filled [36].

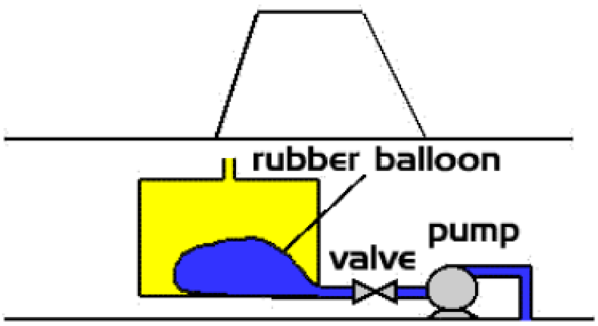

Figure 91 - Flexible ballast tank [36].

Pressure ballast tank

It is a ballast tank consists of sealed ballast tank capable of withstanding high pressure. It is loaded by a pump. But as the air is trapped inside the ballast tank air is compressed so ballast tank can never be fully loaded [36].

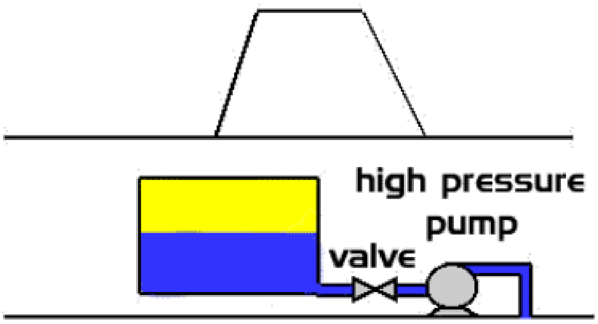

Figure 92 - Pressure ballast tank [36].

Piston ballast tank

The piston ballast tank is composed of a cylinder with a movable piston, which can be shifted using a threaded shaft, spindle nut bearing, and a motor. The piston is sealed with two soft O-rings. To counterbalance the loading and unloading effect of the ballast tank and maintain the center of gravity, two piston tanks of the same size are positioned at equal distances from the center of gravity, effectively addressing this issue [36].

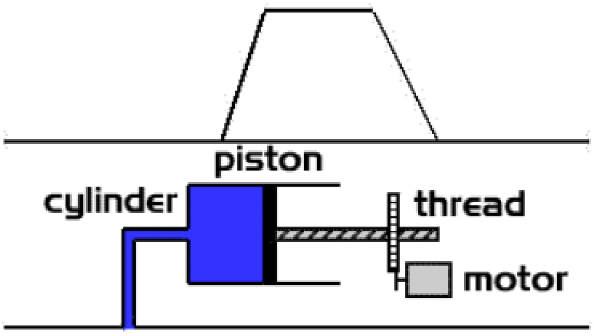

Figure 93 - Piston ballast tank [36].

Compressed air ballast tank

This is the same mechanism used in actual submarines. To flood the tank, the vent valve is opened to release air, allowing water to enter through a hole beneath the ballast tank. To empty the tank, compressed air is introduced into the tank by opening the compressed air release valve [36].

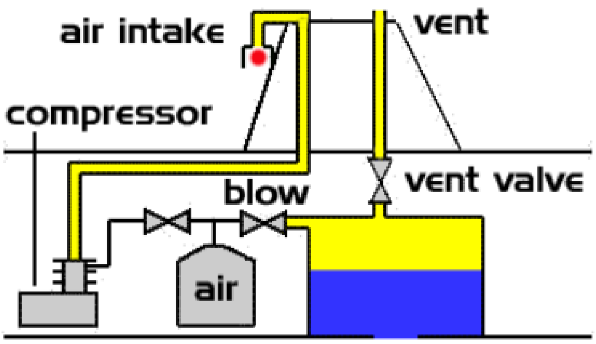

Figure 94 - Compressed ballast tank [36].

So, it is necessary to assess the total weight of the structure and understand which ballast tank concept would best apply to the project to make Model 2 a floating cage. Of course, there are other methods that can be used to construct the idea of a floating cage to this model, but the proposal of the project still not include this part. It may be a study for the future work. Next chapter shows the simulation results for the connection part of blade and structure. Since the idea of floating has come to mind, this evaluation is important.

