Aquaculture and Materials
From Past to Present

Abílio M. Ferreira
abilio.ferreira@tecnico.ulisboa.pt
Instituto Superior Técnico, Universidade de Lisboa, Portugal
January 2021

Keywords: Materials, aquaculture, polymers, cables, nets, cages

Abstract: A journey into the past of aquaculture, to its deep roots, gives us an understanding of the present and a conscious vision of the future.

The history of aquaculture, recently with references to the Neolithic, shows a long way, not always very different from what are the current solutions, safeguarding the proper proportions.

The knowledge of the equipment used in aquaculture shows the existing solutions and gaps.

During the past century, advances in the area of Synthetic Chemistry and the reliability of the produced Metal Alloys, as well as the knowledge of the properties and the prediction of in-service behaviour of the materials, allowed important advances in the construction of safe equipment for various purposes in general, and Aquaculture in particular.

The materials identified in all areas of the aquaculture systems are associated with the purpose of the solutions and open perspectives for the identification of new materials to be used in the future, as well as an important growth in automation, equipment monitoring and biological safety of equipment and installations.

The study of a real case in aquaculture shows the need for a careful choice of materials to be used in each situation.

1. Introduction

Portugal has always had the Sea as an inseparable partnership, and much of what we are today, and in future, is connected to the Sea.

The main difficulties of national offshore aquaculture are associated an unprotected coast directly exposed to the sea

For example, the multiparametric buoys of the Peniche Sea, evidence the difficulties of the sea in this region and point to difficulties of implantation and access to cages,

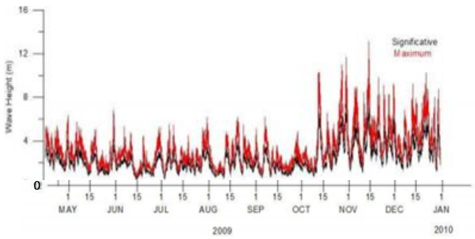

Fig. 1 – Height of waves in the Peniche Sea
Fonte: Multiparametric buoys located between Peniche and Nazaré

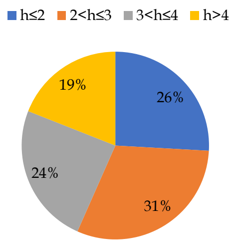

Fig. 2 - Percentage of the significant height of the waves
(from 2011 to July 2013 in the Peniche Sea)
Fonte: Multiparametric buoys located between Peniche and Nazaré

On the other hand, the EES is extensive and the continental shelf is several times the area of the Continent and islands; such situation makes it inevitable to study the conditions and technologies that allow the exploration of this wide national territory, full of potential.

Ocean aquaculture is undoubtedly inevitable.

The extension of our platform is an invitation that cannot be denied. It does not have the same characteristics of wind, temperature and waves throughout its length, providing multiple opportunities and requiring different technological solutions for each location and activity.

The concept of the use of autonomous multi-purpose platforms is adequate for this strategy.

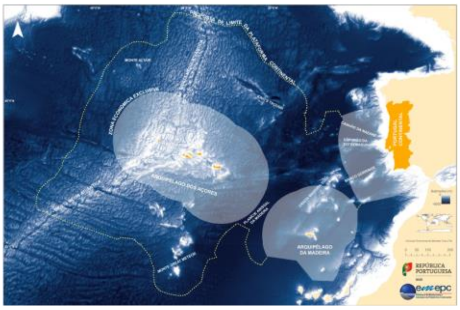

Fig. 3 – Continental Platform shelf extension map
Fonte: https://docs.wixstatic.com/ugd/f3d47f_4622f20d04834af581ccfa1138f4cae0.pdf

Thus, equipment and skills will have to be developed for this purpose, and it is inevitable that activities such as aquaculture, energy, oceanography, exploration of ores, among others, will be associated in multipurpose platforms.

