Predicting the effect of seine rope layout pattern and haul-in procedure on the effectiveness of demersal seine fishing: A computer simulation-based approach

Short Title: Simulating demersal seine fishing

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Abstract

Demersal Seining is an active fishing method applying two long seine ropes and a seine net. The effectiveness of demersal seining relies on the fish near the seabed reacts to the seine rope moving on the seabed during the fishing process. The seine ropes and net are deployed in a specific pattern encircling an area on the seabed. In some variants of demersal seining the haul-in procedure includes a towing phase where the fishing vessel moves forward before starting winching in the seine ropes. During the haul-in process the shape and size of the seine rope encircled area gradually changes. The main purpose of the seine rope movements during this phase is to concentrate the fish population at the seabed in an area where they later are overtaken by the seine net. The initial seine rope encircled area, the gradual change in it during the haul-in process and fish reaction to the moving seine ropes therefore play an important role in the catching performance of demersal seine fishing. The current study investigates this subject by applying a computer simulation model for demersal seine fishing. The demersal seine fishing is dynamic of nature and therefore a dynamic model is applied for simulating the physical behaviour of the seine ropes during the fishing process. Information about the seine rope behaviour is then used as input to another simulation tool which predicts the catching

performance of the demersal seine fishing process. This tool implements a simple model for how fish at the seabed reacts to an approaching seine rope. The tools are applied to investigate catching performance for a Norwegian demersal seine fishery targeting cod (*Gadus morhua*) in the coastal zone. The effect of seine rope layout pattern and the towing phase duration is investigated.

Introduction

The Danish seining or anchor seining is an active demersal fishing technique which was invented in Denmark and in the first half of the 20th century became one of the most important fishing gears used there [1]. When this fishing method was brought to other countries, it was modified to local conditions and customs. Scottish fishermen started to fish without anchoring, making it possible to move the vessel forward during hauling and thereby including a towing phase. This technique is known as Scottish seining, 'Fly-dragging' or 'Fly-shooting', and is also the method primarily applied by Norwegian fishermen targeting cod and haddock [2]. Together these variants of this fishing method can be termed as demersal seining. Today its importance as a commercial fishing method in Denmark and in many parts of the world is increasing due to its low fuel consumption, high catch quality and low ecosystem impacts when compared to trawling [3-6]. For example about 20% of the Norwegian cod quota is caught by demersal seining; the Norwegian style fly dragging [7]. Thus, knowledge about the physical behaviour of this type of fishing gear and its ability to collect fish for the seine net is very relevant. It is relevant to investigate how effective the different variants of the demersal seining is compared to each other in particular the effect on catch performance of layout pattern deployed and by the inclusion of a towing phase and its duration. Demersal seining in

Norwegian fishery targeting cod and other demersal species is practiced by deploying two long seine ropes connected to the wing tips of the seine net in one end and the winches of the vessel on the other end. The length of the seine ropes is restricted to 2000 m each when fishing inside the four nautical mile limit. The seine ropes, made of up to Ø60 mm combination rope (polyethylene with a steel core) weighting more than 2 kg/m, are placed on the seabed often in a quadrilateral pattern in order to encircle the targeted fish [8]. Once the ropes and the net have reached the seabed the vessel starts moving forward at a speed of 1-2 knots. As a result of the vessel movement the seine ropes are moving towards each other and herd the fish into the centre of the encircled area; the collecting phase. At some instance the net will start to move along the seabed when pulled by the seine ropes. When the distance between the ropes has decreased to a certain level the rope drums are activated in order to close the wings fast and to force the last fraction of collected fish into the seine net; the closing phase. This fly dragging principle of demersal seining is shown in Figure 1.

(FIG 1 HERE)

The catching performance of demersal seine fishing depends on the area on the seabed swept and encircled by the seine ropes during the fishing process and by the efficiency the seine ropes are able to herd the fish into and subsequently maintain them in the path of the much smaller seine net until they are overtaken by it in the later stages of the fishing process. Knowledge about how the size and shape of the area encircled by the seine ropes gradually change during the fishing process and how it gradually leads increased density of fish in it is therefore important for an efficient fishery. Thus, understanding and quantifying the physical behaviour of the seine ropes and how this behaviour gradually leads to increased density of fish in the encircled area are important aspects of the demersal seine fishing process. This subject is investigated by applying a simulation model for demersal seine fishing what pre-

dicts the amount of fish being collected between the seine ropes during the fishing process. The simulation model consists of combining a model for the physical behaviour of seine ropes with a simple model for fish reaction to an approaching seine rope at the seabed. Results are provided for a Norwegian demersal seine fishery targeting cod (*Gadus morhua*) in the coastal zone.

Material and Methods

Method for simulation of seine rope behaviour

The dynamics of the demersal seine fishing gear is dominated by the behaviour of the seine ropes. Hence, we needed for the investigations a tool that can predict the physical behaviour of the seine ropes during a demersal fishing process. We applied an existing tool hereafter named *SeineSolver*. *SeineSolver* has an interface that enables the user to specify the gear deployed including the characteristic of the seine ropes and the fishing operation in terms of layout pattern for the seine ropes, towing speed, towing time before starting winching and winching speed. *SeineSolver* uses the FhSim simulation framework [9]. The seine ropes were modelled by cables consisting of a collection of six degree of freedom elements. The cables were connected to the weight at one end, representing the seine net, and to a winch at the other. Since the demersal seine fishing is of dynamic nature a time-domain formulation of the cable dynamics is applied. The *SeineSolver* model implements the method found in [10], which includes a numerical model where the cable dynamics are described as a collection of hinged rigid bodies. The *SeineSolver* tool uses a seabed contact model from FhSim [9] which calculates the reaction force resulting from an overlap between a cylinder element and the seabed surface. The normal force leads to a transversal friction force modelled by a friction

coefficient. Time integration is performed with a simple forward Euler scheme [11] using a time-step of 0.001 sec. The model behind *SeineSolver* and it validation against flume tank experiments is thoroughly described in [12].

Model for fish reaction to an approaching seine rope at the seabed

To be able to predict the effect the seine ropes have on the catch performance of demersal seine fishing by simulation we need a model for how fish near to the seabed reacts to an approaching seine rope. Little information exists for demersal seining but far more observations have been conducted for bottom trawling. The ability of trawls sweeps on the seabed to herd cod into the centre of the trawl are demonstrated in [13]. Cod reacts with an avoidance response when the sweep wire approaches it. This can be interpreted as the cod would keep at least some distance away from an approaching threat, in this case the sweep wire. In line with [14] it can be expected that the cod on average will react by swimming in a direction perpendicular to the approaching wire. We will assume that cod reacts in a similar way to an approaching seine rope during demersal seining. Therefore we will for a first simple model assume that if the seine rope gets closer than a distance l_{min} to the cod it will swim a distance l_{move} from its current position further away from the seine rope in a direction that is perpendicular to the approaching rope. Figure 2 illustrates this behaviour of fish to an approaching seine rope. We will assume no reaction from the cod if it has as a distance to the rope that is greater than l_{min}. In addition we assume that the cod only react to the part of the seine rope which is on the seabed.