4.2.1. Simulation results for aluminum

In this topic will be discussed the results of the simulation for the screw that holds the blade manufactured using Aluminum. This simulation is needed to understand the stress that may be caused to the connection parts of blade and structure. Since this model is also meant to be floating, this evaluation is important. The mechanical properties of aluminum in SolidWorks are presented in the following table.

Table 28 - Mechanical properties of Aluminum in SolidWorks.

Property	Value	Units
Elastic Modulus	3,70 E+11	N/m²
Poisson's Ratio	0,22 E+0	N/A
Shear Modulus	1,50 E+11	N/m²
Tensile Strength	3,00 E+8	N/m²
Compressive Strength	3,00 E+9	N/m²
Yield Strength	2,50 E+8	N/m²
Thermal Expansion Coefficient	7,40 E-06	/K

As a result of the simulation using the parameters described before, in materials and methods, the following outcomes were obtained for von Mises stress and displacement, presents in Figure 95 and Figure 96. The maximum stress was 9,21 MPa and the maximum displacement was 0,011 mm.

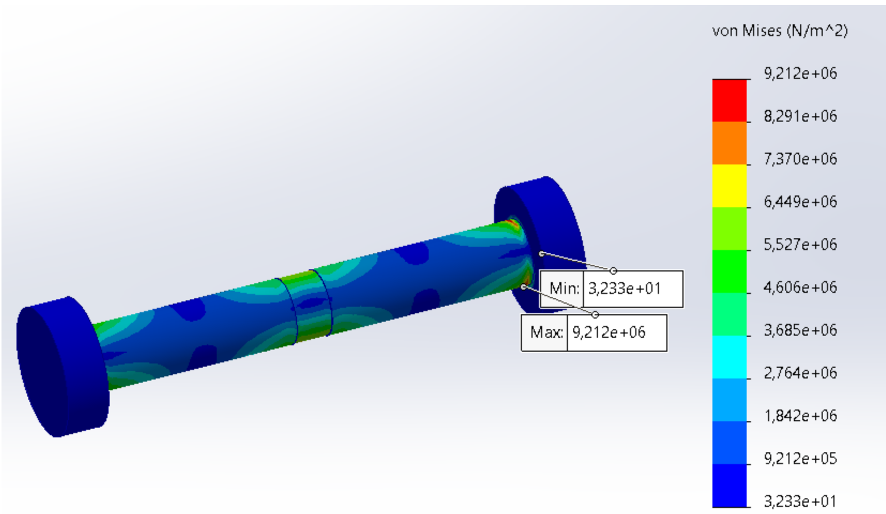

Figure 95 - von Mises result for aluminum.

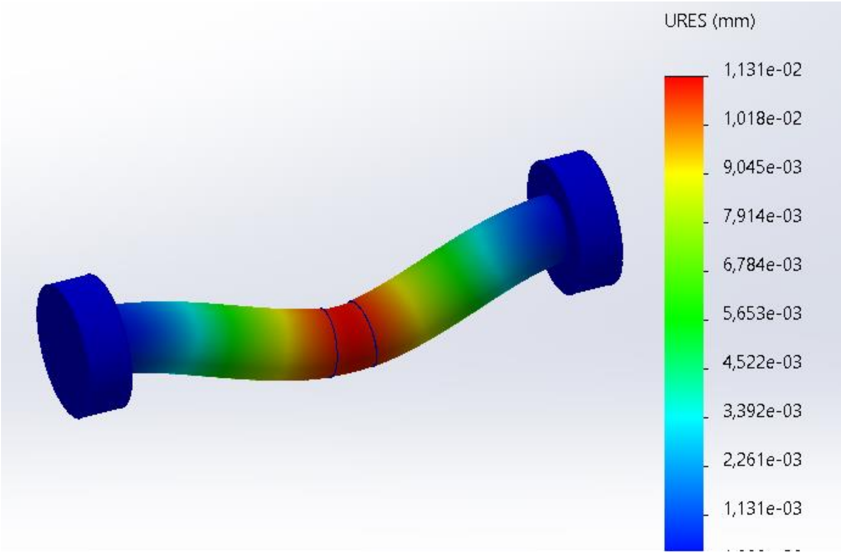

Figure 96 - Displacement result for aluminum.

4.2.2. Simulation results for Stainless steel

In this topic will be discussed the results of the simulation for the screw that holds the blade manufactured using Stainless steel. The same criteria of mesh, fixtures and load were applied to the stainless-steel pin. The mechanical properties of stainless steel in SolidWorks are presented in Table 29:

Table 29 - Mechanical properties of Stainless steel in SolidWorks.

