INdIGO

INnovative fIshing Gear for Ocean

T2.2.1 The two prototypes of net

EUROPEAN UNION

Interreg France (Channel Manche) England
European Regional Development Fund

Content

I. Introduction

Work package 2 includes three successive and complementary activities:

- The development of the semi-finished product (monofilament and multifilament), from laboratory to industrial scale
- The development of new prototype fishing gear, adapted to the fishing and aquaculture sectors
- A technical and economic study of the new fishing gear.

About activity 1, the development of the formulation based on biodegradable plastics was carried out by NaturePlast, in collaboration with the UBS and its CompósiTIC technical platform, which was responsible for transforming the plastic into semi-finished products: a monofilament (filament made up of a single strand such as a fishing line) and a multifilament (filament made up of several strands joined together). Continuous optimization of the formulation is planned based on feedback from professionals, after each stage of the manufacturing process. Two deliverables are available: the selection of formulations (T2.1.1) and the description of tests (T2.1.2).

The semi-finished products developed in this way are then used by the Filt partner to design and manufacture prototype catenary nets. Thanks to its expertise, Filt will be able to check whether the filaments developed by UBS comply with the specifications previously defined in WP1. The prototypes will then be studied in the following WP3 to analyse their behaviour in a marine environment.

One of the aims of Activity 2 is to design and manufacture prototypes of biodegradable nets on an industrial scale using the semi-finished products developed in the previous activity. With the aim of replacing some of the nets currently used for aquaculture (made of polyester and polypropylene) and fishing (polyamide), the use of biodegradable nets will make it possible to reduce the impact of ghost fishing in the long term. In conjunction with NaturePlast, UBS and IRMA, the Filt partner has implemented a specific two-stage process for manufacturing the prototype nets. The first stage involves knitting the multifilaments together. Tests on the prototype fine netting will be carried out by a subcontractor. Several spools of filament will be required for both types of prototype net. Thanks to its expertise, Filt will ensure that the filaments produced by UBS are capable of being knitted with different meshes and different diameters (e.g., tubular nets and flat nets). An optimisation phase is also planned if the filaments are not suitable. The second stage will involve the manufacture of prototype nets from the assemblies using the various knitting machines available at Filt. These prototypes will then be tested by fishing and aquaculture professionals during the deployment stage at sea planned in WP 3.

The main outputs of this activity will be two prototypes of biodegradable nets meeting the specifications (MTT1), one for the fisheries sector and the other for aquaculture.

The partners involved in this deliverable are Natureplast, UBS, IRMA and Filt 1860.

II. Production of mussel aquaculture net

The prototypes of net for aquaculture were produced by Filt 1860, a company specializing in the textile industry (Rachel knitting, braiding, and clothing) and a partner in the INdIGO project. The company operates in a wide range of sectors, including automotive, childcare, shopping nets and mussel farming. Their specific equipment enables them to check the processability of the multifilaments produced as part of the project to produce netting on industrial-scale machines.

1. First knitting test (December 2021)

Initially, there was not enough material to produce a complete net. Filt's partner therefore replaced a cotton yarn on the tubular reference in production with an INdIGO multifilament yarn (Figure 1). The aim was to observe the differences in the behaviour of multifilaments in the knitting machine according to diameter and to validate the additives used to obtain controlled strength, diameter and elasticity.

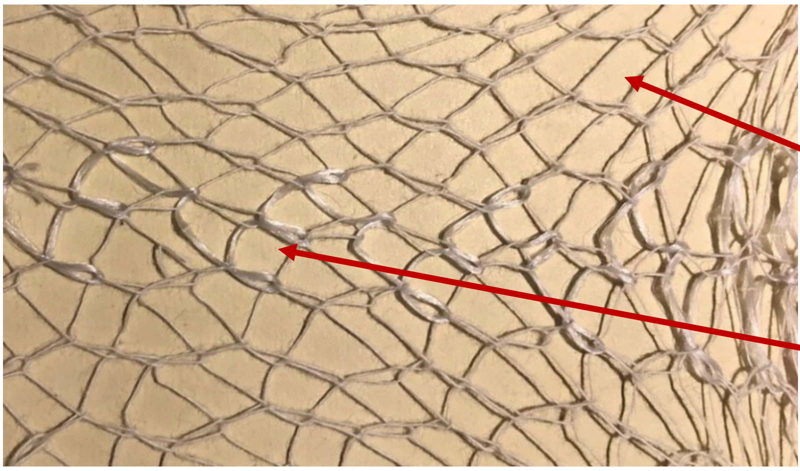

Figure 1: Integration of INdIGO multifilament mesh in a cotton net

2. Second knitting test (July 2022)

Following the initial results (yarn production, multifilament characterisation and knitting tests), the formulation was modified by the partners UBS-ComposiTIC and NaturePlast, and a new spool of multifilaments was produced on a laboratory scale. To knit a 16-mesh tubular net, the knitting machine needs to be supplied with a minimum of 32 spools. The size of the mesh (in other words, the side of the diamond) is defined by the knitting pattern programme (see an example in Figure 2 below).