To make this objective a reality, concepts of highly autonomous aquaculture equipment have been developed, with adapted species, using new materials, automation and design solutions, in order to provide security and attractiveness to the sector.

There are studies on intelligent equipment which, depending on the sea conditions, maneuver autonomously, in order to choose the place and column of water where the stresses resulting from winds, currents and waves, and the shocks of the waves with the structure, do not jeopardize the safety of the equipment and the well-being of the caged fish; in short, solutions associated with the development of intelligent cages, autonomously managing much of the maneuvers and routine tasks.

The concept of “Autonomous Multi-Purpose Platform” then emerges, which consists of autonomous equipment with energy availability to move water and compressed air intake valves, available on the platform, for:

- maintenance of cages;
- maneuvering and providing doses of silage food;
- renewable energy production (e.g. wind, photovoltaic, wave);
- movement of cages;

thereby increasing the efficiency of use of the same marine space.

The synchronization of use of the several pieces of equipment that form this system, or even each one per se, is based on sophisticated control systems, also based on new techniques and materials.

2. Context and State of the art

The capture of fish, bivalves and algae, among other marine species, has been carried out since long ago by man who behaved, exclusively, as a hunter collector using fishing hooks and threads produced from natural products, woven from natural fibers, and bones carved to catch the prey, or spears and harpoons armed with flint tips.

The collective capture of fish occurs, in a first phase, on an occasional basis, which can still be witnessed nowadays. The fish can be trapped in a loop of a river or lake, or in a puddle resulting from the tidal reflux. Later on, the spinning of stems and the use of the net for fishing appears.

Probably, based on this evidence, barriers began to be built to allow fishing and the glimpse of creating fish in an enclosed space. But one was far from mastering the other variables at stake.

It is the materials, even the most elementary ones, that leveraged human activity in its beginnings and that are still used today. These were the inspiration for synthetic materials, competing with them in some circumstances.

The emergence of aquaculture as an organized form of food production is influenced by agriculture and the idea of “domestication of animals”, a singular feature of the Neolithic Period, inheriting many of the designations of this activity that characterized the period, thus emerging aquaculture farms similar to agriculture, with the possession of resources and benefits.

For this reason, the convergence of these factors naturally leads to the coexistence of fish farming with rice cultivation in China, constituting the first extensive aquaculture experience, with carps, which quickly expanded throughout the region, originating devices for breeding carp in bamboo cages; naturally, later extended to the breeding of other species.

In the case of Europe, the propagation of aquaculture was made by the Romans, in a first phase associated with the baths, or in tanks built for this purpose, later for sale.

The observation of migratory flows of other fish, particulary the mullet, led to strategies of capture and fattening in tanks and cages by the sea or river courses.

During the Middle Ages, carp would be cultivated in tanks by monks for fasts.

In the 14th century, the rainbow trout was spread throughout Europe and, in the 13th century, the cultivation of mussels appeared. Oyster culture in Japan was farther away.

In Africa, in the 3rd century BC, arises tilapia, which allows successful cultures in captivity, spreading rapidly.

The first known fish farming facility dates from about 5500 years ago, where the caged fish was fed by man and reproduced in captivity, with archaeological evidence and scientific dating, recently revealed, in late 2019. This discovery is of enormous significance, since, for the first time, man builds housing designed to simultaneously collect, feed, fatten and reproduce fish. It would be the beginning of aquaculture.

The construction of equipment becomes definitely attractive and the selection of materials makes use of the nature and mastery of the transformation processes they had or came to develop. Thus, the main materials are available in nature:

- ❖ **Textile Flora** - such as fruit seeds, cotton; flax stems, hemp, jute, bamboo; sisal leaves, all of textile origin, from among others
- ❖ **Animal origin** - such as silk and wool
- ❖ **Vegetable origin** - different woods, fibrous tree stems
- ❖ **Mineral origin** – such as flint (silex)

There is, therefore, a consistent development line of materials that will sustain aquaculture production technologies.