Property	Value	Units
Elastic Modulus	2,00 E+11	N/m²
Poisson's Ratio	0,28 E+00	N/A
Shear Modulus	7,70 E+10	N/m²
Tensile Strength	5,14 E+08	N/m²
Yield Strength	1,72 E+08	N/m²
Thermal Expansion Coefficient	1,10 E-05	/K

In Figure 97 and Figure 98, we can see the results of the von Mises stress and displacement of the object. The maximum stress was 10 MPa and the maximum displacement was 0,02 mm. Considering the yield strength of 172 MPa, the material supports the load of the blade.

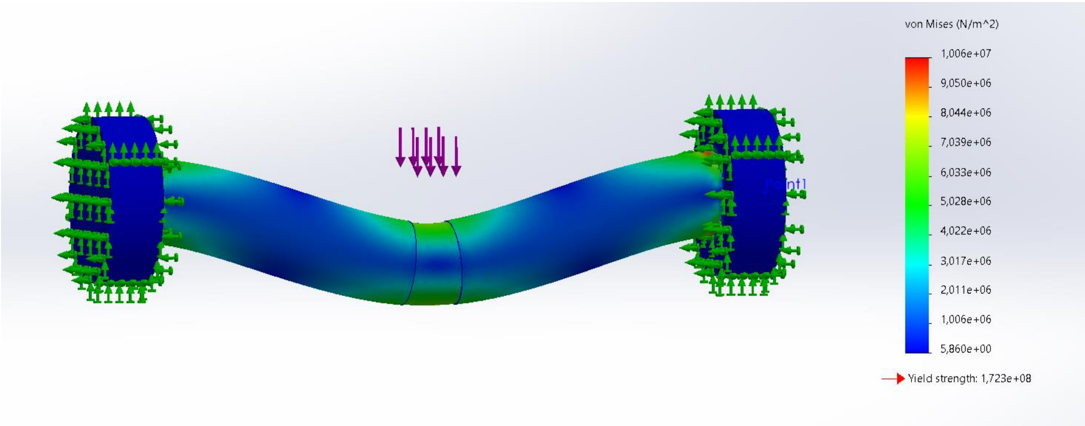

Figure 97 - von Mises result for stainless steel.

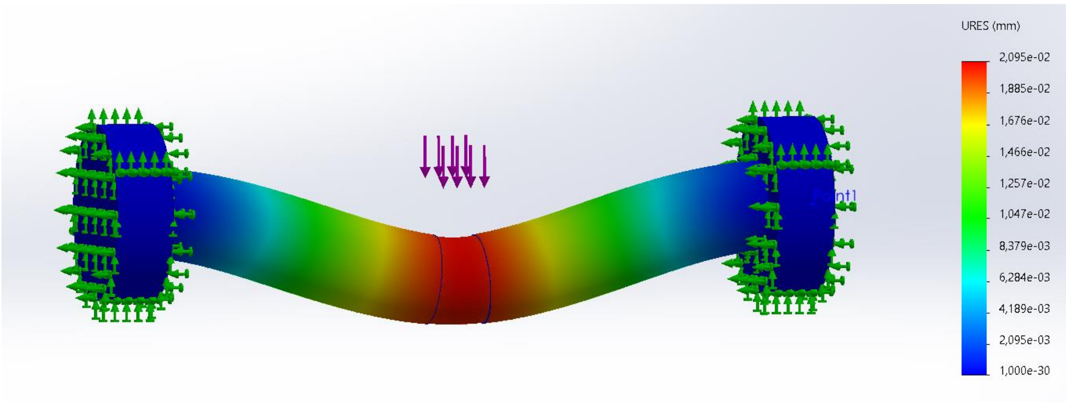

Figure 98 - Displacement result for stainless steel.

Below, in Figure 99, is a representation created in software Blender of the cage model 2 with the net.

