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Numerical optimisation of trawls design to improve their energy efficiency

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Abstract:

Trawls energy efficiency is greatly affected by the drag, as well as by the swept area regarding pelagic trawls and by the swept width for bottom ones. The drag results in an increase of the energy consumption and the sweeping influences the catch. In order to reduce the drag per swept area (or width) a numerical tool dedicated to the automatic optimisation of the trawl design has been developed. Based on a finite element method model for flexible netting structures, the tool modifies step by step a reference design. For each step the best-modified design, in terms of drag per swept area (or width), is kept. Such a methodology was used in two cases: which show a 43% increase in energy efficiency regarding the pelagic trawl case and 27% for the bottom trawl one.

Keywords: Fishing gears; Trawl; Modelling; Optimisation; Fuel consumption; Drag; Swept area; Swept width

1. Introduction

In 2008, the European fishing firms budget account was severely impacted by the fuel price blow-up, which is the quasi-exclusive energy of this industry: the fuel part in a firm's turnover varies from 10 to over 60%. This impact is not recent but is getting more and more unbearable to fishing firms on account of the fuel cost which has been increasing by around 8% per year in constant Euro over the last 10 years (Le Floc'h et al., 2007 P. Le Floc'h, J. Boncoeur, F. Daurès and O. Thébaud, Analysing fishermen behaviour face to increasing energy costs—a French case study, ICES ASC Meeting Helsinki, ICES CM 2007/M:09 17–21 September, 2007 (2007).Le Floc'h et al., 2007) and has doubled over the past year. This effect is even increased on account of the bad state of many fish stocks. Without adaptation, the economic viability of numerous firms will not be guaranteed.

Trawls, being one of the most common fishing gears, are subject to numerous studies devoted to energy efficiency improvement. These studies also bear on alternative techniques: Macdonald et al. (2007) has tested an alternative to trawling: the jig fishing. But this technique has been tested on areas unsuitable for trawling. Anyway the results indicate that jig fishing could be profitable. Thomsen (2005) has analysed the statistics of 8 ships in the Faeroe Islands fisheries. As the main modification, these ships have been converted from single trawling to pair trawling. It was shown that they kept landings but saved 40-45% of fuel. Rihan (2005) suggests to turn back to traditional single rig trawling from twin rigs. This has been experimented on Nephrops fisheries in Ireland. The fuel consumption decrease is partly mitigated by the reduction of the catch.

The studies dedicated to trawl optimisation are not recent: During the seventies, large meshes were introduced in the mouth of the trawl, which led to a decrease of the drag and therefore a decrease of the fuel consumption, without affecting the catch. Recently, new twine materials have been tested in some parts of the trawl with the aim of reducing twine diameter and therefore the drag. Ward et al. (2005) studied trawls involving novel materials, which generated a drag cut down by 6% compared with the usual trawls, and a mouth opening increased by 10%. Parente et al. (2008) has improved bottom trawls by using larger meshes and by changing the panel cuttings, which led to a potential increase of the net cash flow up to 27%. Considering that the drag is also a function of the towing speed many fishermen reduce this parameter in order to lower fuel consumption.

Trawls can be fuel-greedy fishing gears on account of their high drag. In other words their energy efficiency is often very low. In fact, a pelagic trawl must filter a volume of water to catch fish. Considering its swept area or mouth opening, the gear must be towed over a certain distance. The drag energy, or energy required to tow the trawl, is exactly the distance multiplied by the drag. Given the efficiency of the engine and propeller, the fuel energy required is the drag energy divided by this efficiency. In order to increase the energy efficiency, one may increase the efficiency of the engine and propeller, increase the swept area or decrease the drag. This also applies to bottom trawls: they must sweep a bottom surface to catch fish. Their sweeping width, which, for some fish species, may be the distance between wing ends or between doors for others, implies a towing distance. In order to increase the bottom trawl energy efficiency, one may increase the efficiency of both the engine and propeller, increase the sweeping width or decrease the drag. The last suggests that the catch is proportional to the swept area for pelagic trawl and sweeping width for bottom trawl. In fact it is not so clear: numerous works have studied the relation between catch and mouth opening such as Main and Sangster (1981) in case of bottom trawls.

This paper deals with trawl optimisation by decreasing the drag and increasing the swept area for a pelagic trawl (or the sweeping width for a bottom trawl). The method proposed improves the trawl energy efficiency by altering the panel cuttings according to Parente et al. (2008), though by means of an automatic tool which is based on a numerical method devoted to shape calculation of fishing gears.

Yet, such automatic (or numerical) tools for optimisation are not available but only those dedicated to shape calculation: Ferro (1988), Theret (1993), Bessonneau et al. (1998), Niedzwiedz et al. (1998), Tsukrov et al. (2003), Le Dret et al. (2004), Lee et al. (2005) have developed 3D numerical methods which describe the twines of the net as numerical bars. These techniques take into account a large number of twines for each numerical bar. The forces considered are not only the drag due to the water flow, but also the weight and the buoyancy of the net. Some of the methods also take into account the twine elasticity. The drawback of these models is that they cannot represent netting details smaller than numerical bars. O'Neill (1997) has developed a 2D model for axi-symmetrical structures, such as the trawl cod-end. The twine tension, the mesh opening stiffness and the pressure of the fish catch on the net are taken into account. Another drawback of this modelling is that it is devoted to the only axi-symmetrical structures. To avoid the problem of constrained numerical elements and axi-symmetry hypothesis, and yet take into account further mechanical behaviours, a Finite Element Method (FEM) 3D model of the net based on a triangular element has been developed (Priour 1999, 2001, 2002). The triangle was chosen to describe the surface elements, because it is the simplest surface shape, thus all the netting details can be represented by adjusting the triangle size. The FEM model takes into account the inner twines tension, the drag force on the net due to the current, the pressure created by the fish in the cod-end, the floatability and weight of the net, the mesh opening stiffness and the bending stiffness. The FEM model is able to describe the whole net and cables, which means that for a trawl, the cod-end, the wings, the headline and also the rigging up to the boat are taken into account. Triangular elements model the net while linear elements model the cables, warps and bridles. The drag and shape of structures such as trawls can be calculated with these numerical tools.

The whole drag of the trawl can be split between the different parts of the structure. Table 1 gives the drag of the various parts of a pelagic trawl and a bottom trawl, calculated by the FEM model. It clearly appears that most of the drag is attributable to the netting part.

Trawls mostly consist of several panels of netting. The panels are polygons delimited by segments of straight lines joining their vertices. Now, the question is to make out whether the design of the panels or the panels cutting is optimal in terms of drag per swept area for the pelagic trawl or per sweeping width for the bottom trawl, and therefore in terms of fuel consumption. The following part of the paper proposes an answer in the form of an optimisation numerical tool.

3. Methodology

The FEM model described above calculates the drag and the swept area or width of trawls taking into account the following forces exerted on the structure:

3.1. The inner tension in twines

$$Tn = EA\,\frac{n - n0}{n0}$$

Tn: Tension in twines (N),

E: modulus of twine elasticity (Pa),

A: twine section (m^2),

n0: unstretched length of mesh side(m),

n: stretched length of mesh side (m),

3.2. The drag force exerted on the net by the current

$$F = \frac{1}{2}\rho Cd\,D\,L\left(V \sin\theta\right)^2$$

$$T = f\,\frac{1}{2}\rho Cd\,D\,L\left(V \cos\theta\right)^2$$

F: normal force (N) to the twine. This expression comes from the Landweber hypothesis.

T: tangential force which comes from the Richtmeyer hypothesis.

ρ: mass density of water (kg/m^3),

Cd: normal drag coefficient (here 1.2),

f: tangential coefficient (here 0.08),

D: diameter of the twine (m),

L: length of the twine (m),

V: amplitude of the current (m/s),

θ: angle between the twine and the current (radian).

3.3. The drag on the bottom

$$Fc = Coef \; Fv$$

Fc: drag on the bottom (N),

Fv: vertical force on the bottom (N),

Coef: friction coefficient (here 0.5),

The automatic optimisation of the trawl is carried out step by step. A step consists in an automatic modification of the panels, one by one, vertex by vertex. The FEM model described above calculates the drag and the swept area or width for each modification. The best modification in terms of drag per swept area or width is kept. The steps are repeated until no more improvement is achieved.

Since the net being the main part of the drag the optimisation concerns the netting parts. The cables, floats and dead weights are not concerned by the modification and thus remain constant along the optimisation process.