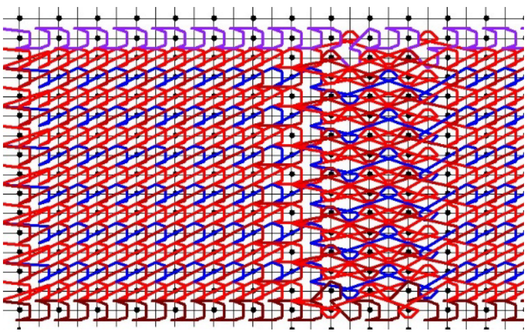

Figure 2 : Example of a knitting design

From the spool of multifilaments received, several intermediate stages are necessary to produce a net.

a) Step 1: cutting of the spools.

On the winder, the spool was re-divided into 8 spools of equal length, so that several diamond stitches of a tubular net could be knitted. Handling the multifilaments on the spooling machine showed that the filaments appeared to be solid, despite being fragile to the touch.

Figure 3 : Illustration of stages 1 and 2, with the coils being cut (left) and loaded onto the machine (right).

b) Step 2: loading the equipment.

The small bobbins obtained after splitting the yarn are placed on the machine during the production of a tubular net. The yarns will be knitted on 6 needles, among black polypropylene yarns (Figure 3 - right).

c) Step 3: knitting

The 8 filaments were installed on the knitting machine in the same way as traditional filaments. The multifilaments were twisted to improve mechanical strength and cohesion. However, as soon as the first metres were knitted, defects such as twists and bulges appeared (Figure 4). Without sustained manual intervention, it would not have been possible to knit the yarn on the loom. This problem was solved by using untwisted multifilaments.

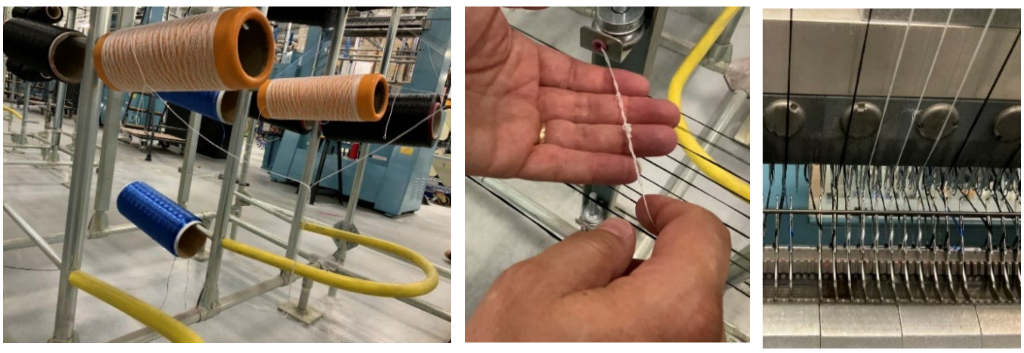

Figure 4 : Example of defects obtained with INdIGO multifilaments

Overall analysis of the second test: The results are encouraging, as the yarn can still be knitted on industrial equipment (Figure 5). A few improvements should be noted, such as the lack of resistance of the multifilaments and the lack of cohesion with the breakage of certain filaments. The difference in elasticity of the yarn does not appear to be a problem, but the excessive number of twists means that industrial-scale production cannot be envisaged for the time being. A compromise in the yarn twisting stage would be necessary to ensure a minimum of yarn cohesion, without increasing the number of twists.

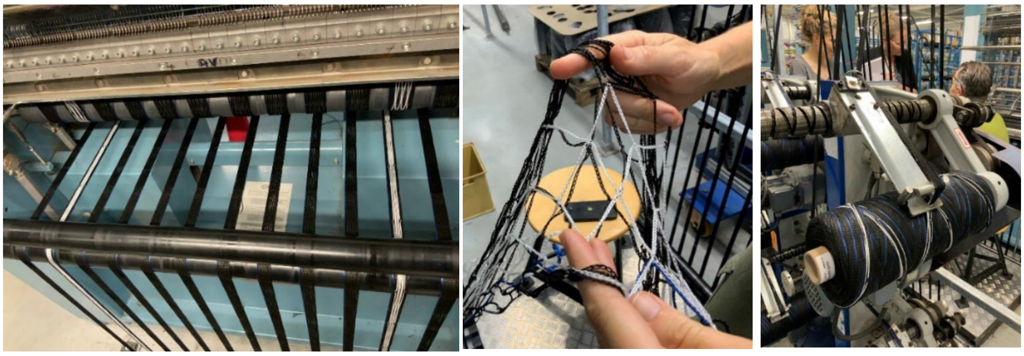

Figure 5 : Integration of INdIGO multifilaments on the production machine

3. Third knitting test (March 2023)

The third test was carried out using spools of filament of the same formulation as the previous one but produced with optimised parameters on industrial equipment. The quantity produced is large enough to produce a complete net, so that trials can begin under real conditions with mussel farmers. It should be noted that broken and non-homogeneous filaments were observed on the spools before prototype production began.