The quality of the environment is the dominant factor that, over time, influences aquaculture. It is inevitable that aquaculture will move to new spaces where the energy of currents and waves impose more robust solutions and equipment, and new materials.

Fish production was carried out in stone tanks and in coastal areas excavated for this purpose, similar to the technology used for the construction of salt pans, or in abandoned salt pans, or in devices in protected areas of rivers, lagoons and protected areas on the coast, which, for a long time, was occupying the coastline.

Meanwhile, bivalves, including oysters, occupied the intertidal areas.

The creation of equipment was gradually responding to these needs, at first using handmade equipment.

Only in the 20th century were the main problems of modern aquaculture solved. In the 60s and 70s of the last century, a surface net cage was developed, which was decisive in the high growth of salmon cultivation and in the development of the Mediterranean culture of sea bass, and the cultivation of sea bream only in the 80s. In the 1990s, a large salmon industry was created.

The first submersible cages are developed, aquaculture suffers an exponential growth in these decades, with environmental concerns arising from the concentration of intensive farming in more accessible areas.

At that time, appear methods to reverse this situation: the creation of cages for fish production in different offshore locations.

Meanwhile, RAS appears as an alternative, on land, usually close to the coast, but not necessarily.

Most cages are now produced by products resulting from synthesis chemistry and move away from the coast, occupying the nearshore area (<500 m from the coast), where increased water circulation lowers the environmental impact.

Several types of equipment adapted to the nearby open sea have emerged. FAO recommends an Hs < 3-4m on the near shore and an access to flexible cages > 90%, which can be floating and semi-submersible.

The first surface cages, with collar, were manufactured in PE, PP, later in PEAD. The cages often have a circular collar that allows the fluctuation and access to the inside of the equipment for feeding and catching the fish, and may have other geometric shapes and other materials. In the African and SW. The cages we just described always stay on the surface, with the collar partially out of water.

The rigid cage structures come from the need to operate in adverse sea conditions, being equipped with more autonomy and automation, and have the capacity to receive the installation of automatic feeding and storage systems of food and energy. They are able to submerge and assume immersion and emersion, having a minimal visual impact. They can operate at > 2 Km, Hs 5 m, requiring periodic visits 3-10 days. If the dimension of the structure justifies, these visits can be replaced by the use of sensors, video for observation of the cage, or use of AUV.

The first submersible cages are created simultaneously, but separately, by the French and Russians too. These create Sadko-SG (2006), still in operation in Italy nowadays and which has a feeding silo.

Nowadays, renewable energy projects are being developed in order to provide energy autonomy to the equipment; in the case of bivalves there have been important developments in the association of the wave and photovoltaic energy necessary for the movement of long lines of bivalve culture.

3. Equipment

The emergence, in the 1960s, of surface or floating collar cages (circular – more frequent and polygonal – more used in the east), in synthesis material, marks a profound change in the fattening technology of the fish, being the salmon culture the first to suffer a strong productive impulse, with considerable returns. This occurrence contributed to relaunch other crops, such as sea bass and later on the sea bream, and other varieties in the following decades.

The growth and fattening phase of the fish was mostly moved from land to sea, allowing, during this period, an environmental improvement since:

- effluents disperse with the currents;
- there is an improvement in water renewal, thereby having a better oxygenation of the caged animals;
    - large increase in production, moving from extensive production (on land), to intensive production (at sea);

promoting the evolution of equipment, an increase in fish produced by this means and a significant improvement in the financial return.

The emergence of nylon, in the 1930s, allowed the development of safe solutions for the containment of fish inside the cages. Being able to support anti-fouling treatments, nylon nets with square and hexagonal mesh, with or without knots, largely fulfill this function. However, there are also steel meshes for rivers where alligators exist and, in the 1990s, copper networks are used in the sea due to their antifouling action.