The modifications brought to a panel represent a percentage of the maximum size of this panel. For example, the panel given on Figure 1 has a maximum size of 120 meshes vertically and 200 horizontally. A modification of 5% of this panel will lead to a displacement of each vertex of 6 meshes vertically and 10 meshes horizontally. There will be 16 modifications: 4 for each vertex (2 vertically called N & S and 2 horizontally W & E). Figure 2 shows the 4 modifications of vertex 3 of the panel. In other words, by using the mesh coordinates of vertices, which are for Figure 1: $\begin{pmatrix}0\\0\end{pmatrix}$, $\begin{pmatrix}0\\200\end{pmatrix}$, $\begin{pmatrix}120\\160\end{pmatrix}$ and $\begin{pmatrix}120\\0\end{pmatrix}$, the panel cutting of Figure 1can be defined by the vector of vertex mesh coordinates (U_{ref}):

$$U_{ref} = \begin{pmatrix}0\\0\\0\\200\\120\\160\\120\\0\end{pmatrix}$$

By this method, the 16 modifications are defined by the following vectors of mesh coordinates, in which only one figure differs from U_{ref}:

4 modifications (N, S, W & E) for vertex 1: $U_N = \begin{pmatrix}6\\0\\0\\200\\120\\160\\120\\0\end{pmatrix}$ $U_S = \begin{pmatrix}-6\\0\\0\\200\\120\\160\\120\\0\end{pmatrix}$ $U_W = \begin{pmatrix}0\\10\\0\\200\\120\\160\\120\\0\end{pmatrix}$ $U_E = \begin{pmatrix}0\\-10\\0\\200\\120\\160\\120\\0\end{pmatrix}$

Vertex 2: $\begin{pmatrix}0\\0\\6\\200\\120\\160\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\-6\\200\\120\\160\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\210\\120\\160\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\190\\120\\160\\120\\0\end{pmatrix}$

Vertex 3: $\begin{pmatrix}0\\0\\0\\200\\126\\160\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\200\\114\\160\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\200\\120\\170\\120\\0\end{pmatrix}$ $\begin{pmatrix}0\\0\\0\\200\\120\\150\\120\\0\end{pmatrix}$ (shown on Figure 2)

Vertex 4: $\begin{pmatrix} 0 \\ 0 \\ 0 \\ 200 \\ 120 \\ 160 \\ 126 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 200 \\ 120 \\ 160 \\ 114 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 200 \\ 120 \\ 160 \\ 120 \\ 10 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 200 \\ 120 \\ 160 \\ 120 \\ -10 \end{pmatrix}$

For trawls, which consist of several panels, the vector will be made of vertex coordinates of all the panels. Each vector, or modification, gives a drag and a swept area or width.

This method of optimisation has been applied to both a pelagic trawl and a bottom trawl:

3.4. Pelagic trawl

The pelagic trawl, named 57 52, has a footrope and headline length of 57m and lateral ropes length of 52m. It is used for scientific surveys (Massé 1996). The mesh side and the rope lengths are presented on Figure 3. The warps are 200m long and the bridles 100m long. The panel cuttings of the reference pelagic trawl are given at the top of Figure 4. The towing speed is 2.058m/s. The calculation will be carried out from the boat with constant doors: the forces exerted on the doors are assumed to be the same for the reference trawl and the optimised one. A modification of 4% has been decided on for the optimisation process.

3.5. Bottom trawl

The design of the bottom trawl, which is used on the research vessel (Anonymous 2000), is displayed on Figure 7 and at the top of Figure 8, the rigging being only partly represented. This trawl is used at a 80m depth with warps of 215m and bridles of 36.6m. 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. In this case a modification of 8% has been decided on for the optimisation process.

Two main numerical parameters control the optimisation process: the discretisation size and the modification size. The influence of these two numerical parameters is analysed.

3.6. Discretisation size

The discretisation size determines the size of the elements used in the model. Here the elements, which model the netting, are triangular. The discretisation size determines the usual distance between nodes, which are used as triangle vertices. This size has a large effect on the calculation duration: a large discretisation size reduces the calculation duration but can affect the optimisation results.

The effect of this parameter on the optimisation process has been evaluated by recalculating the optimised trawl with different discretisation sizes.

3.7. Modification size

The modification size determines the size of the modifications of the coordinate in number of meshes of the panel vertices. It can be expected that these sizes induce the same minimum or different local minimums. This can be partly evaluated by recalculating the optimised trawls with different modification sizes.

3.8. Potential time and money savings

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

i) The first hypothesis is that the quantity of fish caught per year with the optimised trawl is the same as with the reference trawl, which means the same swept volume per year for the two pelagic trawls and 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 10.70KWh and the fuel costs 0.7€/l. These values may be considered as acceptable for 2008.

iii) The third hypothesis is that the duration of trawling of the reference trawl per year is 10h for 200days.

4. Results

4.1. Pelagic trawl

The calculated drag of the reference trawl is 67 226 N and the swept area is 199 m^2, which gives a drag per swept area equal to 337.8 N/m^2.

From this reference calculation, the modifications are calculated for each step. The pelagic trawl comprises 25 panels, which implies 372 modifications per step. In other words, the size of U_{ref}, defined previously, is 372. This figure stands for the number of vertices multiplied by 4, this figure being the number of modifications by vertex (N, S, W & E).

A percentage of modification of 4% gives the results displayed on Table 2 for the first step. This table lists only few of the 372 results achieved for this step.

Table 2 shows that, compared to the reference drag per swept area of 337.8 N/m^2, some modifications give a better result (second line 299.7 N/m^2) while some give worse results (seventh line 338.2 N/m^2). The minimum value (275.8 N/m^2) of the 372 modifications of the first step is due to the modification on panel 2, node 1 and along a modification N (also in Table 2). This modification, called the best, is kept and used as reference for the second step and so on. After 34 steps the drag per swept area reaches 146.2 N/m^2. The next step (35^{th}) doesn't give any further improvement.

The evolution of the drag per swept area along the 34 steps is displayed on Figure 5. The drag decrease is larger for the first steps. The drag computed for the last step is 82 706 N and the swept area 552 m^2, which gives a drag per swept area equal to 149.8 N/m^2. This drag per swept area compared to the 337.8 N/m^2 of the reference trawl indicates a decrease of 56%. The panel cuttings of the optimised trawl are given at the bottom of Figure 4. Figure 6 shows the shape of both the reference trawl and the optimised one. It can be seen that the swept area increases a lot.

4.2. Bottom trawl

The calculation of the shape of the reference trawl is displayed on Figure 10 (top). The calculated drag is 64 450N and the swept width equals 21.7m, which leads to a drag per swept width of 2973 N/m for the reference trawl.

The evolution of the drag per swept width along the 34 steps of the optimisation is displayed on Figure 9. The minimum value is 2176 N/m. This means a decrease of 27% when compared to the reference trawl.

The panel cuttings of the optimised trawl are given at the bottom of Figure 8. The calculated shape is shown at the bottom of Figure 10. The optimised trawl looks more like a uniform cone than the reference trawl, which could explain the decrease in the drag per swept width.

The calculated drag is 63 910 N and the swept width equals 29.4 m. This means more or less the same drag (-1%) and a quite large increase in the swept width (35%).

This bottom trawl (trawl, bridles and doors) has obviously a drag due to the friction on the bottom. The tool calculates this drag: for the reference trawl a value of 14 138 N and for the optimised one a value of 13 204 N were found for bottom drag. This small decrease (7%) could lead firstly to a decrease in the catch efficiency, due to a smaller efficiency in terms of fish lifted from the bottom, and secondly to a smaller impact on the bottom. The vertical opening is 3.6 m versus 3.2 m for the reference trawl. This increase (12%) could lead also to an increase in the catch efficiency.

4.3. Analysis of the influence of the discretisation size

The optimisation results given for the pelagic trawl have been achieved for a discretisation size of 3 m, a large one in order to limit the duration of the calculation. The influence of the discretisation size is analysed by calculating the optimised trawl with 6 discretisation sizes: from 0.8m to 5m. The result is given in Table 3. This gives similar reductions of the drag per swept area (from 43% to 56%), but not close. This means that the optimisation, being carried out with a pretty large discretisation size in order to limit the time of calculation, may be confirmed using a smaller discretisation size. This means that the method may be sensitive to this parameter, but the potential error due to this sensitivity may be cancelled by using a smaller discretisation size on the result obtained by the large discretisation size. The bottom trawl has been optimised using a discretisation size of 2m which has been considered small enough.

4.4. Analysis of the influence of the modification size

The optimisation results have been achieved for a modification size of 4% for the pelagic trawl and 8% for the bottom one. The influence of the modification size is analysed by calculating the optimisation of the pelagic trawl with 4 modification sizes (from 1% to 8%). The result provided in Table 4 shows a drag per swept area variable between the modification sizes (from 149.8 to 183.1 N/m^2). It is clear that the minimum found with a modification size of 4% (149.8 N/m^2) is not the same as the one found for 2% (183.1 N/m^2). This means that the method is sensitive to this parameter even though the reduction of drag per swept area remains quite large for each modification size.