a) Step 1: rewinding and cutting the spools

As in the second trial, the 8 spools received were redivided to obtain a total of 32 spools. The aim is to make a complete tubular net from the INdIGO multifilaments. Several faults were noted at this stage: the filaments broke and did not hold together (Figure 6), but there were no more tendrils.

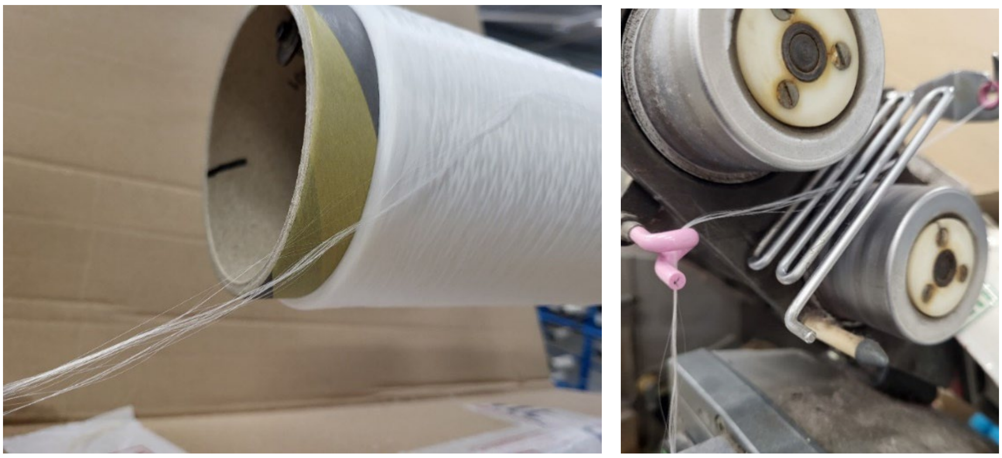

Figure 6 : Observations of the multifilaments during the cutting stage

b) Step 2: Loading the equipment

After a complete cleaning of the equipment, the 32 spools are installed on the spool-holder.

Figure 7 : Installation of the 32 spools on the spool holder of the knitting machine

c) Step 3: knitting

This last trial made it possible to manufacture a complete tubular net with the knitting machine, the first prototype of a catinage net made from biodegradable plastic in the marine environment. Figure 8 shows the tests with the filaments passing through the needles and the result of the knitted and meshed net. Defects were nevertheless visible during production, due to filament breakage and lack of cohesion (see the red arrows in Figure 9 below).

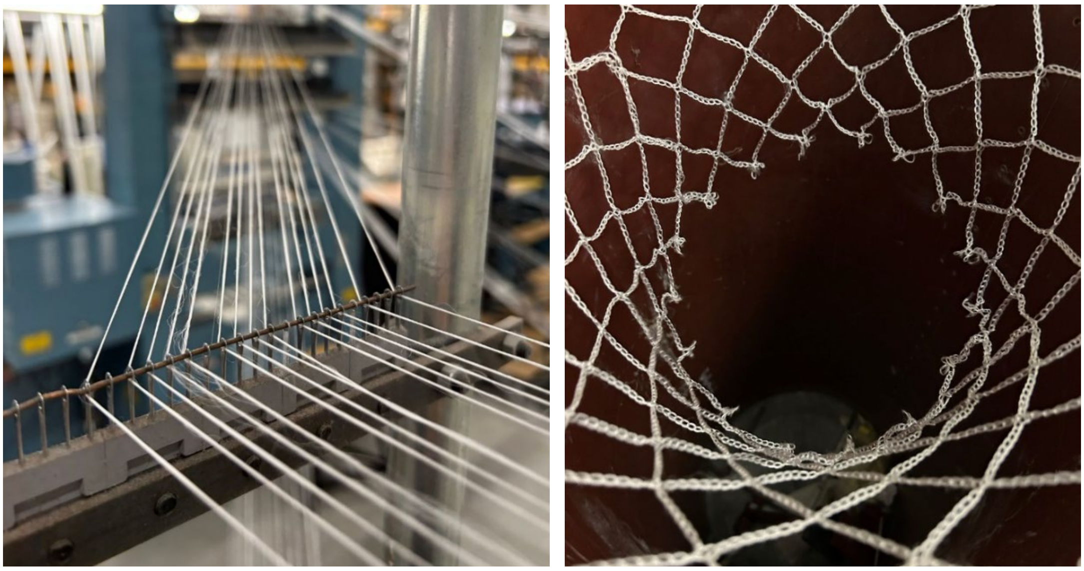

Figure 8 : knitting a complete tubular net from biodegradable multifilament at sea: on the machine (left) and the final result (right)

