

# Numerical method for energy optimisation of bottom trawl

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**Abstract**— Bottom trawl energy efficiency is greatly affected by the drag, as well as by the area covered during fishing operations. Generally, the drag results in an overall increase of the energy consumption; moreover the value of the sweeping width affects directly the amount of fish caught. Many types of optimisation techniques have been developed to tackle bottom trawl design in order to reduce the volume of fuel per kg of fish caught and consequently the drag per swept width of the bottom trawl. Based on a finite element method model adapted to fishing net structures, our constrained optimisation tool modifies a reference design and selects the best according to the drag to swept width ratio. Previously, our strategy was built on a fixed percentage of the panel dimensions, adapted to pelagic trawls optimizing the drag to swept surface ratio. In contrast, the present method is adapted to bottom trawls and based on a set of percentages among which a selection is made with respect to the best drag to swept width ratio. For each step the best-modified design, in terms of drag per swept width is kept. This technique while adapted to bottom trawl design might lead to a decrease of the drag or an increase of the swept area. In the second case, that might lead to a substantial increase in fishing effort. This tool shows potential saving in fuel cost since it reduces drag and increases moderately catch volume leading nonetheless to a sizeable decrease in the fishing effort.

**Keywords:** *Fishing gears; bottom trawl; modelling; optimisation; fuel consumption; drag; swept area*

## I. INTRODUCTION

Fishing industry depends substantially on fossil energy: In some cases the energy part of the budget might reach a few ten percent. The fishing enterprises cannot cope with such large dependence especially when the energy price is so volatile. This is particularly critical when the fish stocks are low.

Usually the ratio between the fossil energy (fuel) consumed per landed fish is considered as a measure to such dependency on energy in the fishing industry. Typically the ratio mean value is around 0.6 litre/kg [1].

The improvement of fuel dependency must proceed through the optimisation of fishing gears to render them fuel sober. Since one of the main fishing gears used in Europe is the trawl, the improvement must concern the geometry and the material it is made of: reduction of twine diameter of netting [2] or the cutting panel [3]. This is specially required when the fish stocks are particularly low.

The general description of the optimisation method is outlined in [4]. This method is called here successive search per parameter. A new method for trawl optimisation (Random search) has been compared to the previous one in [5]. The best method (successive search per parameter) embodying a tool of homothetic transformation of fishing gears has been applied to a pelagic trawl and described in [6].

The present paper describes an automatic optimisation of bottom trawl panel cutting in order to decrease the fuel consumption. It is based on a finite element method model adapted to fishing net structures, through a constrained optimisation tool that starts from a reference model and selects the best result according to the drag over swept width ratio. We show in the sequel that this tool offers potential saving in fuel consumption since it reduces drag. Moreover it leads to a moderate increase of catch volume while decreasing the number of fishing trips.

## II. METHOD

### A. The optimisation objective

We developed previously an optimisation technique to pelagic trawls [4][5][6]. In the present work, the method with some appropriate modifications is applied to a bottom trawl.

In such case, the energy required annually during the hauls is due to the drag ( $D$ ) and the annual distance of the hauls ( $L$ ). If we accept that the efficiency of the propulsion system is known ( $\eta$ ) as well as the heating capacity of the fuel ( $h_f$ ), the fuel volume ( $V_f$ ) can be assessed by the following relation:

$$V_f = \frac{D L}{\eta h_f}$$

$V_f$ : Fuel volume used per year ( $m^3$ ),  
 $D$ : Drag of the gear (N),  
 $L$ : Towed distance per year (m),  
 $\eta$ : Propulsion efficiency, often close to 0.1,  
 $h_f$ : Heating capacity of fuel, around  $36GJ/m^3$ .