4.5. Potential time and money savings

The main results, in terms of time and money savings, for the two pelagic trawls of Figure 6 are displayed in Table 5. On these assumptions, and especially assuming a same filtered volume per year for both the trawls, the duration per year is decreased by 101 days with the optimised trawl and the expected economy on the fuel cost may amount to 77 000 € per year. The results for the two bottom trawls of Figure 10 are provided in Table 6. The optimisation leads to a decrease of 52 days of the number of days at sea per year and expected savings on the fuel cost of 38 000 € per year.

5. Discussion and conclusion

The effect of the modification size has been studied on the pelagic trawl with 4 sizes from 1% to 8% (Table 4). They lead to relatively large differences, which indicate that they reach different minimums, but yet, induce significant decrease in drag per swept area. It seems difficult to predict which modification size (small or large) will lead to the larger decrease of drag per swept area.

The effect of the discretisation size has been studied on the pelagic trawl with 6 sizes from 0.8 m to 5 m (Table 3). The reductions (43% to 56%) of drag per swept area indicate that the discretisation size may affect the result and may be verified using smaller discretisation sizes.

In the method described here the fishing gears have been optimised in terms of drag per swept area or per swept width. It may be decided to optimise the gear in terms of drag only, but in this case the dimensions of the netting may be reduced; thus, some constraints may be introduced in this case. These constraints, which have not been implemented yet, may consist in maintaining some parameters such as the swept area, or the vertical opening, the horizontal opening and so on.

It is obvious that, in the mouth of the trawl, the ropes (head-rope and foot-rope) have a large effect on the swept area or the swept width. It may be planned to adjust automatically the length of the cables in order to optimise the gear. Considering the bottom trawl, the vertical opening increases from the reference trawl to the optimised one (Figure 10). In some cases this increase is not expected. An automatic variation of the floatability of the head-rope may be integrated in this method to adjust the vertical opening.

In the method described here the modification sizes are fixed (e.g. 2%, 4%, 8%) and assessed vertex by vertex. Another strategy may be used to find a minimum. A maximal modification per vertex in each direction may be imposed (e.g. 10%). A modified gear would mean a modification of the vertices all together. The modification would be a random value for each vertex. The random value would be between 0 and the maximal modification. Numerous modified trawls would be calculated, e.g. 1000 or 10000. The best in terms of drag per swept area (or width) would be kept. With this strategy it may be expected to reach a better optimal case than with the strategy described in this paper. In fact, a lot of scientific works have been devoted to optimisation (Haslinger J. & Makinen R.A.E., 2003), but not for fishing gears. Such works define standard methods that could be applied to trawl optimisation.

This tool provides a way to increase the energy efficiency, but it cannot be used alone. Trawl designers may use the results of this tool in order to optimise their designs. In fact they may use the design obtained with the tool and then modify it by hand. If the modifications are not too extensive, the professional will keep the main gain of the tool.

Due to the large number of trawl calculations (up to 10 000), the tool may take a long time: 20h for the optimisation of the pelagic trawl on Figure 6, and 7h for the bottom one on Figure 10. It would be profitable to use the full capacity of a Personal Computer and especially the multi cores.

Such improvement in the fishing gear must be carried out taking into account the biological situation of the stock of concern: this technique must be applied only in the case of well-managed stocks. It may cause considerable damage to the fishery to use such a technique on depleted fish stocks.

Even trawls, just as any other fishing gear, have, generally, a large handicap due to fuel dependency and impact on the biomass; thus, it is expected that for the trawls currently used, such a numerical tool may, in the future, contributes to increase energy efficiency and therefore to reduce dependency to fuel.

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7. References

Anonymous, 2000. Development of predictive model of cod-end selectivity. Final report to the European commission of the RTD project Fair Program CT96 1555.

Bessonneau J.S. and Marichal D., 1998. Study of the dynamics of submerged supple nets, Ocean Engineering, 27, (7)),

Ferro RST., 1988. Computer simulation of trawl gear shape and loading, Proceedings of Word Symposium on Fishing Gear and Fishing Vessel Design, Marine Institute, Saint John's, 1988, pp. 259-262.

Haslinger J. and Makinen R. A. E., 2003, Introduction to Shape Optimization: Theory, Approximation, and Computation, SIAM, Philadelphia.

Le Dret, H., Priour, D., Lewandowski, R., and Chagneau, F. 2004. Numerical Simulation of a Cod End Net Part 1: Equilibrium in a Uniform Flow. Journal of Elasticity, 76(2), 139-162.

Lee, C-W., Lee, J-H., Cha, B-J., Kim, H-Y. and Lee, J-H., 2005. Physical modeling for underwater flexible systems dynamic simulation. Ocean Eng., 32, 331 – 347.

Le Floc'h P., Boncoeur J., Daurès F., & Thébaud O., 2007. Analysing fishermen behaviour face to increasing energy costs-A french case study, ICES ASC meeting Helsinki, ICES CM 2007/M:09, 17-21 September 2007.

Macdonald P., Laurenson C., Johnson A. and Tait L., 2007. Jig fishing pilot study in Shetland coastal waters. NAFC Marine Centre. Fisheries development note N°.25 September 2007.

Main and Sangster, 1981 J. Main and G.I. Sangster, A study of the fish capture process in a bottom trawl by direct observations from a towed underwater vehicle, Scott. Fish. Res. Report **23** (1981), pp. 1–23.

Massé J., Koutsikopoulos C., and Patty W., 1996. The structure and spatial distribution of pelagic fish schools in multispecies clusters: an acoustic study, ICES Journal of Marine Science, 53: 155–160.

Niedzwiedz, G. and Hopp, M., 1998. Rope and net calculations applied to problems in marine engineering and fisheries research, Archive of Fishery and Marine Research, 46, 125 – 138.

O'Neill F.G., 1997. Differential equations governing the geometry of a diamond mesh cod-end of a trawl net, Journal of applied mechanics, March 1997, Vol. 64/7, 453, 7 - 14.

Parente J., Fonseca P., Henriques V. and Campos A., 2008. Strategies for improving fuel efficiency in the Portuguese trawl fishery, Fisheries Research 93 117–124

Priour, D., 1999. Calculation of net shapes by the finite element method with triangular elements. Communications in Numerical Methods in Engineering, 15(10), 755-763.

Priour D., 2001. Introduction of mesh resistance to opening in a triangular element for calculation of nets by the finite element method. Communications in Numerical Methods in Engineering, 17 (4), 229 – 237.

Priour D., 2002, Analysis of nets with hexagonal mesh using triangular elements, Int. J. Numer. Meth. Engng., 56, p 1721-1733. DOI: 10.1002/nme.635.

Rihan D., 2005. A comparison of twin-rig and single-rig trawling in terms of relative fishing efficiency, in Economic performance and fishing efficiency of marine capture fisheries, FAO fisheries technical paper 482, ISSN 0429-9345.

Theret, F., 1993. Etude de l’équilibre de surfaces réticulées placées dans un courant uniforme; application aux chaluts. PhD Thesis, Ecole Centrale de Nantes.

Thomsen B., 2005. Efficiency changes in the Faeroese pair-trawler fleet, in Economic performance and fishing efficiency of marine capture fisheries, FAO fisheries technical paper 482, ISSN 0429-9345.

Tsukrov, I., Eroshkin, O. Fredriksson, D. Swift M.R. and Celikkol B., 2003. Finite element modeling of net panels using a consistent net element, Ocean Engineering Volume 30, Issue 2, February 2003, Pages 251-270.

Ward, N., Montgomerie, M., Lart,W., 2005. Fuel efficiency trials using Jackson trawls with reduced twine diameter on MFV Challenge II Seafish Report No. SR578, p.31.

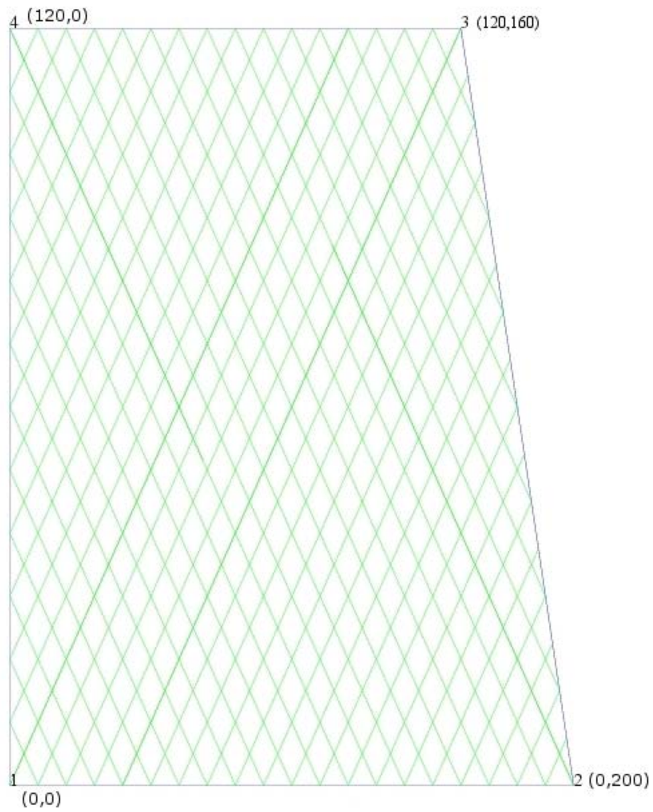


Figure 1: Panel of netting of 120 meshes high, 160 meshes on the top horizontal border and 200 on the bottom one. Only one twine out of tens is drawn. The number of meshes of nodes is noted. The origin of meshing is node 1.