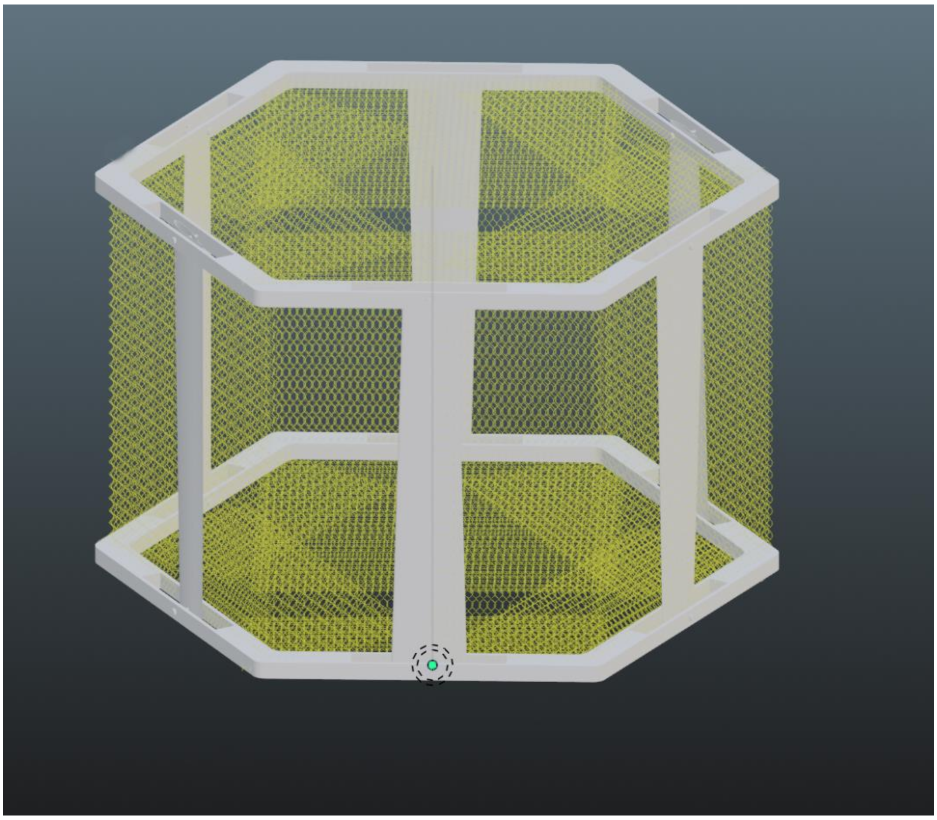

Figure 99 - Representation of cage model 2 with the net.

4.3. Other relevant parameters

Model 4 didn't have any simulation to be discussed, but it's important to mention that the assembly of it is the most proper one and can be the most achievable, since the parts are all connected and is closer to reality. Regarding models 2 and 3, the upper support and the bottom support of model 2 and the upper support of model 3 are very big and demand a very complex manufacturing process, since it was demonstrated as one part only. So, in this case, it's more difficult to manufacture and do the transportation of it.

Regarding a fluctuation system, it's necessary to be studied and try to have the best fit possible for the model of cage developed; Also, the same assessment of a floating model for Model 2, using a submersion and emersion system for the cage, could also be used to Model 3. However, considering that we have the same number of blades and only the upper support, the weight of model 3 is lower. Therefore, the evaluation of which fluctuation system, such as ballast tank, may be different. Anyway, costs of implementation and purchasing needs to be included too, depending on which direction the proposal will take.

The representation of the cage model 3 with the net and an anchoring to help on holding the blades, so they will not be so loose, is presented in Figure 100.