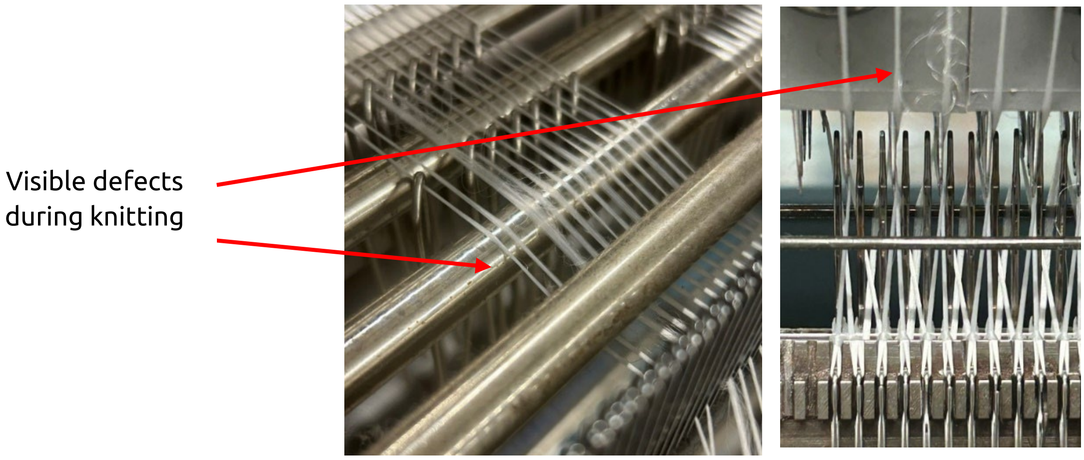

Figure 9: Appearance of defects during knitting

Regarding production rates, the production speed of INdIGO nets is reduced by 30% compared with the maximum capacity of the machine, used for normal production with polypropylene (PP) wire. Machine adaptations were also made for production with the installation of needles with large beaks due to the low resistance of the wire. All these factors result in a loss of production speed. Certain parameters will have to be optimised, but they will not prevent the production of the net.

The table below details the characteristics of the prototype:

Prototype	16/40 version 1
Number of meshes for the whole perimeter	16
Titration of unbleached filament	1380 dtex - 48 filaments
Flat stretched width	64 cm
Diamond side length	40 mm
Weight of stretched mesh	About 16 gr/m

Table 1 Specific parameters of the aquaculture net prototype

III. Development of the fine net prototype

1. Validation of the monofilament

A selection of monofilament was presented in February 2022 to Christophe Yhuel, manager of the Lorient-based *Atelier du pêcheur*, which specializes in net assembly. One of the aims of this exchange was to get the professional's opinion to help us with the final selection. To do this, 7 samples of monofilament were presented to him, from the least good mechanically to the best. Of course, this is an empirical method, but the professional is used to handling monofilaments, so his feedback is essential if we are to meet anglers' expectations as closely as possible.

Table 2 below summarises the various comments made by the professionals following the handling of the 7 samples. The people present during the tests were: Christophe Yhuel (*Atelier du pêcheur*), Fabien Morandeau (Ifremer) and Morgan Deroiné (IRMA).

ref fisherman	ref UBS	ref NTP	Diameter (µm)	F(N)	Professional comment
1	n°4-3 PE n°4-4 PE	0-190	550 545	73 70	very satisfactory, much stronger monofilament (can't see any difference between the 4 samples)
2	n°5-7 PE	AH	510	62	
3	n°5-1 PE n°5-2-2	AJ	380 508	51 62	
4	n°5-4	AL	527	62	
5	n°3-20 n°3-20 PE	AC	440 430	56 48	well too, it's not rigid
6	n°2-14	I	360	15	it's good, resistant despite its thinness
7	n°4-10 PE2	P	580	65	It breaks but that's normal, the larger the diameter, the stiffer the filament (and that's not a problem).

Table 2: professional feedback on the 7 monofilaments tested.

These discussions enabled us to rule out two formulations, I and P (monofilaments 6 and 7), for further testing.

2. Mesh tests

At Ifremer in Lorient, mesh tests were then carried out with the invaluable help of Fabien Morandeau, who made them by hand. Several parameters were studied, including shape memory, knot slippage, breaking strength, and stiffness (or flexibility) ... Those present at the mesh test were Fabien Morandeau and Sonia Méhault (Ifremer), Morgan Deroiné (IRMA).