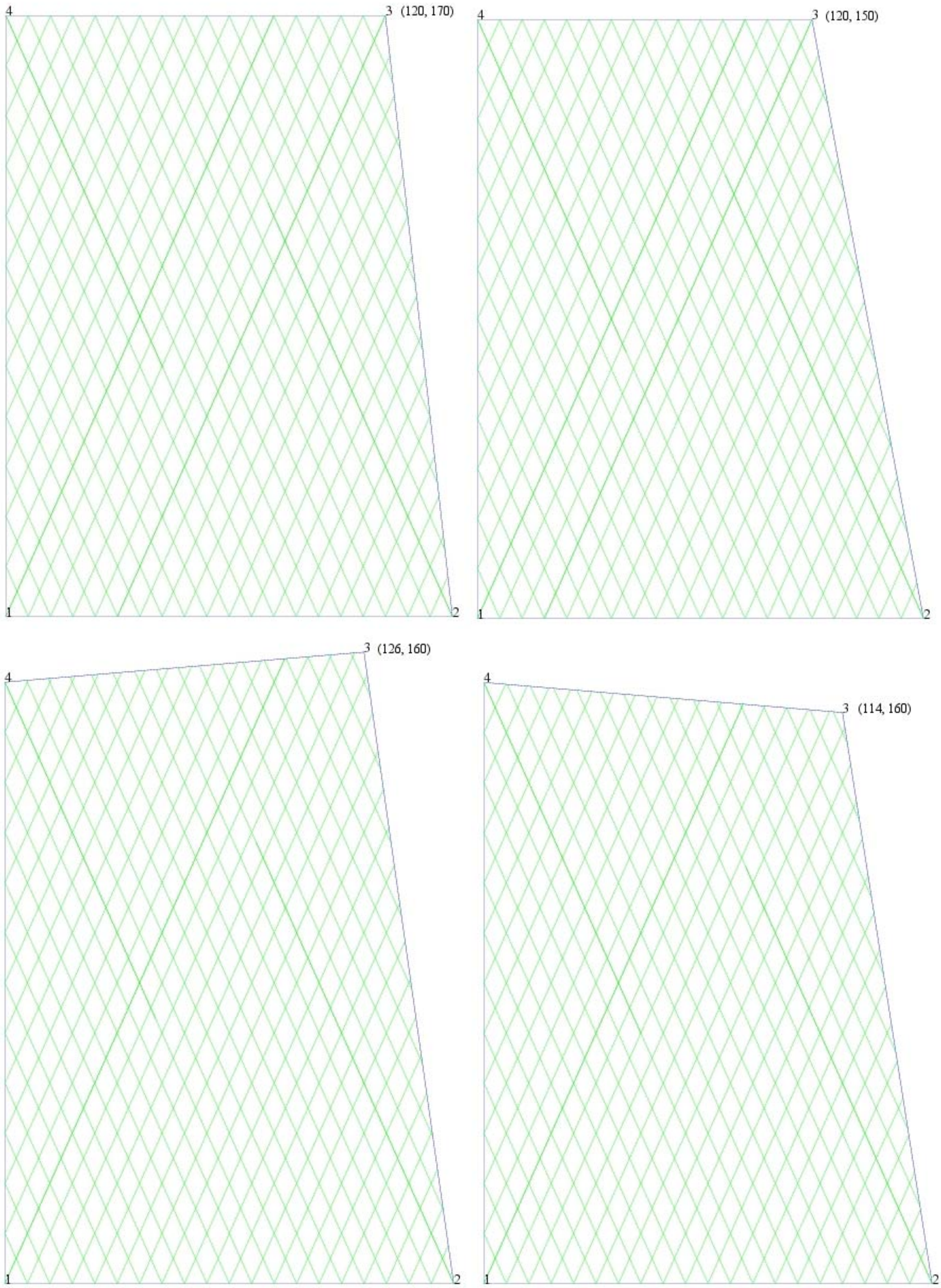


Figure 2: The 4 modifications of the node 3 are shown: horizontally on the top (W & E) and vertically on the bottom (N & S).

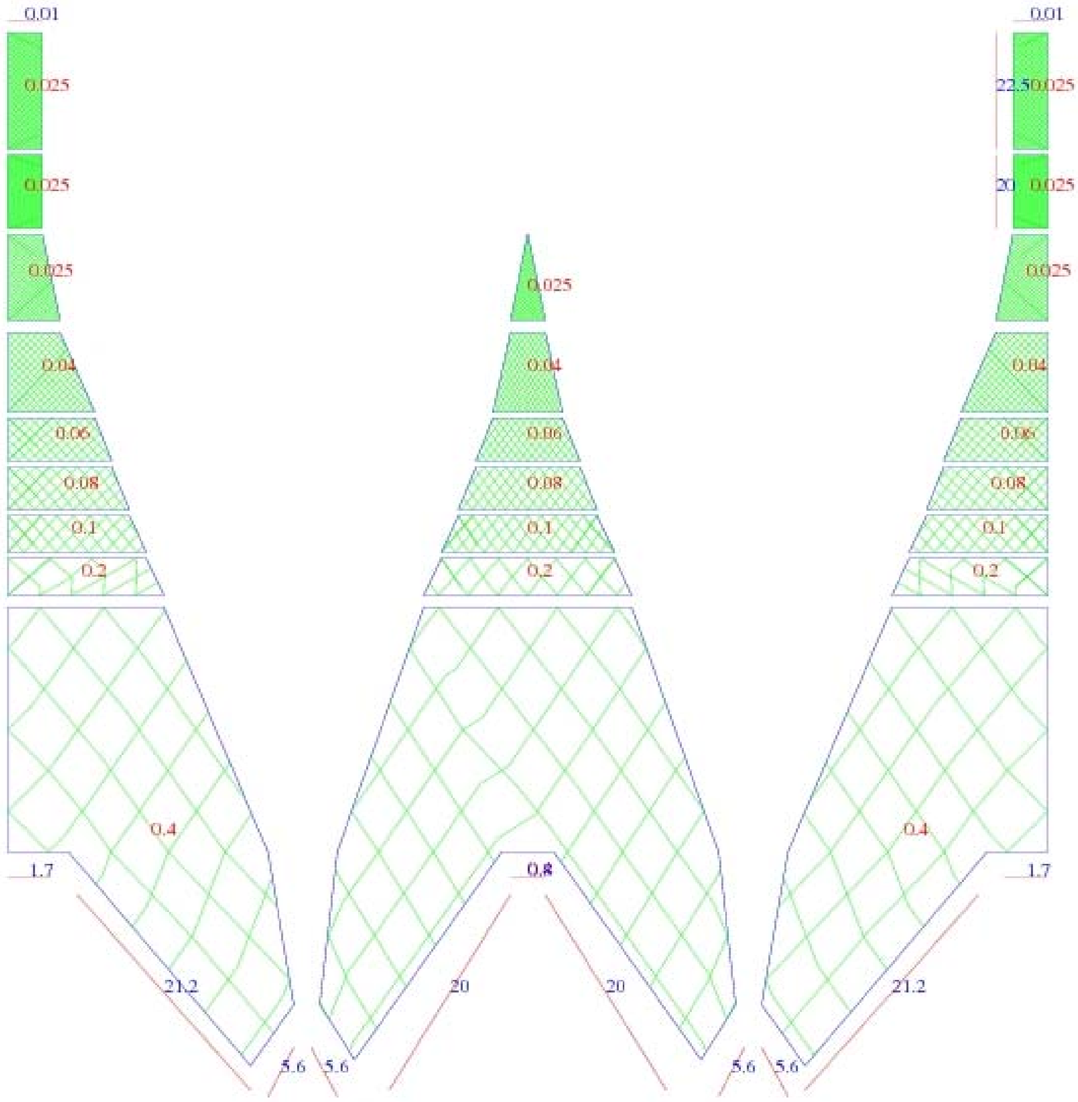
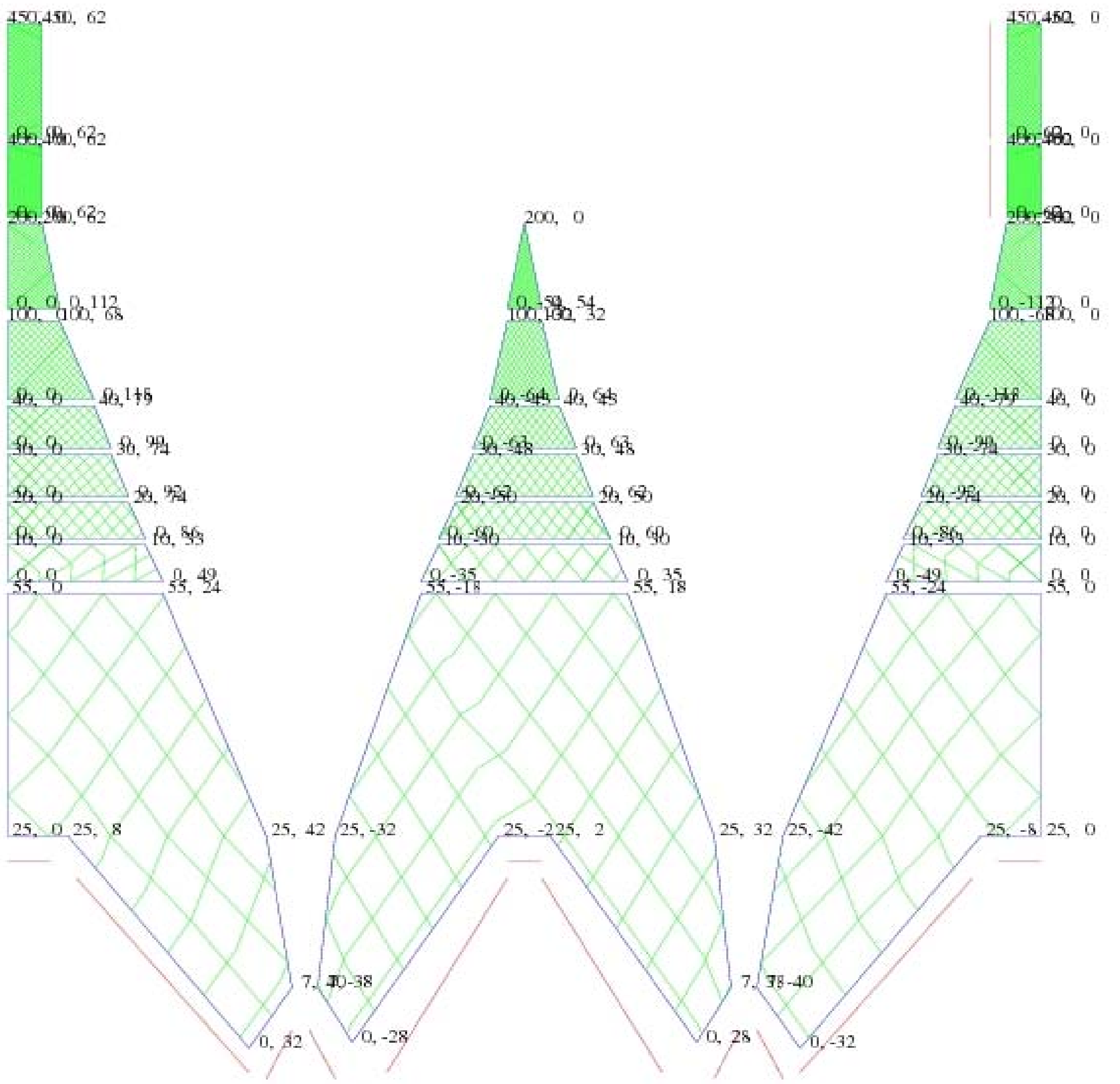