An improvement of fishing gear must be carried out without damaging the quantity of fish caught per year (F). This quantity, for a bottom trawl, is assessed with the bottom swept surface per year by the trawl, which is the product of the annual distance (L) by the swept width of the trawl (W) and by the trawl catchability ( $T_c$ ). Here, the catchability is expected not to be affected by the method of trawl improvement. In these conditions the fish caught per year is:

$$F = W L T_c$$

F: Fish caught per year (kg),  
W: Swept width of the bottom trawl (m),  
L: Towed distance per year (m),  
 $T_c$ : Trawl catchability ( $kg/m^2$ ).

The gear improvement is intended to decrease the ratio between the fuel consumed and the fish caught:

$$\frac{V_f}{F} = \frac{D}{W} \frac{1}{\eta h_f T_c}$$

Since it is expected that the parameters  $\eta$ ,  $h_f$  and  $T_c$  are constant, that means not affected by the optimisation process, the optimisation leads to a decrease of the ratio  $D/W$  where W is the swept width of the trawl and D its drag.

In other words  $D/W$  is the optimisation objective function. This should be contrasted with the pelagic trawl where the objective function is  $D/S$  where S is the surface of the mouth.

As shown further in the paper, the risk of such optimisation is to increase too much the swept width of the trawl (W). In such case the fishing effort of the optimised trawl increases would result in a conflict with stock management conditions.

### B. The netting drag

In TABLE 1, the drag repartition between the trawl components are shown for some examples of bottom trawl. It can be seen that most of the drag is due to the netting. Because the drag is mostly due to the netting, the optimisation tool automatically affects the panel cutting in order to reduce the  $D/W$  ratio. Such optimisation uses a FEM model [7] that has been adapted [4] for such purpose.

TABLE 1. DRAG REPARTITION BETWEEN BOTTOM TRAWL COMPONENTS: WITHOUT (A) AND WITH (B) CATCH ON A BOTTOM TRAWL. THESE FIGURES ARE FROM MODELING, THAT SHOWS THAT MOST OF THE DRAG IS DUE TO THE NETTING.

	a	b
<i>Cables</i>	8%	7%
<i>Otter boards</i>	21%	19%
<i>Netting</i>	66%	60%
<i>Catch</i>	0%	10%
<i>Ground rope</i>	5%	4%
<i>Total</i>	100%	100%

### C. Optimisation process

Following our prior work on pelagic trawls [4][5][6], we developed a new Successive Optimisation Tool (SOT) adapted to the bottom trawl problem. It works on the basis of successive modifications in the trawl structure.

For example the following vector represents the parameters of the simple structure made of 2 panels (Figure1):

$$U_0 = [-40 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20].$$

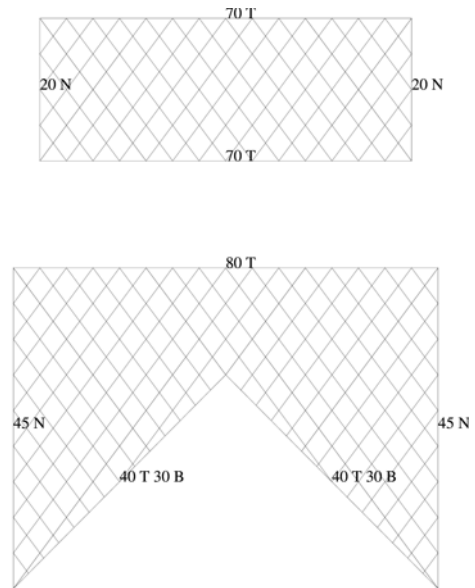


Figure 1. Layout of a simple structure with 2 netting panels having 9 nodes. The first panel (bottom one) has the following coordinates in number of meshes:  $(-40, -40)$ ,  $(-40, 5)$ ,  $(40, 5)$ ,  $(40, -40)$  and  $(0, -10)$ . The second panel has  $(-35, 20)$ ,  $(-35, 40)$ ,  $(35, 40)$ , and  $(35, 20)$ . These coordinates are represented in  $U_0 = [-40 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20]$ . The first nodes of the two panels are the bottom left and the numbering is clockwise. Only one twine out of five is drawn. The panel cutting is displayed.