(FIG 2 HERE)

To account for that all cod might not always react with the avoidance response along the seabed every time the seine rope gets closer than l_{min} to it, we will assume that there will be a small probability p_{raise} for the cod instead of moving along the seabed when approached by the seine rope will react by raising the distance l_{move} up from the seabed for a short while before returning close to the seabed again meanwhile the seine rope passes beneath it. Based on these considerations the probability that the fish will be herded along the seabed for an incidence where the seine rope on the seabed get closer than l_{min} to it will be $p_{herd} = 1.0 - p_{raise}$. Therefore, the cod reaction to the seine rope approaching it will, for each incident when the ropes distance become smaller than l_{min}, be modelled by a binomial process with probabilities p_{herd} and $1.0 - p_{herd}$ that the cod react by respectively a move l_{move}, relative to its current position of the fish, away from the seine along the seabed perpendicular to the seine rope and an avoidance that lets the seine rope pass beneath it. For the current study we will assume $l_{min} = 1.5\ m$. This value has been selected based on experience on how cod typically are herded in front of the ground-rope during demersal trawling, since underwater recordings conducted in Norwegian bottom trawl fishery targeting cod show that cod often try to maintain a distance of 1-2 m ahead of the ground rope. We will for the current study assume l_{move} to be twice l_{min}. For simplicity we will for explorative purpose for the current study assume that the cod reacts with a herding response each time the seine rope gets too close to it. This means we will fix p_{herd} at 1.0.

Simulating the collection phase of demersal seine fishing

The model for fish reaction to an approaching seine rope was implemented in a software tool *SeineFish*. *SeineFish* simulates the collecting phase for a demersal seine fishing operation. To do so *SeineFish* uses external generated information on the physical behavior of the seine

ropes. This information is obtained with *SeineSolver*. The *SeineSolver* output file contains information on the kinematics of the seine ropes and seine net position continuously during a simulated demersal seine fishing operation. Specifically the *SeineSolver* output file contains for discrete steps in time during the simulated fishing process predicted coordinates in 3D for points along the seine ropes. Based on this information *SeineFish* models the geometry of the front part of the demersal seine gear continuously in time and space by using a nested linear interpolation technique. Prior to starting the simulated fishing in *SeineFish* the user defines a virtual fish population distributed on the virtual fishing ground in a pattern chosen by the user. For the current study we will for all fishing cases assume that the cod at the start of the simulation are uniformly distributed on the fishing ground and that all are at the seabed. Besides the distribution pattern the user also input the value $fish_{dens}$ (number of fish per m^2 fishing ground) which defines the average density of fish on the fishing ground. For all the simulations in this study we set $fish_{dens}$ at 0.01 m^2 corresponding to on average 100 fish for each 10000 m^2. This value was considered realistic based on total cases of cod obtained during typical demersal seine fishing in Norwegian coastal zone. During the simulated fishing process the distribution pattern of the fish will gradually change due to interaction with the fishing gear. This interaction is simulated by the fish reaction model and controlled by the values chosen by the user for the parameters l_{min}, l_{move} and p_{herd}.

The simulation of the fishing process in *SeineFish* can be characterized as a time-step integration technique (time step = 0.2 sec) where the position and shape of the seine gear on the fishing ground is gradually updated and the interaction with each of the fish individually is simulated according to the procedure described above. During the simulation the value for key indicators is calculated and logged at each step of the simulation. The indicators are: the area encircled by the part of the seine ropes on the seabed ($A_{encirled}$ (m^2)); entry width of the gear

(w_{entry} (m)) that is given by the horizontal distance across the fish ground between the two points closest to the fishing vessel on respectively the right and left seine rope that has contact with the seabed; and finally the number of fish $fish_{encirled}$ in the encircled area on the seabed. The simulated fishing process is continuously visualized in *SeineFish* by illustrating the fishing gears shape and position as well as the position and movement of the fish caused by their reaction to the fishing gear. Figure 1 and several of the other preceding figures in this paper have been created based on screen dumps during simulations conducted applying *SeineFish*.

Fishing scenario's

To investigate the potential effect of initial seine rope layout pattern on the catch performance for demersal seining targeting cod in coastal zone in Norwegian fishery we simulated four different initial layout patterns: rectangle, square, triangle and diamond (Figure 3).

(FIG 3 HERE)

For each of the four layout patterns (Figure 3) the seine ropes laid out on the fishing ground were approximately 2000 m for each of the ropes, such complying with the legislation for the Norwegian coastal fishery and also enabling a fair comparison between cases. The seine rope diameter was 36 mm as typically used in this fishery. Each layout pattern was then deployed with three different haul back procedures to enable investigating the effect on catch performance by haul back procedure. The difference between the three haul back procedures was the time the vessel was towing before starting to winch the seine ropes, respectively 0, 15 and 35 minutes which are realistic values for this fishery. The first case without towing represents the original Danish seine or anchor seine fishing while the two other represents Scottish sein-

ing or fly-dragging. In both the latter cases the towing speed was 2 knot and the winching speed 0.9 m/s, which are settings also applied commercially in this fishery. For diamond shaped initial layout pattern Figure 4 illustrates the three towing phase cases investigated.

(FIG 4 HERE)

For each of the 12 fishery cases (four different initial layout cases times three different haul in procedures) we first used *SeineSolver* to estimate the physical behavior of the front part of the fishing gear (seine ropes) during the simulated fishing process. The predicted gear behaviours were then subsequently used as input in *SeineFish* to simulate the collection phase for the demersal seine for each of the 12 fishery cases. Since identical fish populations were used for the different fishing we could use the values for the encircled number of fish as relative measure for the effectiveness of the fishing process for the different cases. In addition to monitoring the number of fish encircled during the simulated process we also monitored the size of the encircled area and the entry width between the seine ropes. The entry width is important for the effectiveness of a towing phase because it is only through this that the initial number of encircled fish can increase since the part of the seine ropes on the seabed will herd the fish outside the seine ropes away.

Results

Simulating fishing scenario's

Figure 5 illustrates the physical behaviour of the fishing gear during steps in the fishing process for each of the 12 simulated fishing processes.

214

215 (FIG 5 HERE)

216

217 ## Number of fish encircled

218 The *SeineSolver* and *SeineFish* tools were applied to predict how the number of fish encircled
219 change during the fishing process when applying each of the four seine rope layout patterns
220 considered for respectively a haul back procedure with 0, 15 and 35 minutes towing before
221 starting winching the seine ropes. From Figure 6 it is evident that for the same seine rope
222 length being deployed on the fishing ground, in this case 2 x 2000 m, the number of fish being
223 encircled by the seine ropes depends strongly on the initial layout pattern. This is the case
224 both for the number of fish being initially encircled and for the number of fish encircled at the
225 end of the fishing process. Specifically we see that the square and diamond layout patterns are
226 predicted to encircle a much higher number of fish than for the triangular and in particular the
227 rectangular pattern.

228

229 (FIG. 6 HERE)

230

231 Figure 6 also illustrates that the number fish increases during the towing phase. But also the
232 marginal benefit of a long towing phase (35 minutes) compared to a shorter (15 minutes).
233 Table 1 quantifies for each of the 12 fishing cases the number of fish being encircled initially,
234 when winching begins and at the end of the fishing process.

235 **Table 1.** Number of fish encircled during the fishing process. Numbers in parenthesis are per-
236 centage increase compared to value after initial layout.