The quick evolution of aquaculture in the following decades led to new needs, such as operating offshore in coastal protected areas and going to increasingly exposed areas, with new requirements: more robust equipment, development of new materials such as HDPE in the construction of floating cages, semi-submersible to be able to withstand currents and waves, improvement in equipment management with regard to food, and increasingly safe fishing and moorings.

In the 1990s, new equipment emerged: semi-submersible and submersible cages that allow full immersion for several days.

Fig. 4 – Submersible Cage (OceanSpar)
Fonte: IPMA - Estação Piloto de Piscicultura de Olhão

At the same time, automation started to have a prominent place, making possible: the autonomous control of the equipment; its remote control; and the TV view of the fish. The new equipment will allow the occupation of wider areas of the ocean.

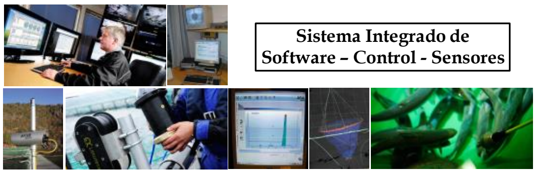

Fig. 5 – Integrated software system – control - sensors
Fonte: Ferreira 2018

During this period, large sea farms were developed in extension, and equipped with means of feeding from barges with feed silos and cage automatic feeders, with means of supervision and control of the marine field for cultivation of marine species, including bivalves.

Fig. 6 – Marine aquaculture fields - Fish farming

Fig. 7 - Marine aquaculture fields - Long lines of mussels
Fonte: Ferreira 2018

Meanwhile, the occupation of the marine space by other activities began, in particular, the fields of wind energy production, at the same time of an increasing opposition to the creation of fields in the proximity offshore, which increases the pressure on this area.

There are ongoing projects to associate wind fields to fish farming, forming multi-purpose platforms.

Fig. 8 – Future Multipurpose Platform - Wind and Aquaculture
Fonte: http://www.innovakeme.com/oips/

The development of the equipment we have been referring to is only a small part of the exponential development of aquaculture. In fact, the reliability, the properties and the excellent behavior of materials from synthetic chemistry in the water have contributed to this.

4. Materials

4.1. Materials for cables and moorings

The most used fibers are Nylon (PA), Polypropylene (PP), High Density Polyethylene (HDPE) and Dyneema (HPPE). They have good physical and chemical properties and allow a choice according to needs in the marine environment, the purposes and the costs.

Steel and copper alloys are generally used in support equipment. Copper alloys have good mechanical strength associated with very good resistance to corrosion and fouling. Steel, in general, is forged and hot-dip galvanized. These metal alloys are used in parts of responsibility and safety of the equipment: in chains, propellers and moorings, usually with anti-corrosion protection.

Nylon (PA) is a material widely disseminated by the various fishing equipment: fishing wire, cables and fishing net, containment net for caged fish and even moorings. It absorbs water, presenting dimensional variations, and its similarity with silk is noticeable. Even in the last century, fishermen called nylon, silks, a material used since prehistory for angling.

Polyester (PES) has an excellent behaviour in the anchoring cables. It has great axial flexibility, greater than a steel cable in the same circumstances, with the advantage of being lighter. It can be associated with steel chains to facilitate immersion and has very low flexural rigidity, allowing any type of mooring in: catenary, TL or TLP (vertical anchoring). It is especially appreciated in deep waters, due to the high coefficient of elasticity and high resilience.

Polypropylene (PP) is used in mussel culture due to its good buoyancy.

Dyneema is a polyethylene that presents high resistance to cutting and abrasion, great impact resistance, is very resilient and tenacious, has low deformation to breakage, thus making it very useful in moorings where it has disputed the choice with PP.

4.2. Materials for the construction of cages and boats

Cage building materials are fundamentally HDPE tubes. In addition to the properties mentioned above, they are easy to apply and maintain, are quite resistant to UV and are available on the market. They are usually used in the PE 100 specification.