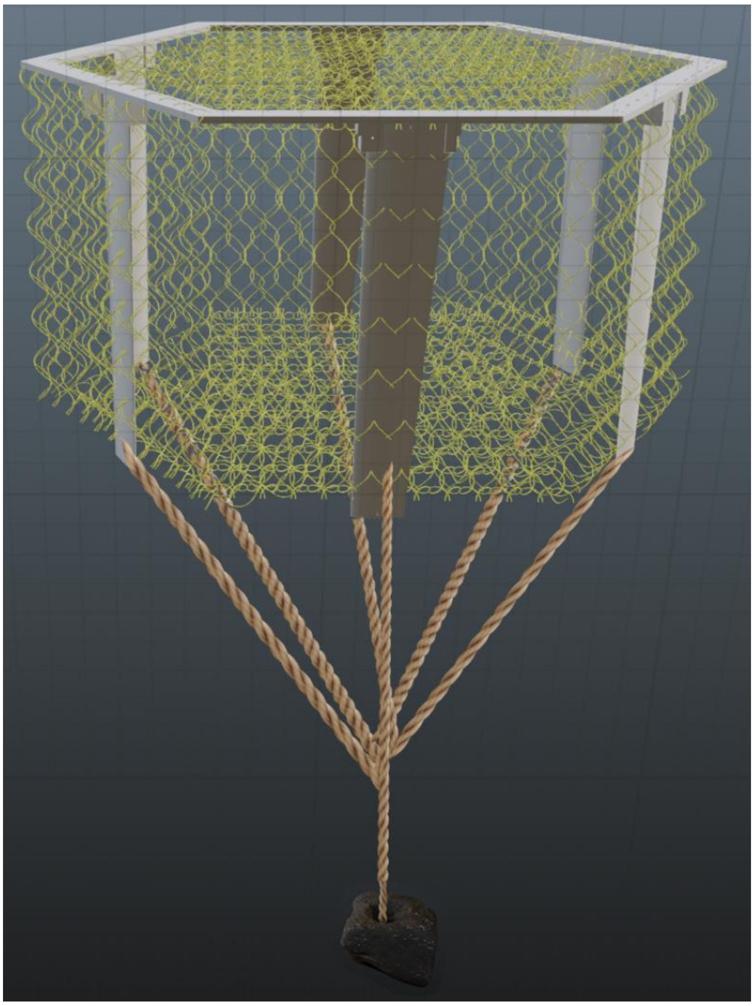

Figure 100 - Representation of cage model 3 with net and anchoring.

Figure 101 represents the cage model 4 with the net, to express how it would look with the net fixed in place. The net representation for all models were created using software Blender.

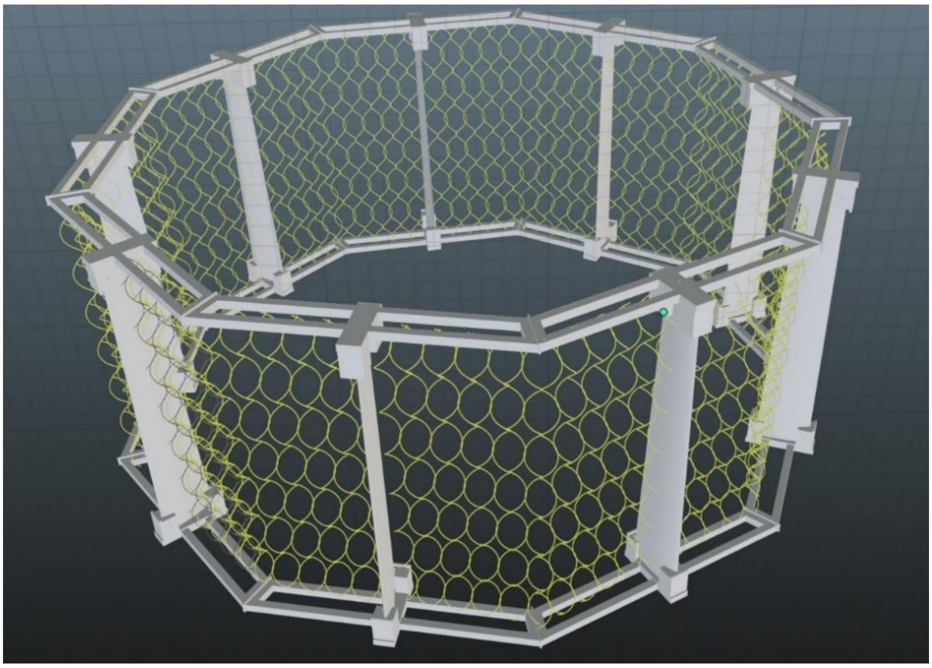

Figure 101 - Representation of cage model 4 with the net.

4.4. Comparison among the models

In this section will be presented a comparison of all models created in this work. The purpose of this analysis is to evaluate each design aspects and parameters that have been studied during the development of these models. Table 30 serves to summarize our results, making it understandable to discern the differences between some parameters of the models proposed. The main differences are the volume and the quantity of blades for each model.

Table 30 - Comparing the characteristics of each model proposed.