Layout pattern	Towing time (minutes)	Number of encircled fish		
		Initial	At start winching	At end of process
Rectangle	0	6399	6399(0%)	5098(-20%)
Rectangle	15	6399	6458(1%)	6564(3%)
Rectangle	35	6399	6813(6%)	6837(7%)
Square	0	9999	9999(0%)	8605(-14%)
Square	15	10000	11505 (15%)	11783 (18%)
Square	35	10000	12684(27%)	12739(27%)
Triangle	0	7581	7581(0%)	7270(-4%)
Triangle	15	7582	8681(14%)	8881(17%)
Triangle	35	7582	9456(25%)	9498(25%)
Diamond	0	9897	9897(0%)	9270(-6%)
Diamond	15	9897	11319(14%)	11526 (16%)
Diamond	35	9897	12150(23%)	12192 (23%)

The rectangular and triangular layout patterns are predicted to initially encircling only respectively approximately 64% and 76% of the number of fish being encircled with the square and diamond layout patterns (Table 1). At the end of the fishing process this difference is increased further and depends also on which of the three simulated haul back procedures that has been applied, it is the duration of the towing phase. Based on the values in Table 1 it can for example be calculated that for respectively 0, 15 and 35 minutes towing before winching that the rectangular layout end up encircling only respectively 59%, 56% and 54% of what

245 could be expected to be obtained with the square layout pattern. Regarding what is obtained
246 by towing and winching on the number of fish encircled compared to the number which was
247 initially encircled the values in Table 1 demonstrate that this strongly depend on the layout
248 pattern employed for the fishing process. For the rectangular layout it is predicted that the
249 encircled number of fish is only increased by respectively 3 and 7% dependent on if the tow-
250 ing time applied is 15 or 35 minutes. Contrary for square, diamond and triangle patterns are
251 the increases being predicted to be respectively 18, 17 and 16% for 15 minutes towing and 27,
252 25 and 23% for 35 minutes towing. In general it is found that without towing will the number
253 of encircled fish decrease from the initial value with a percentage that depends on initial lay-
254 out pattern. This illustrates the benefit of a towing phase as the drop in encircle number of fish
255 can be as big as 20%.
256

257 ## Area encircled on the seabed by the seine ropes

258 To help understanding the difference in performance of the layout patterns regarding their
259 ability to encircle fish during the fishing process it can be useful to look on how some of the
260 geometrical properties for the gear develop during the fishing process. The first to look at is
261 the area encircled by the seine ropes on the seabed. Figure 7 illustrates for a towing phase of
262 15 minutes as example the development in area encircled by seine ropes on the seabed (green
263 filled areas on Figure 7).
264

265 (FIG. 7 HERE)
266

267 The difference in the development in the encircled area for the different initial layout patterns
268 during the fishing process is clear (Figure 7). The development in entry width (where the

seine ropes are lifted from the seabed) into the encircled area is also seen in Figure 7 and the narrowness of it is clear. This illustrates the challenge to make benefit of a long towing phase. But also why a short towing phase gives benefit compared to none. The reason for this is that when the seine ropes are first pulled by the vessel the parts of the seine ropes lifts of the seabed leading to a decrease in the encircled area and thereby of the collected fish. During the first part of a towing phase this amount of fish is regained through the entry width and the area covered through this. This pheromone is also clear from Figure 6 which shows the drop in the initial number of fish encircled when the vessel starts pulling the seine rope. Without any towing phase (Figure 6 top) this loss is never regained during the remaining fishing process. Contrary with a towing phase of 15 or 35 minutes is this loss regained (Figure 6 middle and bottom). Figure 8 quantifies the development in the encircled area during the fishing process for each of the 12 fishing cases investigated.

(FIG 8 HERE)

From Figure 8 it is clear the initially encircled area depends strongly on layout pattern applied and we can as expected fully explain the differences in initial number of fish being encircled between the different layout patterns (Table 1). We see how the seine rope encircled area gradually decreases during the fishing process and when combined with Figure 6 would mean increase in the density of fish in the encircled area. It is seen for a fishing process without a towing phase (Figure 8 top) that the encircled area diminishes earlier than if a towing phase of some duration was included in the fishing process (Figure 8 middle and bottom). However to understand the increase in number of fish encircled during the fishing process we need to look on another geometrical indicator for the gear. We have to look on the entry width to the encir-

293 cled area since it is through this that additional fish enters the encircled area when the seine
294 ropes are dragged forward to cover additional area on the seabed. Figure 9 quantifies the entry
295 width during the fishing process.
296
297 (FIG 9 HERE)
298
299 From Figure 9 is it evident that the predicted entry width for much of the fishing phase is far
300 smaller for the rectangular layout when compared to the other layouts and in particular with
301 the square. This provides a potential explanation for why the predicted increase in number of
302 fish encircled increase far less for this layout compared to each of the other layouts (see Table
303 1). It is interesting to see that the initial entry width is big for the rectangular layout but that
304 quickly decreases while the opposite happens for the diamond layout.
305

306 ## Discussion

307 In this study we investigated how the catch performance for a demersal seine fishing opera-
308 tion may be affected by the initial seine rope layout pattern and by the haul back procedure.
309 Specifically we investigated the effect of including a towing phase of some duration since this
310 is one of the major differences between the variants of the demersal seine fishing method. We
311 tried to make our study as realistic as possible to represent demersal seining targeting cod in
312 Norwegian coastal zone. Our study was based on applying sequentially two different simula-
313 tion models. The first *SeineSolver* for estimating the physical behaviour of the seine ropes
314 during an artificial fishing process and the second *SeineFish* which uses the output from
315 *SeineSolver* to simulate fishing when the gear is deployed on a virtual fishing ground with a

316 prescribed fish population distributed on it. *SeineFish* implements a simple model for how
317 cod is assumed to react to an approaching seine rope dragged over the seabed during a demer-
318 sal seine fishing operation. This model may be too simplistic but we expect that it anyway
319 will enable to estimate fairly realistic how different layout patterns and haul back procedures
320 may affect the catching effectiveness of a demersal seine as least relative to each other. Fur-
321 ther, this behavioural model can easily be made more complex by for example considering
322 endurance of the fish after they have been forced to swim over some distance. An easy way to
323 implement this would be to make p_{herd} a decreasing function of the total distance the fish has
324 been forced to swim. Further p_{herd} can be made dependent on the size of the fish.
325 One obvious advantage of using simulation for our study is that we have control over what is
326 on the fishing ground. Specifically this means that we were able to test the different fishing
327 cases on identical fishing conditions with respect to number of fish and spatial distribution on
328 the fishing ground which is essential for being able to conduct a fair comparison between the
329 different fishing cases tested. It further provides a cheap and fast method for exploring how
330 different aspects can affect the effectiveness of demersal seine fishing. In this study we found
331 that the effectiveness of demersal seining in the Norwegian coastal zone targeting cod will
332 depend on the seine rope layout pattern applied. Specifically we predict that the rectangular
333 layout we deployed, which is not unrealistic compared to what is applied in the commercial
334 fishery [17], will only catch 54-56% of the cod that would be obtained with a square layout
335 pattern. This highlights the importance of considering initial layout pattern when planning
336 demersal seine fishing at least when the cod are uniformly distributed on the fishing ground as
337 assumed in our simulations. Our results also demonstrated that the length of the towing phase
338 can significantly affect the total catch but that the extent also depends on the layout pattern
339 applied.