One of the aims of the 5 monofilament formulations previously selected was to produce hand-made meshes to check their technical feasibility. The test was carried out in several successive stages. The first step was to assemble a piece of cloth by hand (Figure 10).

Figure 10 : step 1: knitting by hand.

The first assembly was made with a standard nylon monofilament, to provide a reference for stiffness and knot behavior (Figure 11).

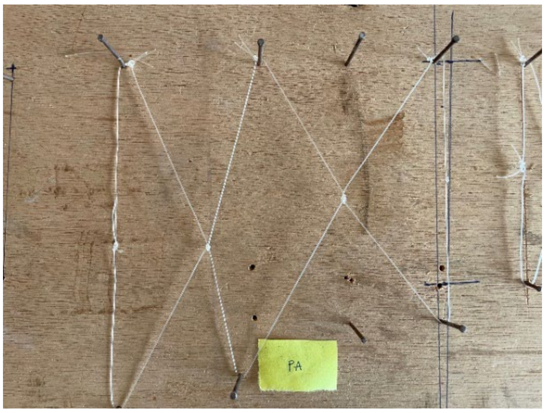

Figure 11 : Behavior of meshes with a traditional polyamide (PA) monofilament.

The observations are as follows: the monofilament is stiffer (but is it better?), the meshes are clean, with less 'fuzziness'. The knots hold together perfectly. Figure 12 below highlights the two samples AC and AH which show the best behavior.

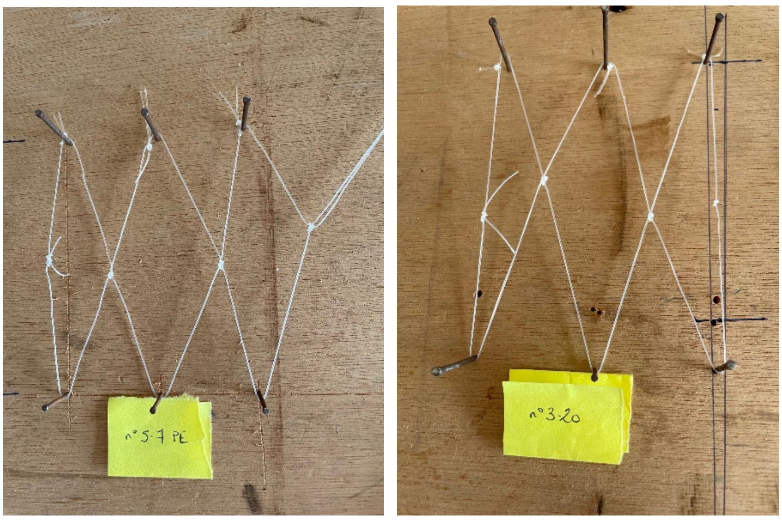

Figure 12 : Best-performing mesh tests carried out on 2 monofilament samples.

Indeed, the mesh on the left (n°5.7) corresponding to the AH formulation is good, the monofilament is thinner, more flexible and easy to handle. The knots also hold (quite a difference from the other monofilaments tested). The mesh on the right (n° 3.20) corresponding to the AC formulation is also correct, despite the fact that a few loops appear (no shape memory, it holds less well after handling).

The other meshes made with the other references are shown in Figure 13.

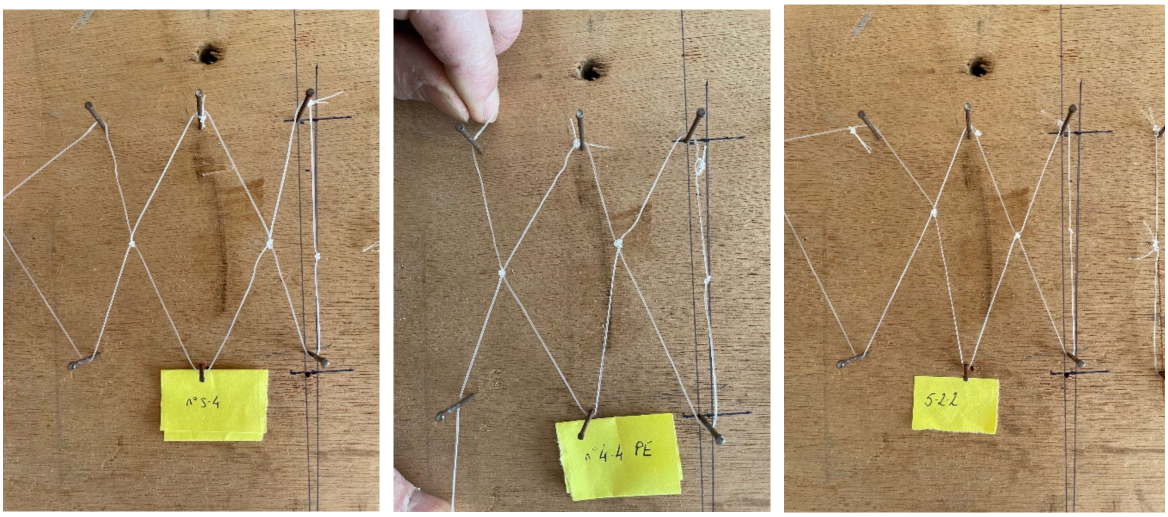

Figure 13 : mesh tests carried out on the 3 other samples.