Figure 3: Mesh side (half mesh size) and cable length of the pelagic trawls (reference and optimised). The values are in m. The panels and few ropes are represented. Due to the symmetry of the trawl only half part of the back and the belly are presented. Due to the large number of twines only 1 twine out of 5 is drawn.


200, 0
100, 68
25, 0
25, 8
25, 42
25, -32
25, 2
25, 32
25, -42
25, 0
0, 32
0, -28
0, 28
0, -32
55, 24
55, -18
55, 18
55, -24

1

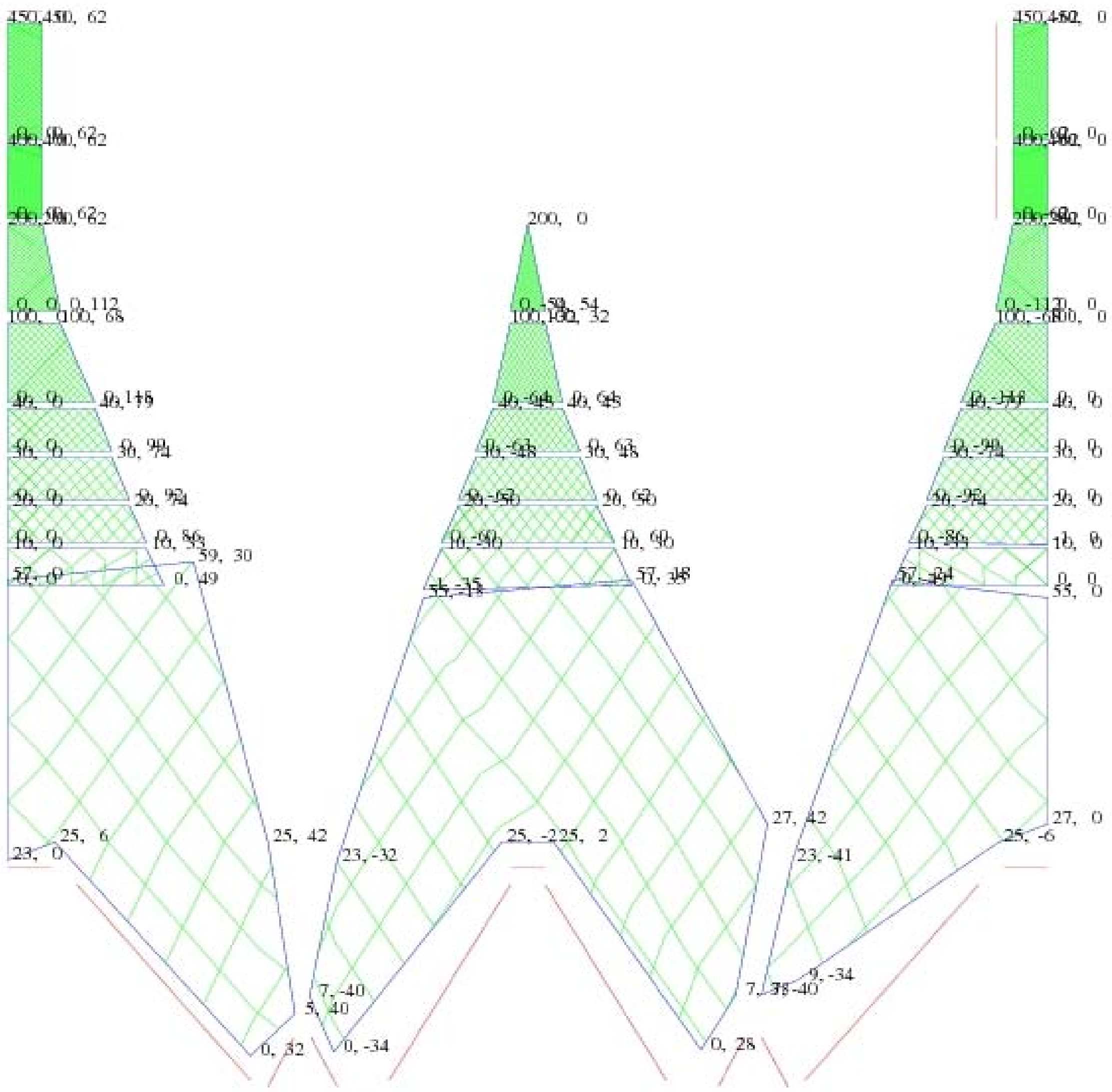


Figure 4: Design of the reference pelagic trawl (top) and the optimised one (bottom). The number of meshes of vertices is noted. The optimisation has modified mostly the panels of the trawl entry.