This parameter vector begins by the number of meshes along the horizontal of the first node of the first panel, followed by the number of meshes along the vertical of the same node,

followed by the second node of the first panel up to the last node of the first panel followed by the second panel and so on until we reach the last panel. The size of this parameter vector is the number of nodes multiplied by 2 (the number of meshes coordinates of each node).

The optimisation tool modifies this parameter vector step by step until it finds the best solution that minimises the objective function. Two modification strategies (successive search per parameter and random search) have already been compared in [5], however only the best method (successive search per parameter) is used in this paper.

In this method, the modifications involved are brought into the parameter vector components one by one in mesh units, leaving the other components unchanged and equal to their starting value. In addition, the modifications are applied with opposite signs successively on couples of vectors. For illustrating the method we choose an arbitrary modification step of 6 meshes for the first panel and 9 for the second one. The first step is the positive modification of the first parameter. This leads to:

$$U_1 = [-34 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20].$$

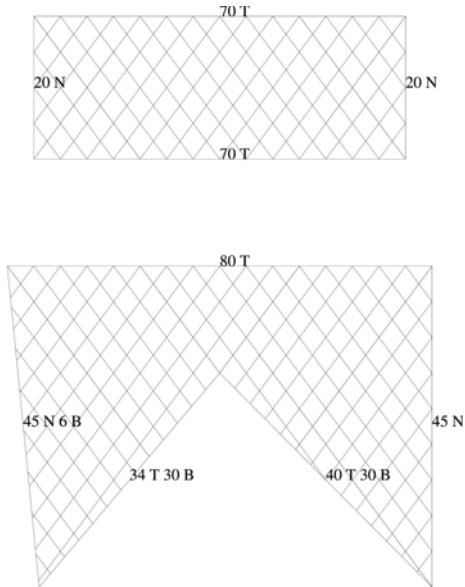


Figure 2. Appearance of the structure after we move the first node in terms of horizontal number of meshes along the positive direction. The coordinates of this structure are represented by  $U_1 = [-34 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20]$ .

The second step involves a negative modification of the first parameter. That gives a second parameter vector:

$$U_2 = [-46 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20].$$

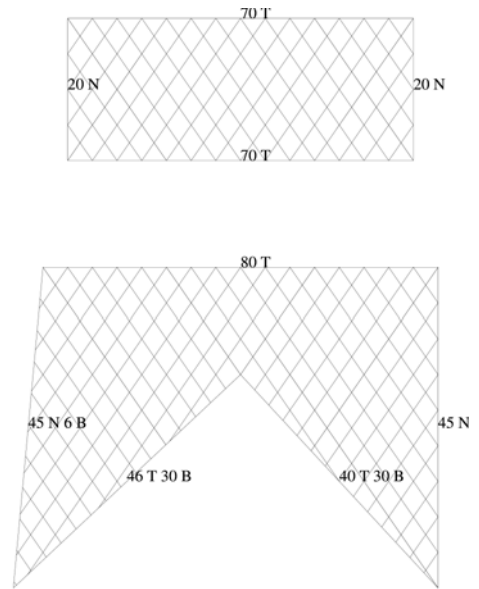


Figure 3. Appearance of the structure after we move the first node in terms of horizontal number of meshes (6 in this case) along the negative direction. The coordinates of this structure are represented by  $U_2 = [-46 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20]$ .