Overall, the meshes obtained from the other three samples are not sharp and the nodes do not hold together. The mesh on the left (n°5.4) corresponding to the AL formulation has a slightly different color (whiter) than the others and is satisfactory overall. For the central mesh (no. 4.4) corresponding to the "O-190" formulation, the knots tend to slip, despite good mechanical strength. Finally, for the mesh on the right (no. 5.2), relating to the AJ formulation, the monofilament holds less well in the needle and makes spirals or loops. These 3 samples were therefore discarded for further testing.

Summary: These tests, although empirical, helped the INdIGO partnership in the final selection of two formulations. Based on feedback from professionals, combined with the mesh tests, the two monofilaments selected are:

- Choice 1: AH monofilament

- Choice 2: AC monofilament

3. Producing a prototype

a) Design of the net sheet

The basic unit of the net is the "netting" or sheet: it is made up of a set of meshes of identical size, varying according to the species of fish targeted, over a variable length and height. The lengths of these webs generally vary between 25 meters, 50 meters and 100 meters and are then joined together. In France, depending on the fishing zone and the species targeted, professionals use different types of net, including the following examples:

- In Lorient: simple monofilament netting

- In Normandy: fine multi-monofilament net in twisted polyethylene (PE), more flexible

- In Boulogne: fine polyamide (PA) twisted net, 2 threads made up of multifilaments, very flexible and very strong, ideal for hard bottoms with blocks of stones.

As part of the INdIGO project, the partnership decided to develop a fine net of the straight or "gill" type with a single sheet placed in the water column and made from monofilaments. For the mesh, the type of knot was also selected: the sheet knot, also known as the weaver's knot, because it is used to join lengths of weft or warp on a loom, and the "net knot", because it is used to form the meshes (Figure 14). It is the only knot that can be made with two ends of different diameters.

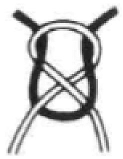

Figure 14 : type of knot used for the fine nets in the INdIGO project.

Another important parameter for ensuring that the net holds up well over time concerns the first and last lines of mesh, at the edges, which will be in contact with the floated and leaded ropes. In our case, as the mechanical properties of monofilaments are slightly lower than those of traditional monofilaments, option n°2 "double selvage" presented in Figure 15 will be preferred to reinforce and better distribute the forces between the netting and the ropes.

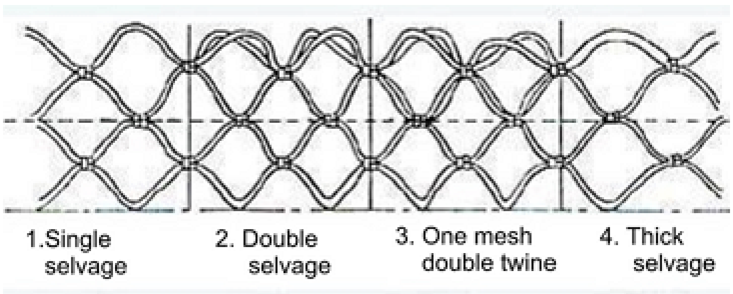

Figure 15 Different types of finish for the selvage in contact with the ropes

There is therefore a multitude of possible netting designs, which will differ according to the feedback from professionals and fishing sectors. Figure 16 is an example of a technical data sheet for a netting recovered from the fisherman's workshop:

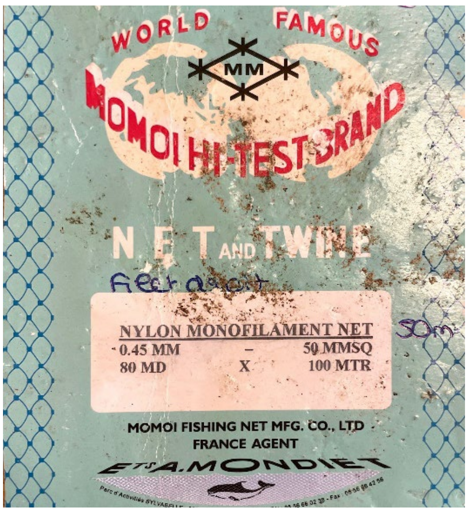

Figure 16 : Example of a data sheet for a net purchased by a fisherman in Lorient.