	Model 1	**Model 2**	**Model 3**	**Model 4**
Volume	25800 m³	686 m³	847 m³	7580 m³
Quantity of blades	4	6	6	9
Location	Off the coast	Off the coast	Off the coast	Off the coast
Type of cage	Submersible	Floating / submersible	Floating / submersible	Submersible
Anchoring needed	-	Yes	Yes	-
Emersion and Immersion system	-	Ballast tank	Ballast tank	-

4.5. Swot analysis

In this topic will be conducted a SWOT analysis to evaluate the strengths, weaknesses, opportunities, and threats associated with the innovational idea. Through this analysis, we aim to gain a better understanding of how the upcycling of wind turbine blades can contribute to the future of aquaculture. Table 31 will show each matter evaluated.

Table 31 - SWOT analysis for the proposed models.

Strengths	Environmental Sustainability: Upcycling wind turbine blades for aquaculture structures gives the idea of sustainability by reusing the blades that would otherwise be disposed in landfills. Cost Efficiency: Wind turbine blades are readily available as waste materials, reducing the initial material cost for aquaculture cage structures. Reduced Carbon Footprint: Reusing materials reduces the need for new manufacturing and production, thereby reducing the carbon footprint in case of incineration of the blades. Innovation and Technological Integration: Integrating wind turbine blades into aquaculture cages demonstrates innovation between industries.
Weaknesses	Material Handling: Wind turbine blades can be large and heavy, making transportation, handling, and modification challenging and costly. Limited Availability: The availability of wind turbine blades for upcycling may vary by region and depend on the decommissioning of wind farms. Compatibility Issues: Wind turbine blades may not be immediately suitable for aquaculture applications, requiring modifications and customization. Quality Control: Ensuring the structural integrity and safety of upcycled materials may require rigorous quality control processes.
Opportunities	Market Demand: The aquaculture industry is growing, creating a demand for cost-effective and friendly materials regarding environment for aquaculture cages. Collaborative Partnerships: Collaboration between the wind energy and aquaculture industries. Research and Development: Opportunities exist for future research and studies to optimize the use of wind turbine blades in aquaculture. Regulatory Support: Government incentives and regulations in favor of sustainable practices may give support to upcycled materials from Eolic sector in aquaculture.
Threats	Regulatory issues: Regulations or environmental concerns may restrict the use of upcycled wind turbine blades in aquaculture. Competition: Other sustainable materials and technologies may emerge as competitors. Technological Challenges: Adapting wind turbine blades for aquaculture may require advanced engineering studies and solutions. Environmental Impact Assessment: Potential environmental impacts of using wind turbine blades in aquaculture, such as leaching of chemicals.

In summary, the upcycling of wind turbine blades to develop aquaculture cage structures presents several strengths and opportunities, primarily related to cost efficiency and sustainability. However, it may face difficulties related to material handling, transportation, regulatory considerations, and technological obstacles. A successful implementation would require collaboration, research and be careful regarding environment and its safety factors.

5. Conclusion and expectation of future work

5.1. Conclusion

In conclusion, this work indicates the promising potential of repurposing wind turbine blades at the end of their operational life to make part of sustainable aquaculture cages. Through the development and simulation of four cage models, this study offers valuable insights into increasing the performance of these systems. Furthermore, considering the enhance of the demand for aquaculture solutions in the following years and the notable quantity of wind turbine blades that will become decommissioned, highlight the opportunity for their eco-friendly reuse in the aquaculture sector is an innovative idea and very promising.

Finally, by creating a SWOT matrix, this research identifies some major parameters of this innovative project, such as its strengths, weaknesses, opportunities, and potential threats. Briefly, this thesis supports the principles of a circular economy and sustainability within aquaculture, introducing an inventive approach to integrate wind turbine blades in end of life into aquaculture structures.

Of course, that there are many other steps needed to integrate this innovational idea into the market. In this thesis, only the design of the products and some simulations for them were conducted, among other relevant factors, but future work will have to be done to ensure and establish the idea in the market.

5.2. Expectation of future work

As a follow-up to the work conducted in the context of this dissertation, the following future developments are proposed:

- Study on how the feeding system for the cages would be;
- Evaluate systems already available in the market, to perform the immersion and emersion work of floating models;
- Prescribe the maintenance process for each model;
- Study environmental impacts from inserting wind turbine blades in the concept of aquaculture world and regulations to check how it can be possible;
- Evaluate how the weight of the blade can be reduced and, in this case, decrease the total weight of the cages;
- Analysis of blade wear and corrosion in the aquatic environment to evaluate the estimated lifespan and strategies for its extension.

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