HDPE and HPPE have high crystallinity. They are used in the construction of the cage structure tubes and have good mechanical properties, among which we highlight flexibility and high resistance to shock, good resilience and tenacity.

Polyethylene has a wide range of properties due to the degree of HDPE crystallinity. It allows the manufacturing of parts used in cages, by.

Nylon 6.6 is the most used for the manufacture of containment nets. The meshes are square or hexagonal, usually without knots so as not to injure the fish and must undergo anti-fouling treatment before application in the cage. The nets can serve as protection against aerial predators, cormorants or attacks of marine predators. The use of HDPE tubes, as we have seen, has tenacity that allows the structural tubes to be shaped as to be surrounded by the fish containment net.

The presence of steel in construction (SADCO) or, currently, in the salmon fattening cage (SALMAR), resulting, or not, from the domain of offshore oil exploration technology, which aims to solve problems experienced by the salmon industry.

The steel structures may indicate the proximity of a new era of aquaculture,

Offshore cages must be equipped with energy, sensors and automatisms that perform a wide number of tasks, avoiding or reducing human intervention. The introduction of composites today in AUV and Drones, which monitor marine farms and, in the case of AUV, the state of moorings and nets, making simple repairs.

There must be support boats designed according to the dimensions of the installed farm. The support boats are built mainly in aluminium or composite, equipped with winches and cargo holds for transportation of feed.

4.3. Case Study

The Cage4Ptsea project aims to build a prototype of a semi-submersible cage, which is under development.

The cage was at sea for a period of 6 months, from 2020-01-07 to 2020-07-02 (without fish during the first 2 months and with fish from 2020-02-27, for 4 months).

Fig. 9 – Prototype of a semi-submersible cage of the Cage4PtSea project
Fonte: Cage4PtSea project

When he left the sea, after a six-month stay:

- All connecting links between the central tube and the structure were destroyed, both in the connections at the base and at the top;

In the case of cage Cage4PtSea the distance to the bottom of the sea was small the reduced probe of the site is 5 m, it is visible the trail of bottom mud.

Fig. 10 – Cage when it left the sea after a stay of 6 months
Fonte: Cage4PtSea project

As can be seen in fig 10, there was shock of the cage with the bottom, where mud is visible, at the time of removal, it is important to mention that this shock is made, inevitably by the vertical tube.

The shocks were transmitted to the structure of the cage by the cufflink connecting the vertical tube to this.

Fig. 11 – Base risers before staying at sea
Fonte: Cage4PtSea project

Fig. 11 can be seen in the construction phase, the connection of the links, the flange of the pipe to the lower ring of the structure.

Fig. 12 – Stretchers in the upper zone after staying at sea for 6 months
Fonte: Cage4PtSea project

In Fig. 12, the upper risers are broken.

Fig. 13 – View of the end of the tensioner
Fonte: Cage4PtSea project. Ferreira A.

View of the end of the tensioner, with the threaded zone and tension adjustment nut.

Fig. 14 – Central tensioner body
Fonte: DRX Francisco M.-IST

The Fig. 14, shows the central body with inner thread, with inlays, which suggest an attack on austenitic stainless steel, in the body of the stretcher, it was verified by XRD to be Aragonite, resulting from the colonization of crustaceans.

Fig. 15 – Tensor frature
Fonte: Cage4PtSea Ferreira A.

Fracture of the threaded tensioning rod was on the nut's face.

Fig. 16 – Fractured screw inside the central body
Fonte: Francisco M. - IST

Fracture of the threaded rod seen outside the central body nut, evidencing plastic deformation and pitting in the fracture area.

Fig. 17 - Fractured screw inside the nut
Fonte: Cage4PtSea project. Ferreira A,

View into the inside of the nut.