340 Simulation models have previously proven to be useful for predicting fish capture with active
341 fishing by combining models for the physical behaviour of the fishing gear with models for
342 fish behavior to the gear. To our knowledge those models have focused on trawls and mainly
343 size selectivity in codends. One such model for codend is the selectivity simulator PRESEMO
344 [18] which have used input about the physical behavior of the gear from respectively the
345 model of Priour [15] or the model of O'Neill [16]. But, to our knowledge is this the first time
346 that such combination of physical and behavioral models have been applied to investigate
347 aspects of effectiveness of demersal seining.
348

349 ## Acknowledgements

350 The investigations in this study were funded by the Research Council of Norway (project no.
351 225193 (MAROFF-2)) and the Norwegian Seafood Research Fund (project no. 900861
352 (FHF)). We are grateful for their financial support.
353

354 ## References

355 1. Thomson, D.B., 1981. Seine Fishing: Bottom Fishing with Rope Warps and Wing
356 Trawls. Fishing News Books, Farnhem.

357 2. Herrmann, B., Larsen, R.B., Sistiaga, M., Madsen. N.H.A., Aarsæther, K.G., Grimaldo,
358 E., Ingolfsson, O.A., 2016. Predicting Size Selection of Cod (Gadus morhua) in Square
359 Mesh Codends for Demersal Seining: a Simulation-based Approach. Fish. Res. In press.
360 DOI 10.1016/j.fishres.2015.07.015.

3. Thrane, M. 2004. Energy consumption in the Danish fishery: Identification of key factors. Journal of Industrial Ecology 8(1–2): 223–239.

4. ICES. 2010. Report of the ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB), 31 May - 4 June 2010, Copenhagen, Denmark. ICES CM 2010/SSGESST:14. 252 pp.

5. Walsh, S.J., Winger, P.D., 2011. Bottom Seining in Canada, 1948-2010: Its Development, Fisheries, and Ecosystem Impacts. Can. Tech. Rep. Fish. Aquat. Sci. 2922.

6. Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D., 2012. Low impact and fuel efficient fishing – looking beyond the horizon. Fish. Res. 119, 135–146.

7. Norges Råfisklag. http://www.råfisklaget.no.

8. Sainsbury, J.C. Commercial fishing methods. An Introduction to vessels and gears. Fishing News Books. Wiley, August 1996.

9. Reite, K.J., Føre, M., Aarsæther, K.G., Jensen, J., Rundtop, P., Kyllingstad, L.T., Endresen, P.C., Kristiansen, D., Johansen, V., Fredheim, A.. Fhsim - Time Domain Simulation of Marine Systems. In ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, volume 8A: Ocean Engineering. Ocean, Offshore and Arctic Engineering Division, 2014.

10. Johansen, V. Modelling of Flexible Slender Systems for Real-Time Simulation and Control Application. PhD thesis, ISBN 978-82-471-4915-7, NTNU, December 2007.

11. Egeland, O., & Gravdahl, J. T. (2002). Modeling and simulation for automatic control. Marine Cybernetics, Trondheim, Norway, ISBN 82-92356-00-2.

12. Madsen, N.A., Aarsæther, K.G., Herrmann, B., Hansen, K., Jensen, J.H – THE PHYSICAL BEHAVIOUR OF SEINE ROPES FOR EVALUATING DEMERSAL SEINE FISHING– Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2015, May 31-June 5, 2015, St. John's, Newfoundland, Canada.

13. Sistiaga, M. Herrmann, B., Grimaldo, E., Larsen, R.B., 2015. Effect of lifting the sweeps on bottom trawling catch efficiency: A study based on the Northeast artic cod (*Gadus morhua*) trawl fishery. Fisheries Research 167, 164-173.

14. Winger, P.D., He, P., Walsh, S.J., 1999. Swimming endurance of American plaice (Hippoglossoides platessoides) and its role in fish capture. ICES J. Mar. Sci. 56, 252-265.

15. Priour, D., 1999. Calculation of net net shapes by the finite element method with triangular element. Commun. Numer. Meth. 15, 755-763.

16. O'Neill, F.G., 1997. Differential equation governing the geometry of a diamond mesh cod-end of a trawl net. J. Appl. Mech. 64/7 (453), 1631-1648.

17. Digre, H., Aursand, I.G., Aasjord, H.L., Geving, I.H., 2010. Fangstbehandling i snurrevadflåten. Sintef report no SFH80 A105002 (in Norwegian). ISBN 978-82-14-049329-5.

18. Herrmann, B., 2005. Effect of catch size and shape on the selectivity of diamond mesh cod-ends: I Model development. Fisheries Research 71: 1-13.

Figure captions

Figure 1: Demersal seine fishing procedure (collection and closing phase) from top to bottom. 1: seine net. 2: seine rope. 3: fishing vessel. 4: fish collected ahead of seine net. The grey dots represent aggregations of fish at the seabed. In this case the fish is being uniformly distributed. Seine net, fishing vessel and fish aggregations are scaled up compared to the length of the seine ropes for illustration purposes.

Figure 2: Fish (grey ellipses) reaction to an approaching seine rope (green curve). The zoomed picture at right side illustrates that when the seine rope gets closer to the fish than the distance l_{min} it reacts by swimming the distance l_{move} further away from the seine rope in a direction perpendicular to the seine rope. Seine net, fishing vessel and fish aggregations are scaled up compared to the length of the seine ropes for illustration purposes.

Figure 3: The four different initial layout patterns simulated. From left: rectangular, square, triangular and diamond. Seine net (grey triangle) and fishing vessel (blue pentagon) are scaled up compared to the extent of the seine ropes for illustration purposes(screen dumps from simulations using *SeineFish*).

Figure 4: Illustration of the fishing process (from left to right) for each of the three towing phase cases investigated. From top: no towing, 15 minutes towing and 35 minutes towing. Here illustrated for the diamond shaped initial layout pattern. Seine net (grey triangle), fishing vessel (blue pentagon) and fish aggregations (grey dots) are scaled up compared to the length of the seine ropes (green curves) for illustration purposes (screen dumps from simulations using *SeineFish*).

Figure 5: Illustration of the physical behaviour of the fishing gear during different steps of the fishing process for each of the 12 fishing cases investigated. From top to bottom: no towing, 15 minutes towing, 35 minutes towing. From left to right: rectangular, square, triangular,

diamond initial layout pattern. Seine net (grey triangle) and fishing vessel (blue pentagon) are scaled up compared to the length of the seine ropes (green curves) for illustration purposes (screen dumps from simulations using *SeineFish*).

Figure 6: Development in the number of fish encircled by the seine ropes on the seabed (fish count) during the fishing process for deployment of each of the four different initial layout patterns investigated and for each towing phase scenario's.

Figure 7: Illustration of the development in the area encircled (green area) by the seine ropes on the seabed during the fishing process (from left to right) for each of the four initial layout patterns (from top to bottom). Here illustrated for 15 minutes towing phase. Seine net (grey triangle), fishing vessel (blue pentagon) and fish aggregations (grey dots) are scaled up compared to the length of the seine ropes (green curves) for illustration purposes (screen dumps from simulations using *SeineFish*).