The sheet net was manufactured by the Japanese company Momoï and resold by Mondiet in France. The information given includes the composition of the monofilament, the diameter, the mesh size, the height of the netting and the length, i.e., a diameter of 0.45 mm and a height of 8m and 100m respectively. For the prototype net developed as part of the project, the partnership used the same parameters to ensure that the gear was perfectly suited to the fisherman's needs. The properties of the net are shown in Table 3 below:

Diameter of monofilament	0,45 mm
Mesh type	Diamond-shaped mesh
Mesh aperture size (stretched dimension)	100 mm
Knot type	Double knot
Dimension of net prototype	Length 50 m Height 60 or 80 MD

Table 3: Main characteristics of the net developed in the INdIGO project.

b) Net assembly

Once the sheets have been manufactured, they need to be joined together, which is what we commonly call assembling the net. When it comes to testing the net in real conditions with end users, the ideal solution is to propose a prototype net that is not too far removed from its usual gear. Two proposals for alternating netting have therefore been put forward over a length of 1000 meters, shown in Figures 17 and 18:

- Proposal 1:
  Alternation of 4 sheets of 50 m: 200 m of biodegradable net and 200 m of traditional net.
- Proposal 2:
  Alternation of 2 sheets of 50 m: 100 m of biodegradable net and 100 m of traditional net.

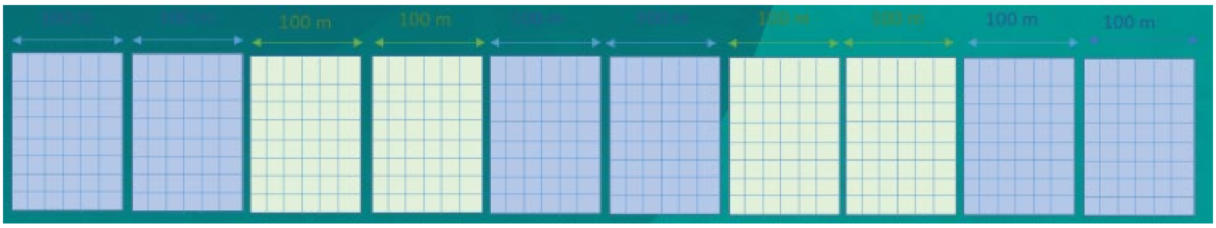

Figure 17: Proposal 1: Alternate INdIGO and nylon nets every 200 meters

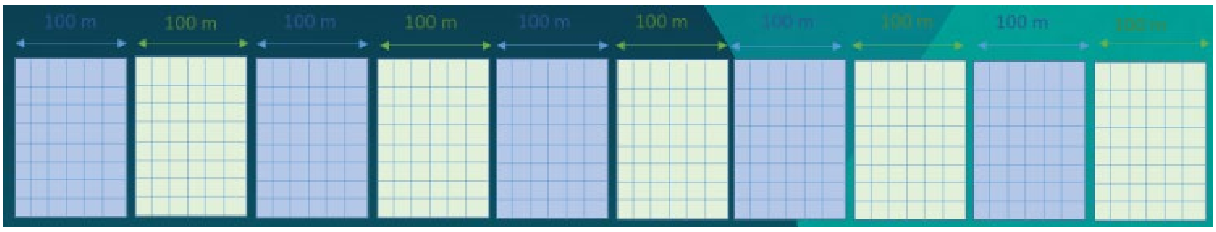

Figure 18 : Proposal 2: Alternate INdIGO and nylon nets every 100 meters

Proposal 2 was chosen after discussions with industry professionals and INdIGO project partners. In addition, all the components used in the installation, such as leaded and floated ropes and floats, will be the same as those normally used.

Questions concerning the presence of visual markers to differentiate the nets also aroused the interest of the partners involved, as did the duration of the study. The ideal is to have a marker for the observer but not for the fisherman, so as not to bias the test results.

c) On-board test protocol

Tabatha Thiebaut-Rizzoni, a doctoral student working on the INdIGO project, studied the behavior of fishermen on board their vessels in detail. The results of her analysis are summarized in his thesis manuscript. The project was also supposed to study how fishermen would appropriate the new fishing net, but this part of the project was not carried out. The partnership had nevertheless anticipated these trials by starting work on a test protocol at sea.

The observations were to take place on boats of the gillnetter type. Based on 3 embarkations per boat from the first uses (d=0) then 3 embarkations per boat at the end of the period of use of the prototype (d=20). A wide range of information will be collected, including:

- Situational factors: weather, GPS coordinates of the fishing area, etc.
- Catch status: valid (fish), invalid (spiders, starfish), inert (seaweed, etc.)
- Catch count: species; weight
- Counts of incidents related to fishing gear during spinning and turning

Each time an observer was taken on board, compensation was also paid to the fishermen so that their income did not suffer because of the various analyses. At the end of the net trial, a comparison between the INdIGO net and the traditional net was planned to assess premature wear linked to use.