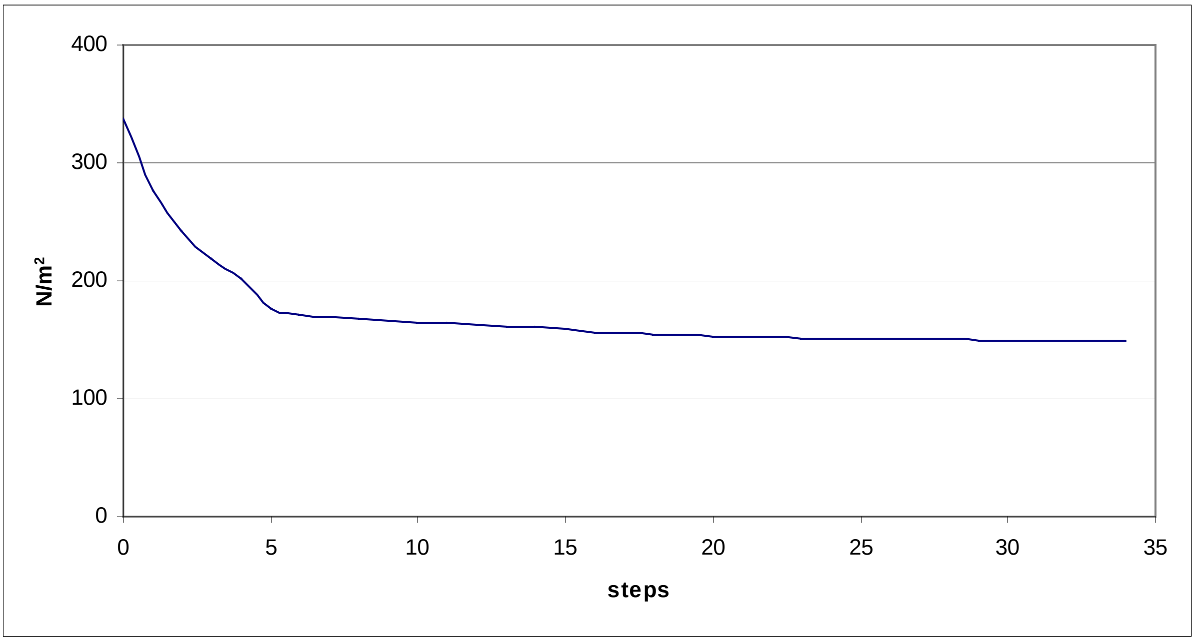


Figure 5: Minimum drag per swept area for the 34 steps of the optimisation. Step 0 refers to the reference trawl.

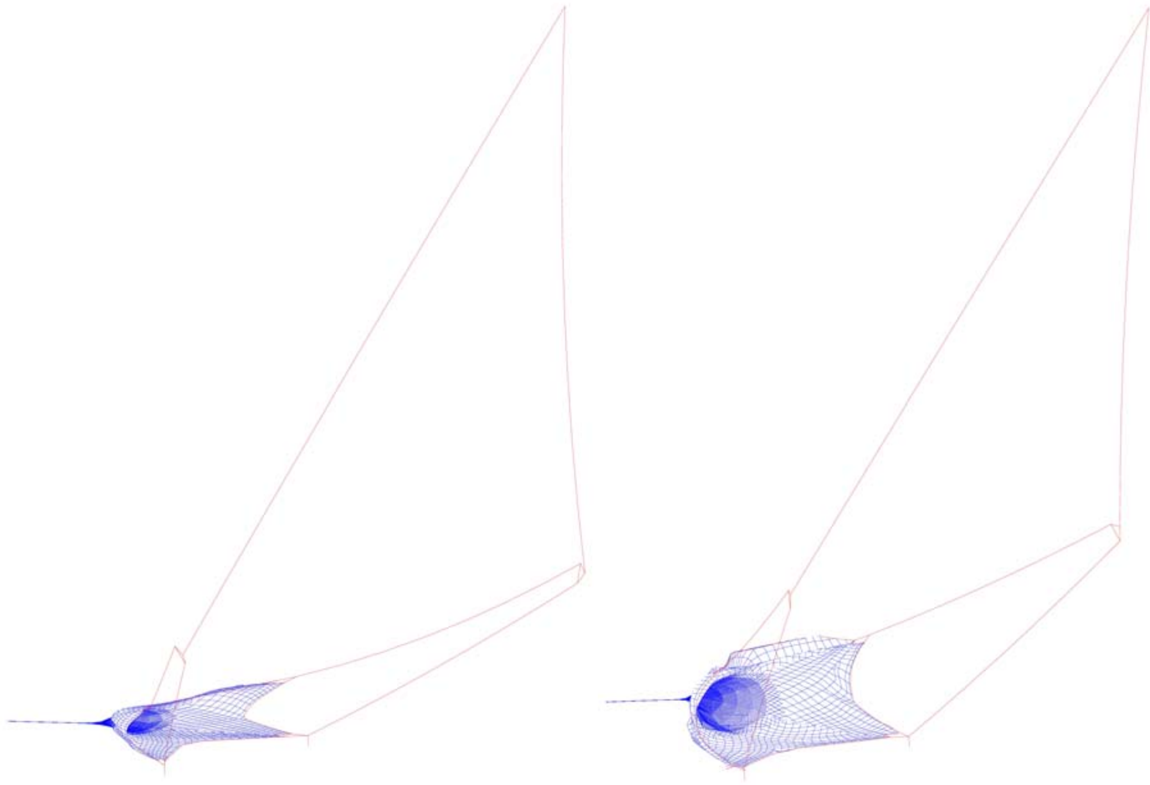


Figure 6: Shapes of the reference trawl (left) and optimised one (right). Only 1 twine on 5 are drawn.