Figure 8: Development in the area encircled by the seine ropes on the seabed during the fishing process for deployment of each of the four different initial layout patterns investigated and for each towing phase scenario's.

Figure 9: Development in the entry width into area encircled by the seine ropes on the seabed during the fishing process for deployment of each of the four different initial layout patterns investigated and for each towing phase scenario's.

Fig. 1

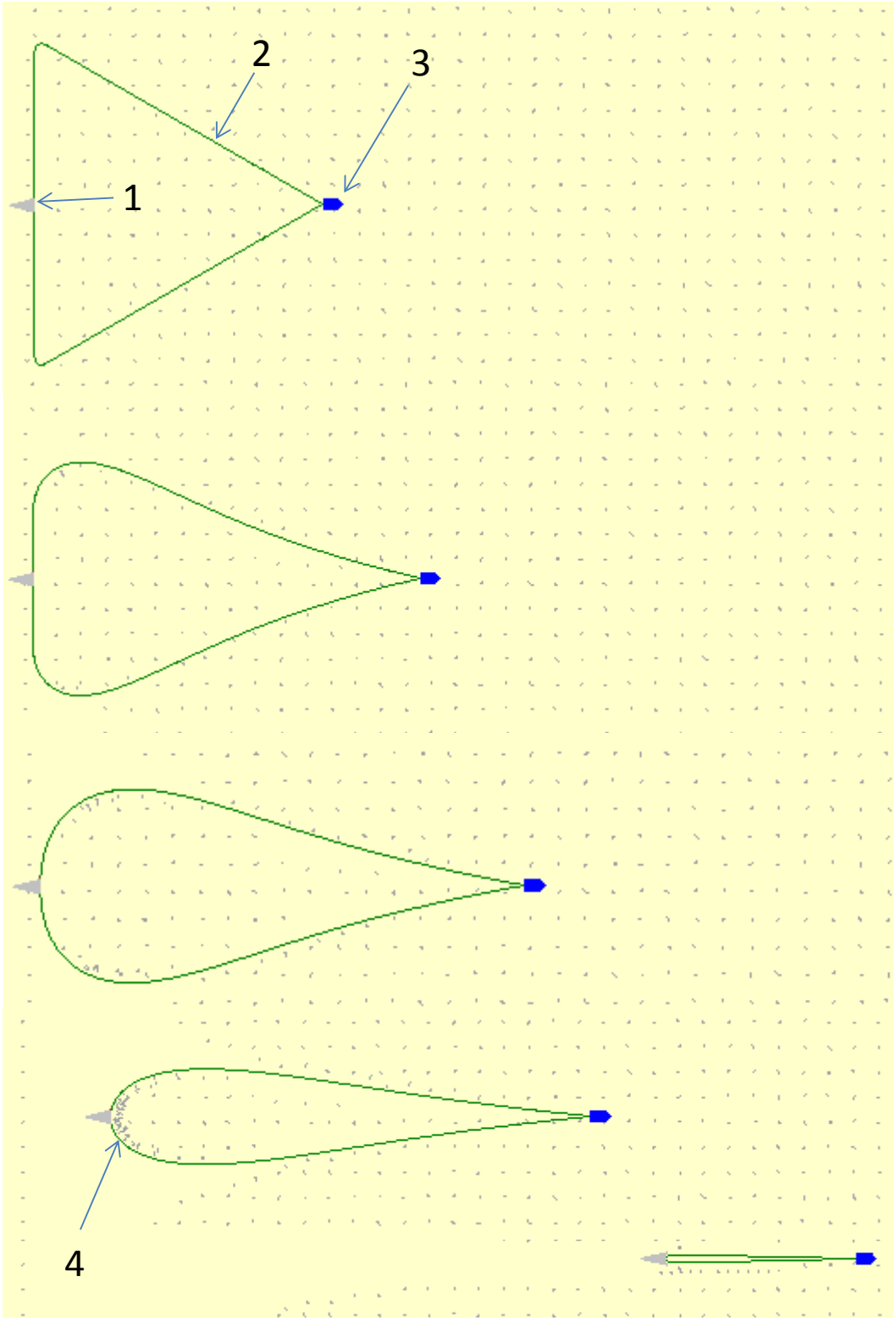


Fig. 2

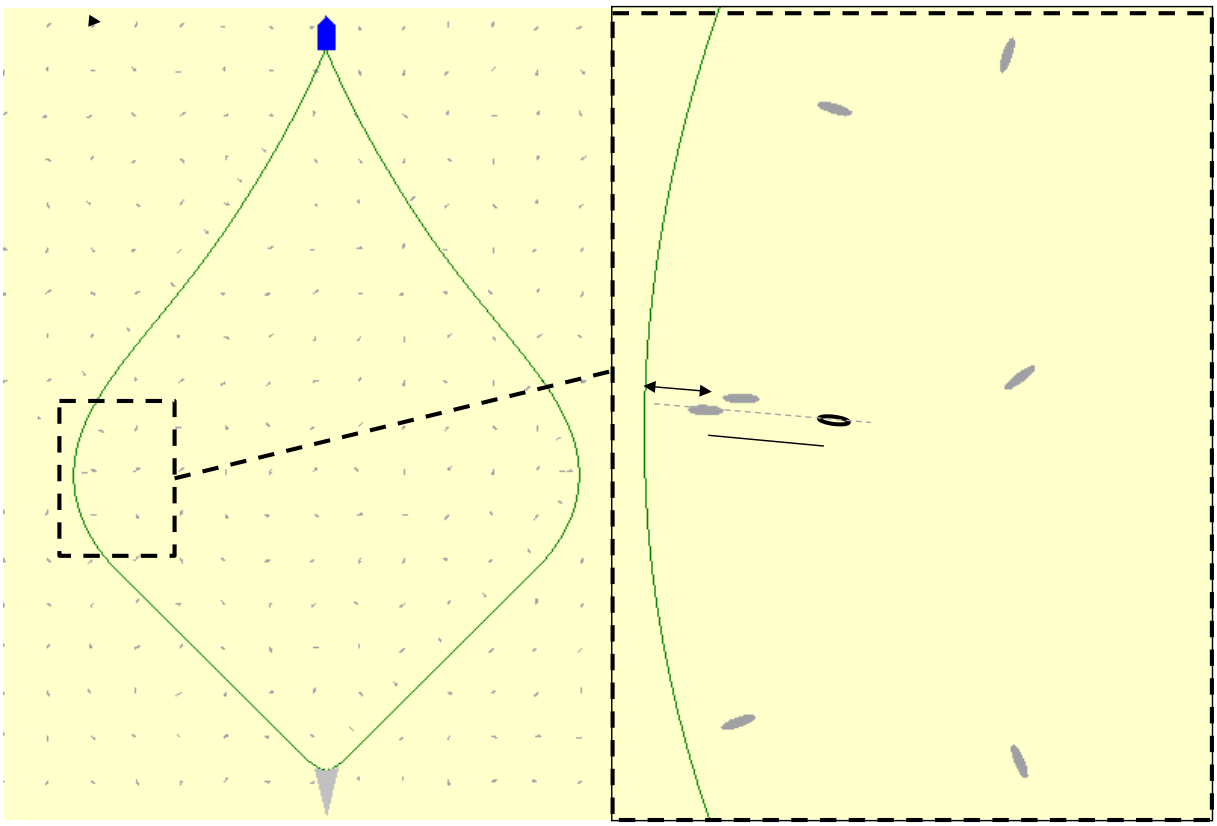


Fig. 3

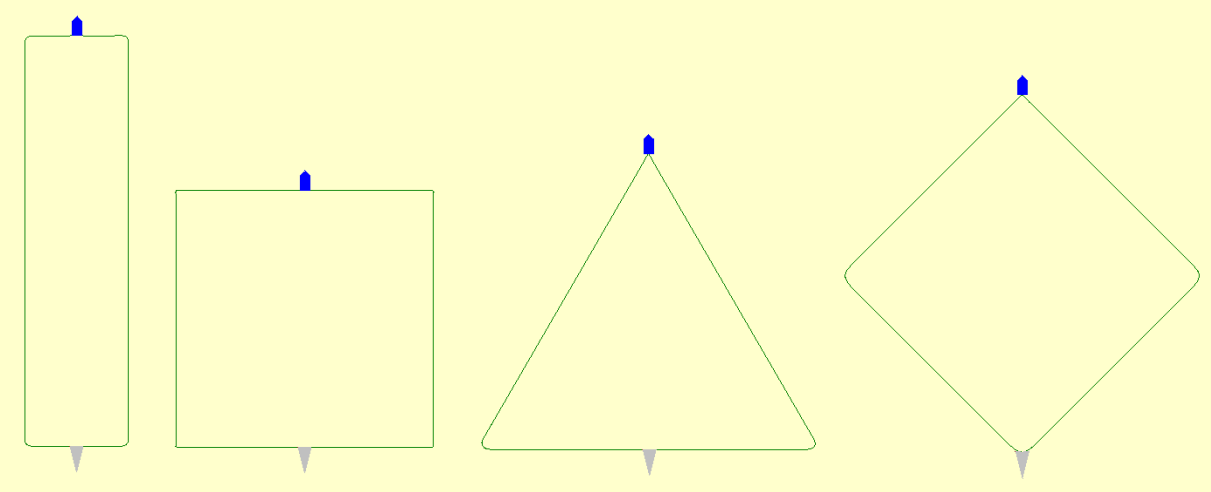