The third step involves a positive modification of the second parameter. This gives a third parameter vector:

$$U_3 = [-40 \ -34 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20].$$

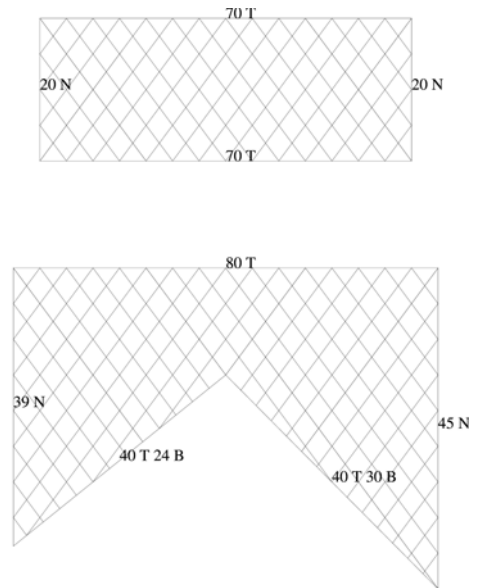


Figure 4. Appearance of the structure after we move the lowermost left node in terms of vertical number of meshes along the positive direction. The coordinates of this structure are represented by  $U_3 = [-40 \ -34 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 20]$ .

This process sweeps the entire parameter vector space. In this case, it means 36 modifications (4 per vertex: 2 vertically

and 2 horizontally for the 9 nodes). The last step involves a negative modification of the last parameter. That gives the following parameter vector:

$$U_{36} = [-40 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 11].$$

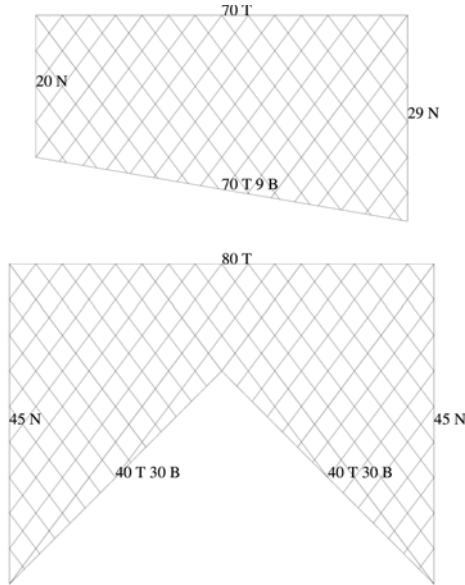


Figure 5. Appearance of the structure after all the modifications (36) have been performed. The coordinates are represented by  $U_{36} = [-40 \ -40 \ -40 \ 5 \ 40 \ 5 \ 40 \ -40 \ 0 \ -10 \ -35 \ 20 \ -35 \ 40 \ 35 \ 40 \ 35 \ 11]$ .

From these 36 modifications, the best case in terms of drag per swept width (D/W) is kept and the process starts again. The best case means that the drag is the least obtained during this sweep. The process stops when no improvement in the results is obtained.

The optimization modification proceeds along the following strategy:

a- Starting from the reference model (Figure 6 and Figure 8), we perform a first optimisation with a given Modification Size (MS) [4]. The latter defines the size of the horizontal/vertical step with respect to the panel length (in mesh units) along the horizontal/vertical direction.

b- After the first optimisation, we perform another one with respect to the results found (and not with respect to the reference model). Thus MS varies according to the following set from which we select the best ratio (drag to swept width): 32%, 16%, 8%, 4%, 2% and 1%.

#### D. Bottom trawl

The design of the bottom trawl, which is used on a research vessel [8], is displayed in Figure 6, the rigging being only partly represented. This trawl is used at a 80m depth with warps of 215m and bridles of 36.6 m. The towing speed is

1.69m/s. In this paper the sweeping width has been chosen to be the distance between the wing ends and not between doors. More precisely, the swept width is defined here, as the mean spread between the bottom and the top wing ends. Two main numerical parameters control the optimisation process: the discretisation size and the modification size. The influence of these two numerical parameters have been analysed in [4].

In the case of Figure 6, representing the design of a bottom trawl, that means 269 modifications. From these 269 modifications, the best case in terms of drag per swept width is kept and the process starts again.