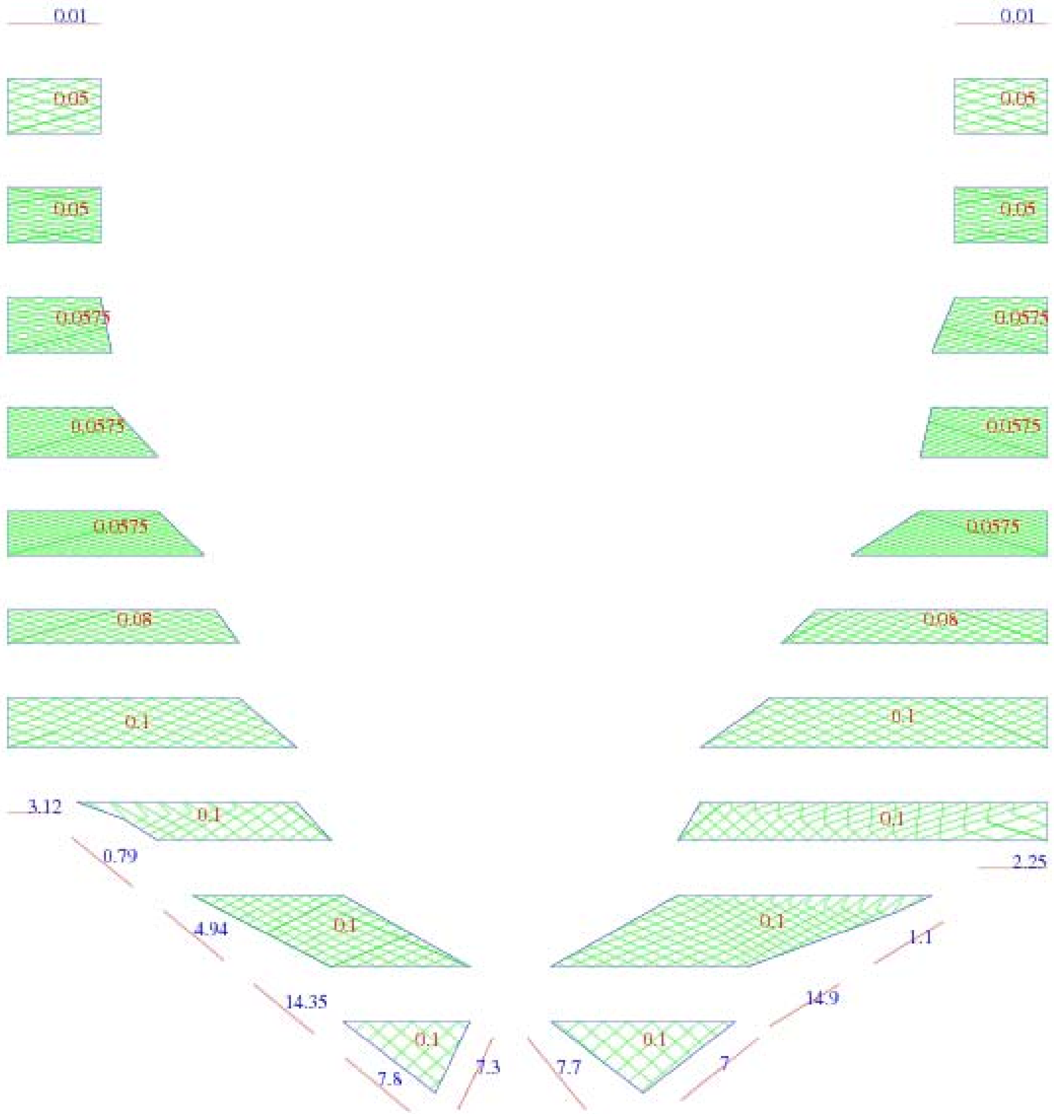
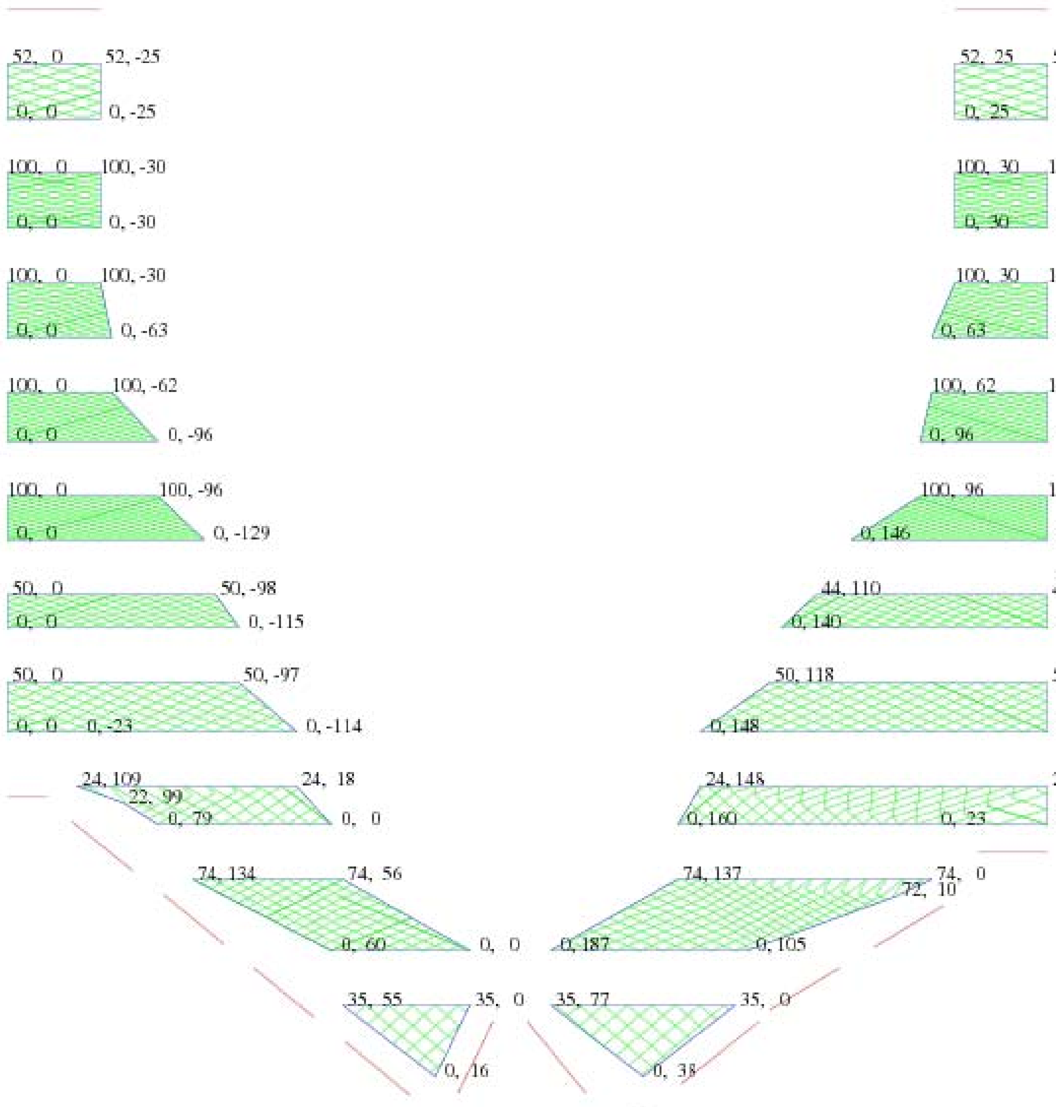


Figure 7: Mesh side (half mesh size) and cable length of the bottom trawls (reference and optimised). The values are in m. The panels and few ropes are represented. Due to the symmetry of the trawl only half part of the back and the belly are presented. Due to the large number of twines only 1 twine out of 10 is drawn.

1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52, 25
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0, -23
0, -114
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24, 0
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74, 56
0, 60
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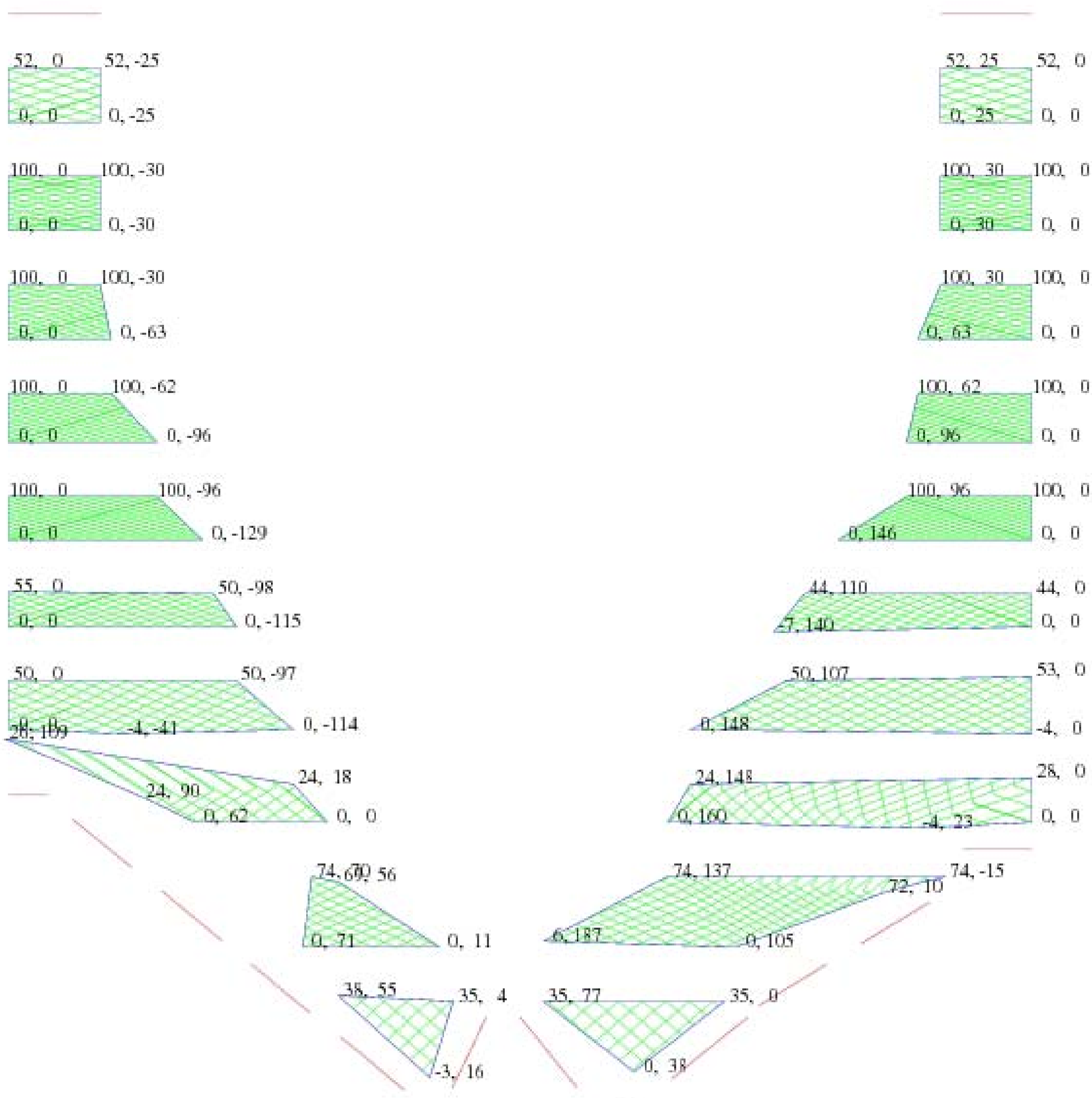

Figure 8: Design of the bottom trawl (top) and the optimised one (bottom). The number of meshes of the vertices is noted. The optimisation leads to a modification of panels mostly in the mouth of the trawl.