Fig. 4

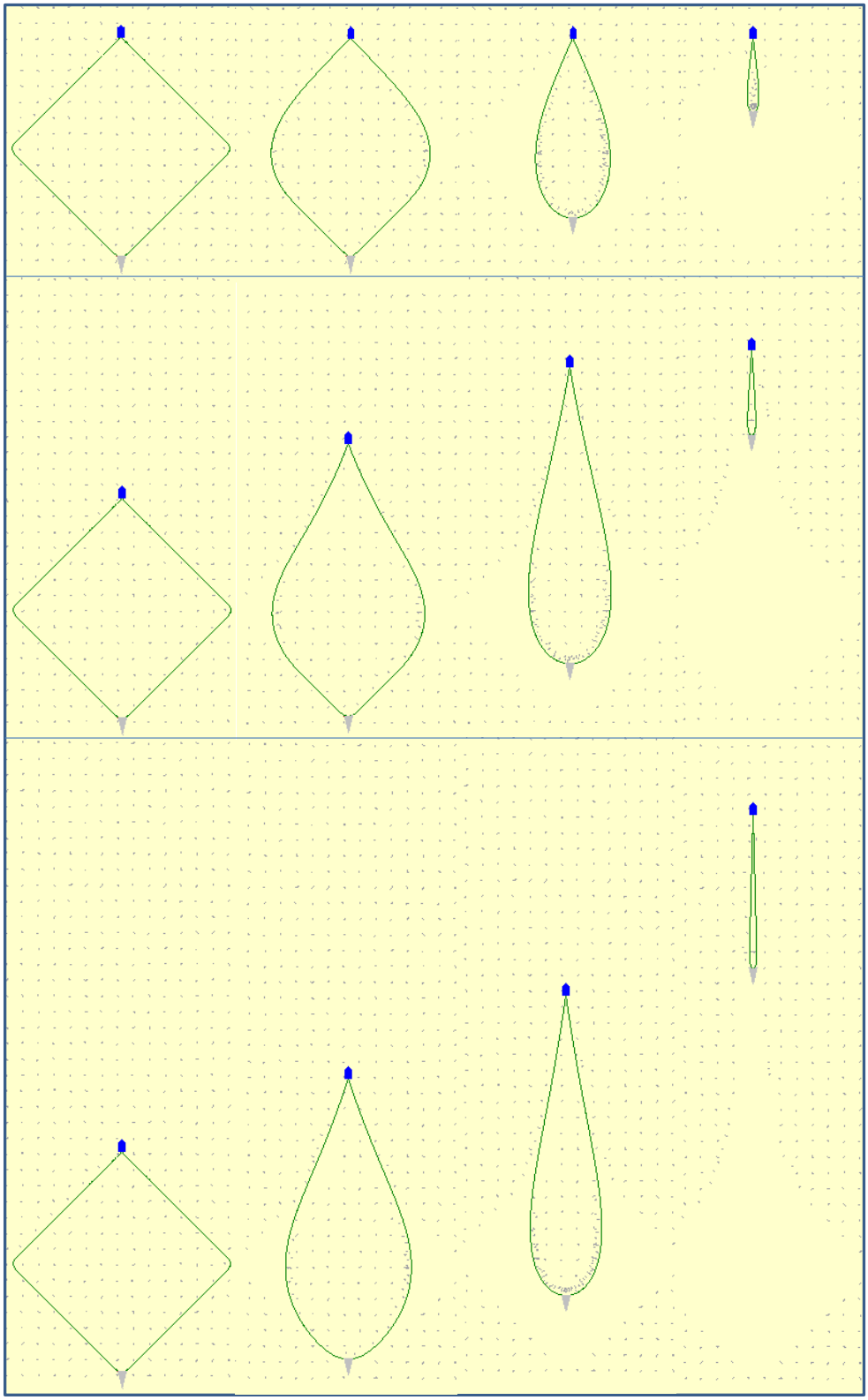


Fig. 5

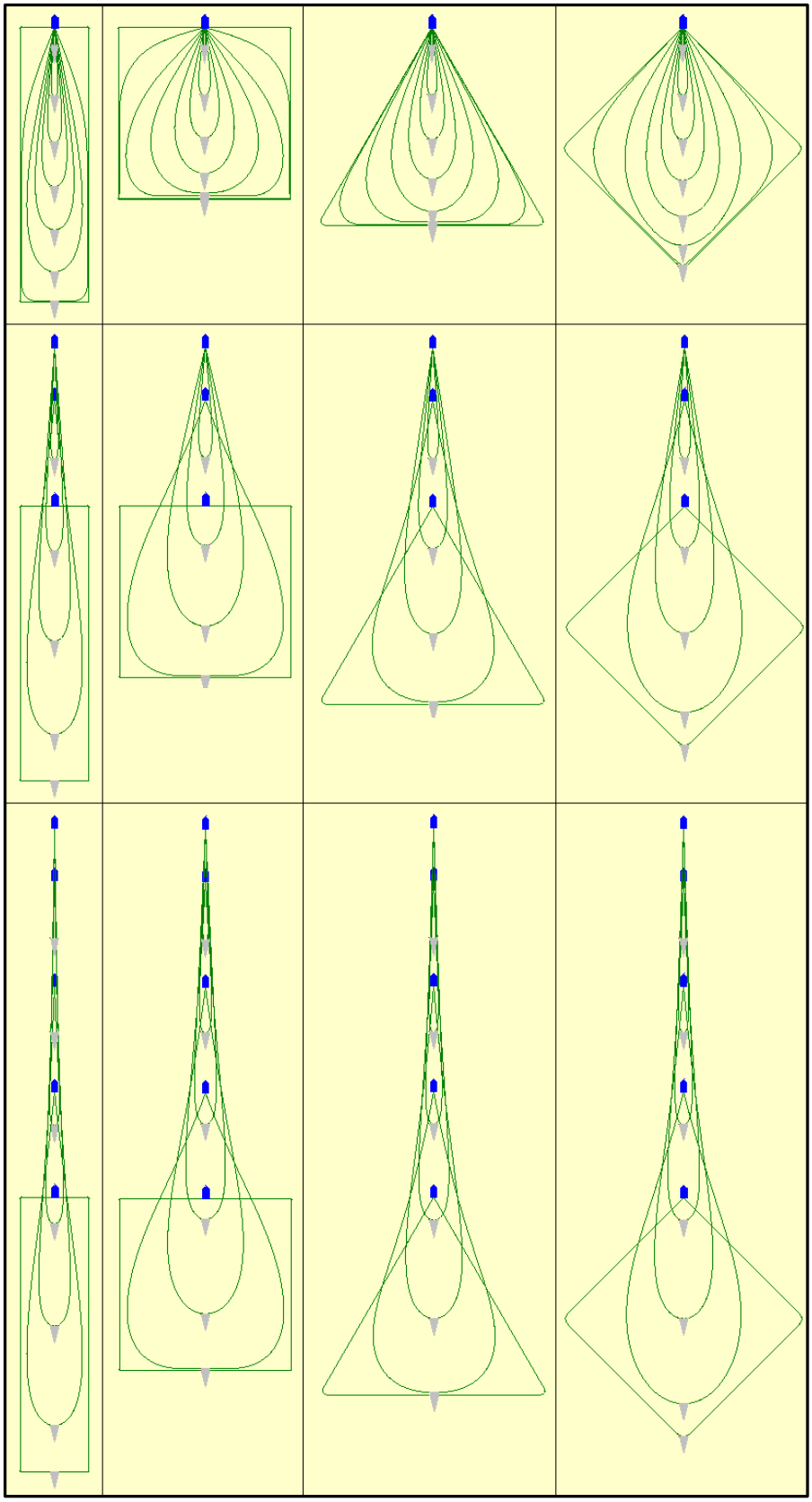


Fig. 6

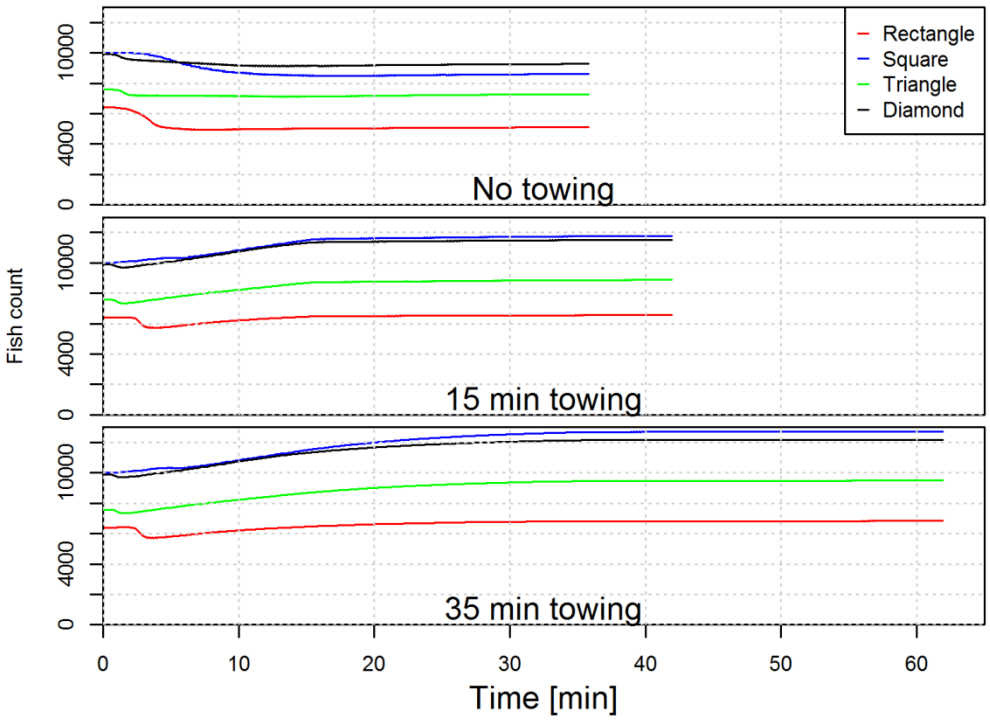

Rectangle
Square
Triangle
Diamond
No towing
15 min towing
35 min towing
Fish count
0
4000
10000
0
10
20
30
40
50
60
Time [min]