Concluding

- Recommendations for the anchoring of cages have not been complied with:
  - *minimum total depth of 40 m for the site;*
  - *maximum depth of sinking, shall ensure that the bottom of the cage when immersed, has a distance of more than 10 m from the bottom of the sea;*
- The main cause identified as the determinant of the accident was the direct contact of the central tube (fixed to the structure by the linkers), with the seabed.
- The dingers went into overload, since they were not sized for the efforts to which they were subjected, with dynamic loads associated with the undulation, shocks and laying of the tube on the seabed. The tube had important vertical movements that were discharged into the tube and cage through the dingers, sufficient tensions to cause the rupture of these.
- The incident described and identified enables the recovery of the equipment and the return soon to sea trials.

The links between the flange of the tube were in contact with the mud, remains of food and fish waste were an anoxic medium, albeit limited, but which favored corrosion in the area connected to the flange, promoting anaerobic corrosion.

5. Conclusions

The nylon cables and nets, are widely used, have a good elasticity, with a stretch of breakage that varies according to their ccrystallinity and good resilience. These characteristics mean that you can increase the length of each component after a working period of a few months, by about 10%; therefore, a nylon mooring system will need to be tensioned again a few months after it has been installed. Nylon mesh cages will increase in depth by 5 to 10 percent because of the lengthening of cables and nets, due to loads from biofouling or sinkers in the net; on the other hand, they can also shrink, causing problems on the net, and it is possible that the horizontal dimensions of the cage can be reduced by 3-5%. Therefore, when setting up the net, this factor should always be considered, by giving extra compensation, incorporated into the project.

Bearing in mind the above, nylon, despite its price, availability and frequent use, will not be the best solution for mooring purposes. However, nowadays, other materials are already being used, namely

Polypropylene-PP and Dyneema-HDPE.

Moving to the Open Sea is not a choice, it is an inevitability considering:

- the issues raised in Coastal Aquaculture;
- the insufficient capacity of Land and/or Estuarine Aquaculture.

There is already a broad consensus in the aquaculture sector that its implementation in the **Open Sea** involves returning to the design phase and treating it as an entirely new activity, from a completely different perspective of coastal aquaculture.

When it comes to the **OpenSea**, the diversity of local conditions requires **"Taylor Made"** solutions.

It is essential to have accurate information about the topography of the place where the platform is to be installed, and it is essential to make a study, based on data of at least one year, on the **determining properties of the system**:

- Currents (speed and direction); Water temperature; Salinity; Oxygen levels; Chlorophyll levels; Wave regime.
- In Portugal, offshore fish farming, preying on great attractiveness and its productive potential, remains virtually intact, although with recent advances in the sector, in the Autonomous Region of Madeira, in Sines and now in the Algarve, it constitutes an opportunity for the production of food resources that responds to the challenges posed, mainly by the containment of extractive fishing. The same cannot be said of bivalves, which are in good condition.

Technological constraints in fish farming are fundamentally related to: high wave energy; open sea winds; sea currents; water temperature gradients; particular aspects of the species to be cultivated; richness of nutrients, which also promotes the growth and development of fouling in the cage networks, which causes the water renewal and consequently the available oxygen to decrease; and the distance from “sea farms” to a port. All of these conditions must be taken into account by those who intend to operate in the open sea.

It can be said that the **"Surroundings of the Open Sea aquaculture system"** are:

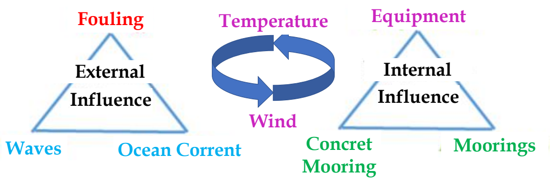

Fig. 18 - Surrounding the Open Sea aquaculture system
Fonte: Ferreira 2018

The study of constraints *on site* determines the type and characteristics of the equipment to be used, and the critical success factors.