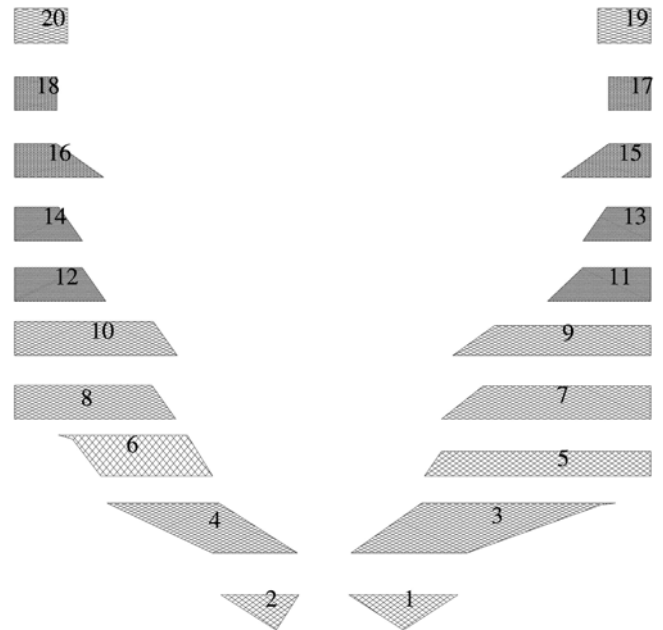


Figure 6. Netting panels of the reference bottom trawl. Due to the symmetry of the trawl only half parts of the back and the belly are presented. Due to the large number of twines only 1 twine out of 5 is drawn.

#### E. Objective function

The objective function is the drag divided by the swept width. The drag is the total drag on the trawl (Cables, netting, floats). The swept width is the mean value of the top horizontal opening and bottom horizontal opening (Figure 7).

#### F. Potential time and money savings

The potential time and money savings generated by this optimisation are evaluated on the following assumptions for both bottom trawls previously described.

(i) The first hypothesis is that the quantity of fish caught per year with the optimised trawl is expected to be the same as that with the reference trawl, which means the same swept bottom

surface for the bottom trawls, on the assumption of a constant density of fish and a constant catchability.

(ii) The second hypothesis is that the efficiency of the engine and propeller equals 10%, the energy per litre of fuel equals 10.70 kWh and the fuel costs 0.6€/l. These values may be considered as acceptable for 2010.

(iii) The third hypothesis is that the duration of trawling of the reference trawl per year is 21h 36' per day during 260 days. This duration is calculated from usual week trip where each haul consists in 3h of trawling and 20' of hauling operations.

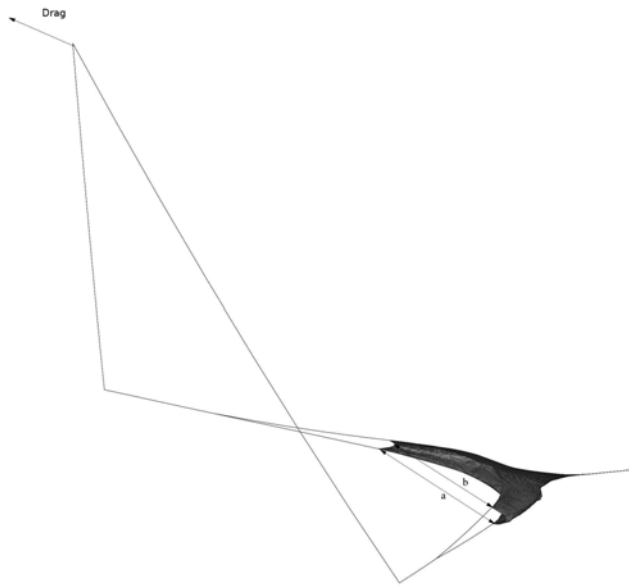


Figure 7. The objective function is the drag divided by the mean value of horizontal openings  $((a+b)/2)$ .