Fig. 7

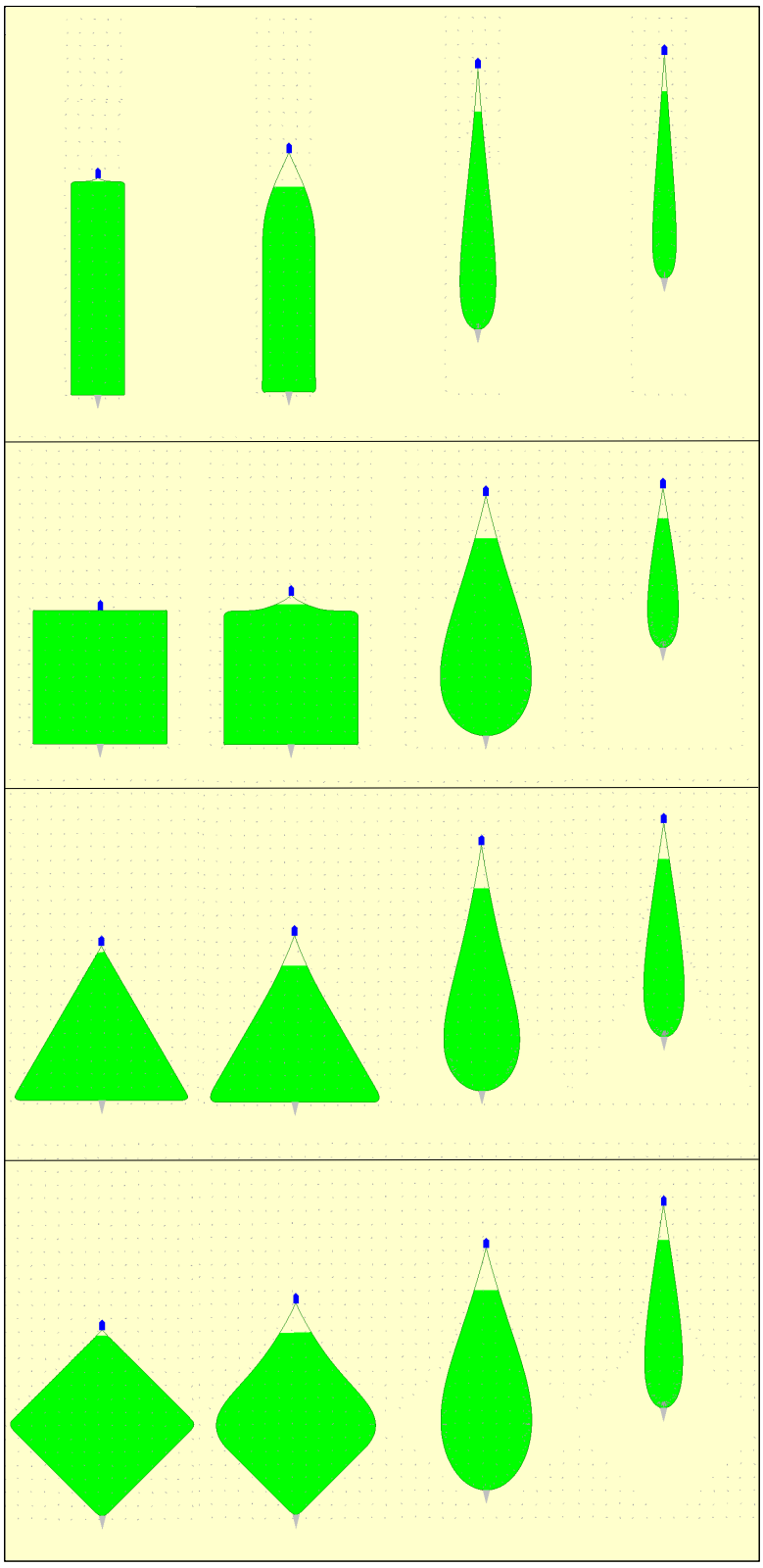


Fig. 8

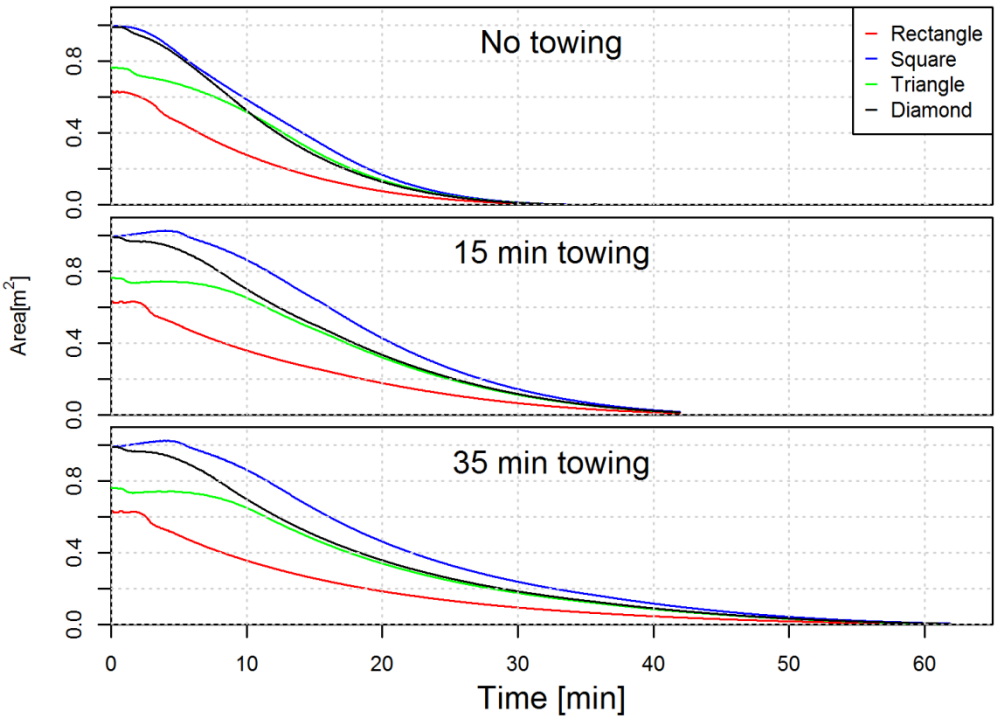
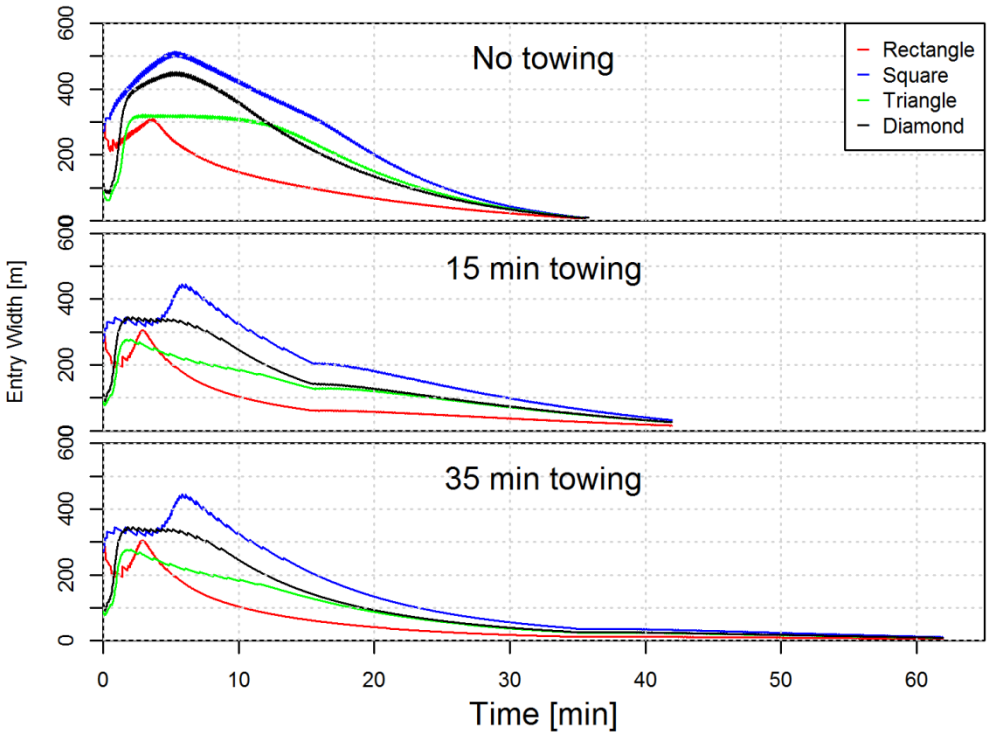

No towing
15 min towing
35 min towing
Rectangle
Square
Triangle
Diamond
Area[m^2]
0.0
0.4
0.8
0
10
20
30
40
50
60
Time [min]

Fig. 9


No towing
15 min towing
35 min towing
Rectangle
Square
Triangle
Diamond
Entry Width [m]
Time [min]
0
200
400
600
0
10
20
30
40
50
60