The main problem is to improve plant safety and animal welfare, essential for adequate growth, even in adverse environmental conditions.

The cage and associated equipment should, if necessary, move vertically along the water column and over the surface of the sea.

In offshore aquaculture, restrictions are mainly related to high wave and wind energy at sea, as well as distance from the coast or a port.

The existing offshore technology does not yet have this automation standard, which involves the identification of risks and the in situ automatic resolution decision of the detected and validated problems. Energy autonomy, associated with offshore production, will provide aquaculture with the necessary capacity for new equipment and automatisms.

In aquaculture, we can say that, in its different equipment, there is a relevant variety of materials, as shown in this presentation.

6. Future vision

To develop submersible systems, operated according to sea conditions, by remote control, or through the automatic location and depth self-control system, based on the monitoring installed in the structure, repositioning in the smallest possible permissible depth, automatically imposed, using the generated information and the maneuvering means installed, guaranteeing the safety of the equipment, animal welfare and optimizing the temperature value that constitutes a critical factor of these equipments in the growth of the caged fish.

When planning to develop an

aquaculture facility, the following points should always be taken into account:

- In-depth studies of "External Surroundings" - Waves, Currents and Fouling;
- Mobility of Equipment in order to monitor the most favorable conditions of the "External Surroundings" according to oceanographic studies;
- Design of equipment with: New Materials, in order to minimize the negative effects of external surroundings.

The resolution of the two main problems associated with the behavior of the cage in the difficult open sea is the main concern: **resistance to mechanical stresses**, for example, by wave impact; and **fouling inlays**, which often appear associated, causing dragging and sinking accidents.

The material of the nets, as well as the composites of the support structure, are formulated and tested to confirm the anti-fouling characteristics and thus minimize the problems with increasing depositions (fouling). The paints and protective barriers must have rheological and adhering properties that allow the coating of cage components. They shall ensure the comfort of the fish, and the hygiene conditions and food safety of the products used in the equipment, in accordance with the corresponding standards and tests, taking into account the cost-benefit assessment of their adaptation and use in the project.

Concerning the nets, production mechanisms should be developed, using a modern anti-vegetative technology developed by IST, within the scope of the European project FoulXspell, which was coordinated by IST, and that will reduce the frequency with which cleaning is necessary and thus significantly reduce maintenance costs.

The application of the anti-fouling incorporated in the materials through covalent, non-leaching connections, leads to great energy savings and savings of other costs, since technology avoids the changing of nets.

In the Ocean, the occurrence of a storm for several consecutive days imposes the need to install autonomous fish feeding systems for periods of 15 to 20 days, as well as the installation of surveillance devices, accompanied by systematic records of failures, analysis and continuous improvement, even for traceability and food quality certification reasons.

Innovative composite materials are now being tested, that can be equipped with easy to install fiber optic sensors, which will provide real-time information on the stresses to which critical organs of the cage structure are subject: deformations, inclinations, temperatures and accelerations.

All these systems need energy, so the most suitable solution will be to have multi-purpose platforms, with renewable power generation, especially The association with wind energy is inevitable with aquaculture in its different aspects, according to the conditions of the place.

The construction of structures and equipment must take into account a selection of materials, namely in the area of polymeric fibers and composites. And also a careful association with partners in areas such as automation, energy, shipbuilding and marine biology.

The construction of the boats should tend to the use of fiberglass and eventually carbon and Kevlar, or all of them, ideally in the form of pre-fixing, being the gelling and hardening phases processed in autoclave. It is, undoubtedly, the most advanced technical solution, but also the most expensive.

However, it is predictable that pipes and composite structures will integrate equipment for aquaculture, lighter and resistant, reducing the restoration forces due to the lower weight of the cage, also allowing the integration of antifouling in the composite itself, increasing its effectiveness and useful life, also allowing to incorporate sensors that will inform in real time the sea conditions:, strength and strains temperature, wind and sea currents.