### III. RESULTS

#### A. Reference trawl

The calculated drag of the reference trawl is 63 kN and the swept width is 22.3 m, which gives a drag per swept width equal to 2840 N/m. The shape of the reference trawl is on Figure 8.

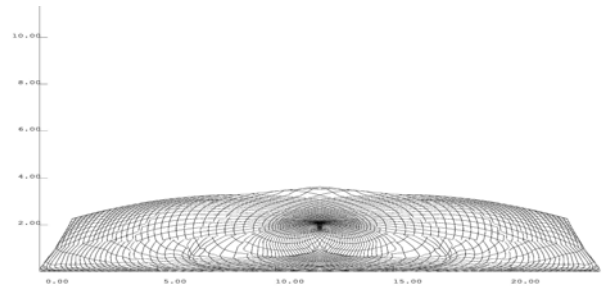


Figure 8. Front view shape of the reference trawl, we display in the figure only the netting. Only 1 twine out of 10 are drawn.

#### B. Optimisation process

The main results of the optimisation process are displayed in TABLE 2.

TABLE 2. MAIN RESULTS OF THE OPTIMISATION AND CONSIDERING MODIFICATION SIZES FROM 1% TO 32%. THESE RESULTS ARE: DRAG OF THE TRAWL, SWEEP WIDTH, VERTICAL OPENING, MOUTH AREA, TWINES SURFACE, BOTTOM DRAG, OBJECTIVE (DRAG/SW) AND REDUCTION OF OBJECTIVE RELATIVELY TO THE REFERENCE TRAWL.

	Reference trawl	SUCCESSIVE OPTIMISATION TOOL (SOT)					
		1%	2%	4%	8%	16%	32%
<b>Drag (kN)</b>	63	64	64	64	64	62	57
<b>Swept width (m)</b>	22.3	26.1	26.3	26.6	27	31.2	32.5
<b>Vertical opening (m)</b>	3.6	3.5	3.6	3.6	3.8	3	1.8
<b>Mouth area (m<sup>2</sup>)</b>	68	73.2	75	74.4	82.4	65.2	40.6
<b>Twines surface (m<sup>2</sup>)</b>	189.8	193.9	193.8	192.1	188	172.4	121.6
<b>Bottom drag (kN)</b>	14	14	14	14	14	13	15
<b>Objective (N/m)</b>	2840	2467	2449	2419	2357	1990	1755
<b>Reduction (%)</b>		13	14	15	17	30	38

This table shows that the best results are obtained for a modification of 32% from the objective function point of view and subsequent fuel consumption reduction (38%). Due to the vertical opening (1.8m) which is considered to be too small the case (32%) is rejected. For the same reason the 16% case is rejected (vertical opening of 3m) as well. Finally the 8% case is selected: Sizeable reduction of objective function (17%) and quite large vertical opening (3.8m). The corresponding shape is shown below in Figure 9 and in 3D in Figure 10. The design is shown in Figure 11, and the panels cutting is on TABLE 3 .

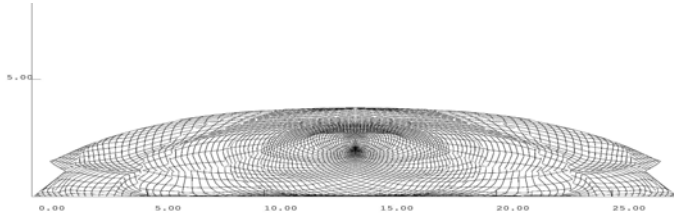


Figure 9. Front view shape of the optimised trawl, we display in the figure only the netting. Only 1 twine out of 10 are drawn.