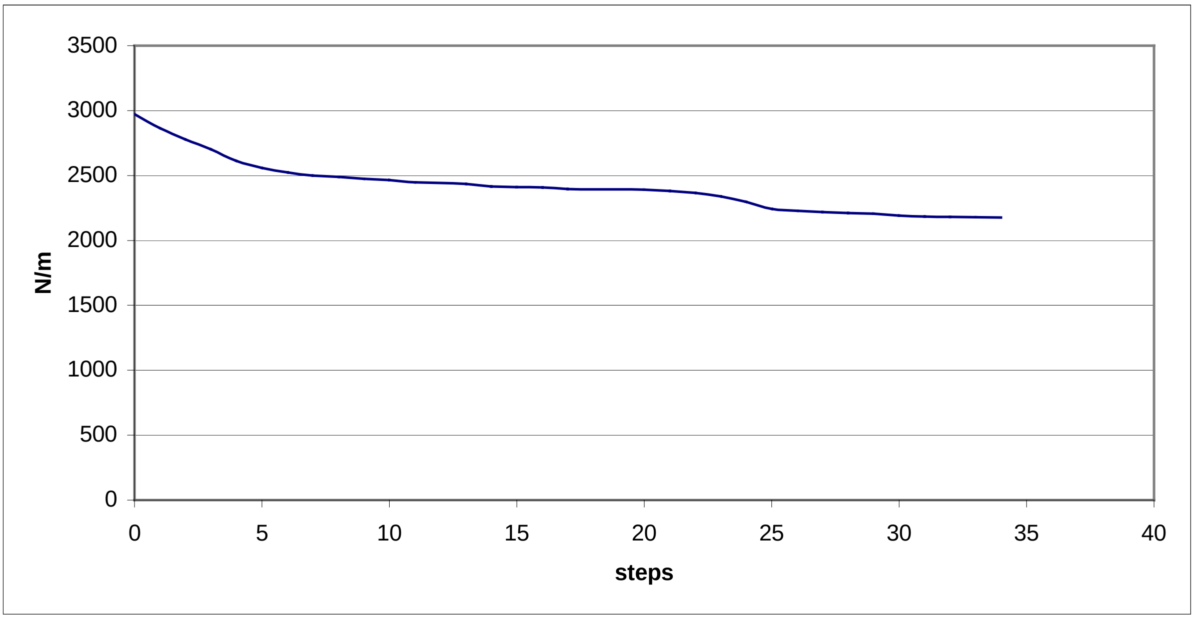

Figure 9: Minimum of drag per swept width for the 34 steps of the optimisation. Step 0 refers to the reference trawl.

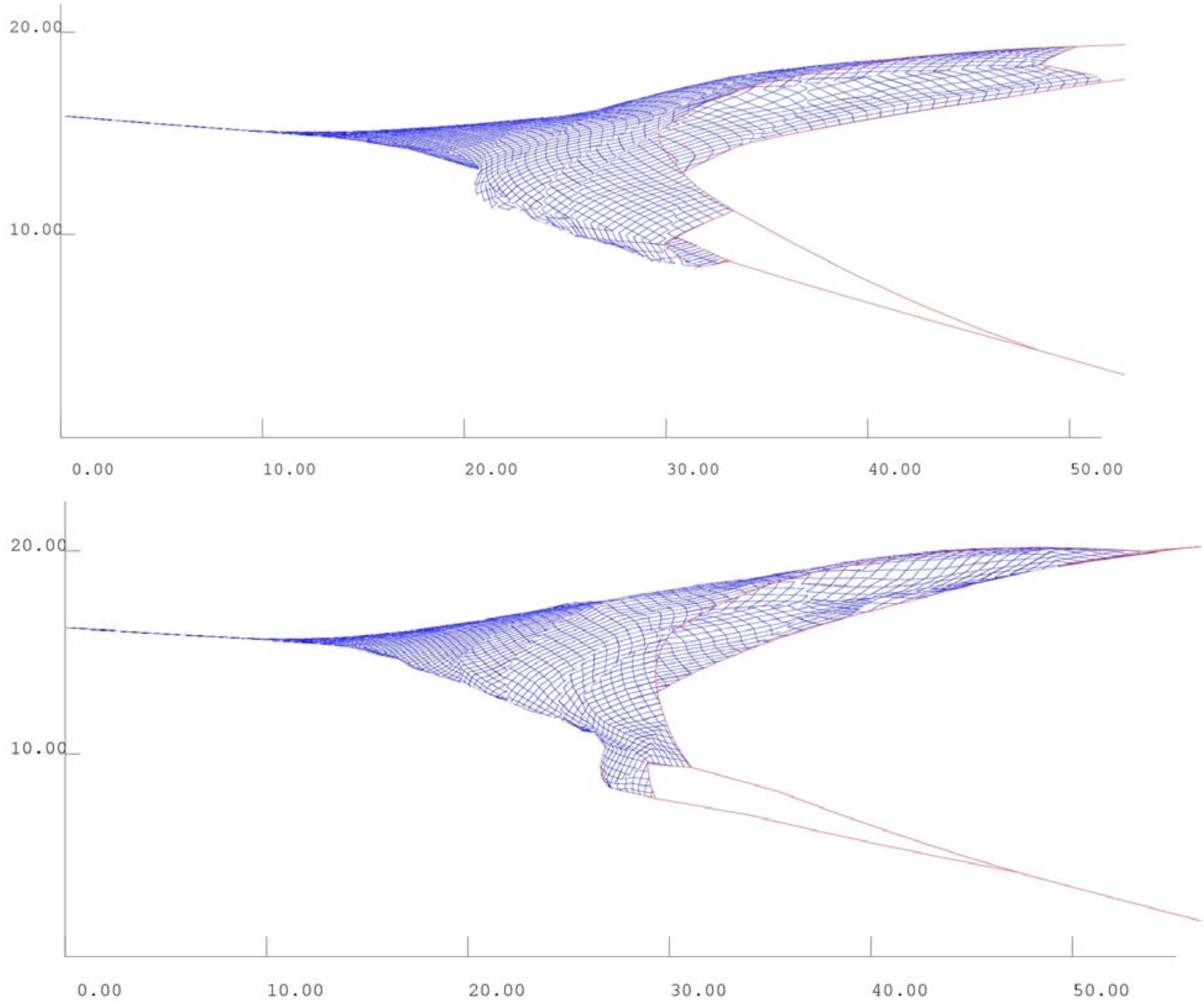

Figure 10: Shapes of the reference bottom trawl (top) and optimised one (bottom). Due to the large number of twines only one twine out of ten is drawn.

Table 1: Drag repartition between components for trawls: without (a) and with (b) catch on Italian bottom trawl, without (c) and with (d) catch on a 57/52 pelagic trawl. These figures are from the FEM model.

	a	b	c	d
Cables	8%	7%	28%	24%
Otter boards	21%	19%	17%	15%
Netting	66%	60%	55%	44%
Catch	0%	10%	0%	17%
Ground rope	5%	4%	-	-
Total	100%	100%	100%	100%

Table 2: Few results of calculations of drag and swept area for a modification of 5% on the pelagic trawl for the first step of optimisation.

Panel	Node	Modification	Drag (N)	Swept area (m^2)	Drag/swept area (N/m^2)
Reference			67226	199	337.8
1	1	N	67192	224	299.7
	1	S	67238	200	337.0
	1	W	67220	199	338.0
	1	E	67230	199	337.8
1	2	N	67718	226	300.1
	2	S	67686	217	311.9
	2	W	67230	199	338.2
	2	E	672187	199	337.3
2	1	N	68598	249	275.8

Table 3: Effect of the discretisation size on the drag and on the swept area. Values of the reference trawl are noted.

Discretisation size (m)	Ref.	0.8	1	2	3	4	5
Drag (N)	67226	77728	81278	84150	82732	83706	78458
Swept surface (m^2)	199.0	401.5	431.5	480.9	552.3	469.9	466.9
Drag per swept surface (N/m^2)	337.8	193.6	188.4	175.0	149.8	178.2	171.1
Reduction	0	0.43	0.44	0.48	0.56	0.47	0.49

Table 4: Effect of the modification size on the drag per swept area of the optimised trawl. Values of the reference trawl are noted.

Modification	Reference	1.00%	2.00%	4.00%	8.00%
Drag per swept surface (N/m^2)	337.8	170.6	183.1	149.8	153.1
Reduction relatively the reference	0	0.50	0.46	0.56	0.55

Table 5: Comparison of the reference pelagic trawl with the optimised one in term of time at sea and fuel cost.

	Reference trawl	Optimised trawl	
Trawl drag	67 226	77 728	N
Trawl swept area	199	401	m^2
Towing duration	200	99	days/y
Towing distance	14 818	7 346	Km/y
Filtered volume	2.95	2.95	Km^3/y
Drag energy	277	159	Mwh/y
Fuel volume	259	148	m^3/y
Fuel cost	181 020	103 758	€/y

Table 6: Comparison of the reference bottom trawl with the optimised one in term of time at sea and fuel cost.

	Reference trawl	Optimised trawl	
Trawl drag	64 450	63 910	N
Trawl swept width	21.68	29.37	m
Towing duration	200	148	days/y
Towing distance	12 168	8 983	Km/y
Swept surface	264	264	Km^2/y
Drag energy	218	159	Mwh/y
Fuel volume	204	149	m^3/y
Fuel cost	142 513	104 330	€/y