4. Industrial scale-up

a) Production of monofilaments

Most of the monofilament manufacturing tests were carried out at laboratory scale on the extruder on the ComposiTIC technical platform. This is a horizontal extruder, equipped with several dies to meet demand for different diameters. Production of small quantities of monofilaments on this scale is sufficient to check mechanical properties and carry out ageing tests. The throughput is not high enough to produce enough to produce prototypes. The partnership therefore approached Cousin Composites; a company based in France (Wervicq-Sud, 59) that can manufacture monofilaments on a larger scale.

Several formulations were tested, and improvements had to be made, particularly in terms of viscosity.

b) Production of fine nets

Although it is still possible to manufacture a monofilament semi-finished product in France, albeit at high production costs, it is no longer possible to manufacture a fine net in France or England. During this project, the partnership was confronted with a lack of industrial network in this sector, explained by the relocation of production to Asian countries more than twenty years ago.

On a European scale, there are still a few companies, including: Le Drezen, Badinotti, Cittadini, DIOPAS... but they are not, or are no longer, in a position to manufacture fine nets to the specifications expected in the INdIGO project.

After extensive research, only three companies can produce prototypes to INdIGO specifications, including Cadilhe & Santos, Momoï, S-ENPOL.

IV. Conclusions

The main achievements of this activity were to produce two prototypes of biodegradable nets in the marine environment that met the specifications: a fine net for the fishing industry and a catining net for aquaculture.

This report highlights all the trials and technical advances involved in developing the prototypes, but also highlights the difficulties and limitations. The fishing and aquaculture gear sector is highly specific. Each professional works with his or her own gear, adapted to the species targeted, the seasonality and the fishing zone. For example, there is no such thing as 1 straight net, but rather a multitude of nets made from mono, multi or multi-monofilaments... with different sizes and assemblies, making it difficult, if not impossible, to manufacture a common prototype to meet the expectations of all professionals. This is why the partnership has adapted and chosen to manufacture a net for the Lorient gillnetter, adapted to their use, as well as a net adapted to the Normandy mussel farmer for the first installation in June.

One of the positive aspects of the INdIGO project was that it looked at the entire net production process, from the raw material in the form of plastic granules, to the machine used to produce the net sheets, right through to assembly. At each stage, specific technical features were required, and the partners gained a great deal of experience. The project has also demonstrated that biodegradable plastics can be used on traditional production lines, requiring mostly minor process modifications (temperature, flow rate, etc.).

Regarding the development of the aquaculture net, the various tests have made it possible to manufacture a complete tubular net using the knitting machine, the first prototype of a multifilament net made from biodegradable plastic in a marine environment. Despite some visible defects during production (broken filaments, lack of cohesion, etc.), the prototypes will be tested in real conditions on piles by an associated mussel farmer in the summer of 2023.

The proof of concept for the development of a fine mesh was also put forward. Only the final stage of manufacturing the netting was not launched because the mechanical property targets were not met.

On the negative side, the weak industrial network hampered the progress of the industrial-scale trials. As far as the catenary net is concerned, the network is clearly identified, with the Filt partner contributing all its know-how. For the fine mesh, the partnership lost time in identifying the right structure to meet the specifications. In addition, the partnership did not sufficiently anticipate the problems associated with changes of scale when setting up the project, and adapting the formulations was very time-consuming, with numerous trips back and forth between semi-industrial and laboratory scale tests to revalidate each stage (process, mechanical properties, etc.). Finally, the lack of time at the end of the project should also be highlighted.

➔ ***Perspectives***

These 3 years of collaborative project have highlighted the complexity of multidisciplinary research and development projects. Many tests have been carried out, providing many answers but also raising other questions as the project has progressed.

At the scale of the plastic material, to deepen our understanding of chemical bonds, additional tests to study the structure/properties relationship of the formulations developed would be very interesting (molar masses, rheology of mixtures, evolution of crystallinity, etc.).

At net level, further characterization of products/semi-finished products, in particular the determination of knot strength, has not yet been explored. The study of knot typology could be very useful in determining which knot would be best suited to biodegradable monofilament...

Other avenues could be explored to compensate for the weaker mechanical properties of biodegradable monofilaments, such as

- Reducing the mesh size, while slightly increasing the diameter: this option would need to be validated by sea trials... (care must be taken not to 'denature' the net)
- Optimizing process and post-process parameters such as hot-drawing.

Finally, the use of multi-monofilament filaments for this type of application would offer a good compromise between the flexibility of the multifilament and the strength of the monofilament.