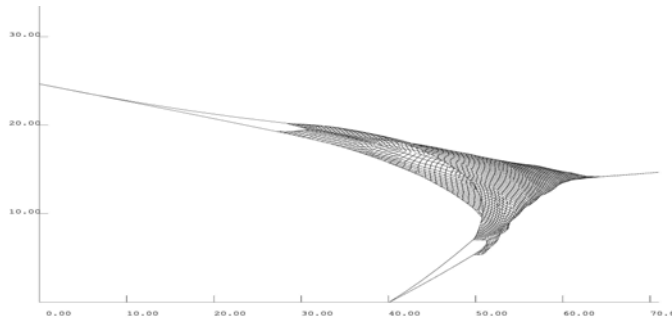
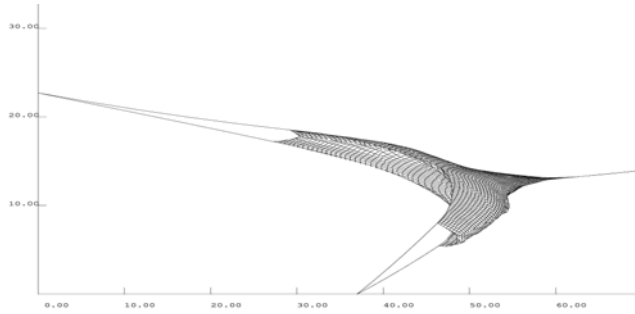


Figure 10. 3D aspects of the reference bottom trawl (top) and the optimised one (bottom). Only 1 twine out of 10 are drawn.

TABLE 3. PANELS CUTTING OF THE REFERENCE AND OPTIMISED BOTTOM TRAWL. THE CUTTING IS DISPLAYED FOR EACH PANEL, BEGINNING BY THE TOP SIDE, TURNING ANTICLOCKWISE. SEE FIGURE 6 AND FIGURE 11 FOR THE PANELS NUMBERING.

Panel	Reference	Optimised	Panel	Reference	Optimised
1	77N	71N 3B	2	55N	46N 6B
	39N 35B	45N 32B		39N 35B	41T 35B
	39N 35B	35T 26B		35T 16B	35T 12B
3	137N	167N	4	79N	79N 6B
	75T 50B	75T 35B		75AB	75T 64B
	82N	67N		60N	60N 6B
	95N 72B	110N 72B		75T 56B	75T 45B
	10N 3B	25N 3B		91N	Unchanged
5	148N	Unchanged	6	10N 3B	Unchanged
	25T 12B	Unchanged		22T 20B	29N 24B
	137N	137N 8B		79N	70N 2B
	23N	23N 2B		25T 18B	Unchanged
	25T	30T		97N	79N
7	119N	95N	8	51T	Unchanged
	50T 30B	53N 50B		23N	41N 4B
	148N	148N 8B		91N	73N 4B
	50T	57T		51T 17B	51T 35B
9	111N	88N	10	98N	Unchanged
	45T 30B	52N 45B		51T	Unchanged
	140N	Unchanged		115N	115N 4B
	45T	Unchanged		51T 17B	46T 17B
11	96N	Unchanged	12	96N	Unchanged
	101T 50B	Unchanged		101T	Unchanged
	146N	Unchanged		129N	Unchanged
	101T	Unchanged		101T 34B	Unchanged
13	63N	Unchanged	14	63N	Unchanged
	101T 34B	Unchanged		101T	Unchanged
	96N	Unchanged		96N	Unchanged
	101T	Unchanged		101T 34B	Unchanged
15	30N	35N	16	30N	Unchanged
	101T 34B	101T 28B		101T	Unchanged
	63N	Unchanged		63N	Unchanged
	101T	Unchanged		101T 34B	Unchanged
17	30N	Unchanged	18	30N	Unchanged
	100T	Unchanged		100T	Unchanged
	30N	Unchanged		30N	Unchanged
	100T	Unchanged		100T	Unchanged
19	25N	Unchanged	20	25N	Unchanged
	52T	Unchanged		52T	Unchanged
	25N	Unchanged		25N	Unchanged
	52T	Unchanged		52T	Unchanged

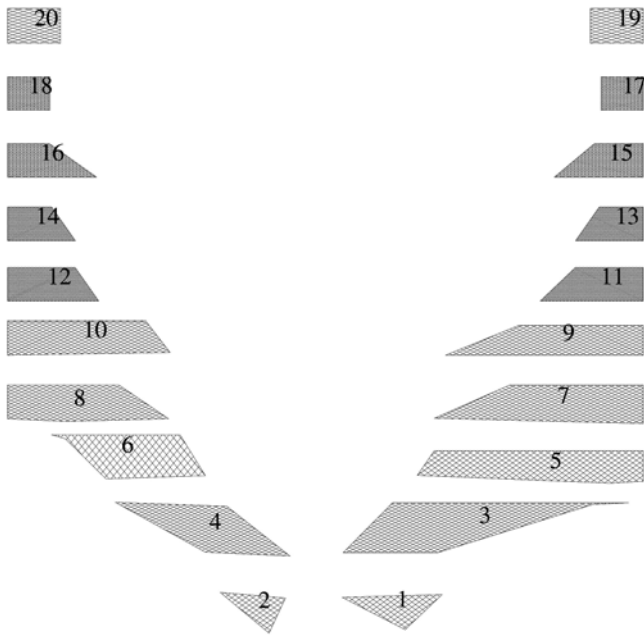


Figure 11. Design of optimised trawl. Only 1 twine out of 5 are drawn.

It can be seen on the design (Figure 11) and with the panels cutting (TABLE 3) that few panels have been modified relatively to the reference one (Figure 6). It is clear also that the shape of the optimised trawl (Figure 9) is close to the reference one (Figure 8).

The optimised trawl has a larger swept width (27 m) than the reference one (22.3 m), however. That means a potential increase of fishing catch leading to a decrease in the number of fishing trips.

### C. Potential time and money savings

The main results, in terms of time and money savings, for the two bottom trawls (Shape of the reference trawl in Figure 8 and the optimised one in Figure 9) are displayed in TABLE 4. With these assumptions, and considering the same swept surface per year for both trawls, the duration per year is decreased by 45 days with the optimised trawl and the expected economy of fuel cost may amount to 54,000€ per year.

TABLE 4. COMPARISON OF THE REFERENCE BOTTOM TRAWL WITH THE OPTIMISED ONE IN TERM OF TIME AT SEA AND FUEL COST.

	Reference trawl	Optimised trawl
<i>Trawl drag (kN)</i>	63	64
<i>Trawl swept width (m)</i>	22.3	27
<i>Towing duration (days/y)</i>	260	215
<i>Towing distance (km/y)</i>	34168	28222
<i>Swept surface (km<sup>2</sup>/y)</i>	762	762
<i>Drag energy (MWh/y)</i>	598	502
<i>Fuel volume (m<sup>3</sup>/y)</i>	559	469
<i>Fuel cost (€/y)</i>	335400	281400

## IV. DISCUSSION AND CONCLUSION

In this work we describe a novel optimisation tool proper to bottom trawls based on a selective method targeting minimisation of drag to swept width ratio while keeping the same swept area per year. We find that regarding fuel consumption, the optimisation results give an improvement of 17% (TABLE 2).

Accounting for the fishing industry regulations that impose quotas regarding the total quantity of fish caught during a well defined period of time as well as the optimisation tool (SOT) introduced in this work might lead to a perverse conclusion obtained from the results we obtain presently. This conclusion signifies that a less efficient fishing gear should be used and that is logically unacceptable. Nonetheless, there exists another way to reduce the fishing effort and that is through temporal presence at sea reduction in order to have the same swept area per year between the reference trawl and the optimised one [4]. The solution found by SOT leading to a reduction in the fishing effort i.e. the annual number of fishing trips is compatible with the previous solution.

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