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Understanding sorting grid and codend size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*)

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ABSTRACT

We studied the size selectivity of Greenland halibut (*Reinhardtius hippoglossoides*) using the fish morphology-based FISHSELECT methodology, size selectivity data from two sets of sea trials carried out in the Barents Sea and the Norwegian Sea, and historical selectivity data collected for this species from 1981 onwards. When compared, the historical codend size selectivity data fitted well with the selectivity predictions from the FISHSELECT analyses. The historical grid selectivity data and the results from the two sea trials showed considerably lower L50 values than what would be expected from the morphological-based limit estimated by FISHSELECT. The size selectivity results obtained from the analysis of the two sea trials differed significantly, even though they were conducted using grid sections with similar bar spacing that previously were shown to have similar selective properties for other species. The differences were not caused by differences in the ability of the fish to contact the grid. Instead, these differences can be explained by differences in the ability of the fish to turn before they attack the grid. In earlier grid selectivity studies, the influence of angle of attack (θ) was not quantified. We show that the ability to contact the grid with a more or less optimal θ differs between individuals. This is important to consider in grid selectivity studies for flatfish species such as Greenland halibut because it can potentially influence results considerably and therefore can be a source of variability in results between cruises.

1. Introduction

Greenland halibut or Greenland turbot (*Reinhardtius hippoglossoides*), a flatfish that belongs to the family *Pleuronectidae*, lives in polar and cold regions of the North Atlantic and North Pacific oceans (Sohn et al., 2010). Despite its wide distribution in depth (200–1600 m), it is mostly considered a deep water fish because it is commonly harvested at the edge of the continental shelf at depths between 300 and 1000 m. In the Northeast Atlantic, Greenland halibut is harvested by means of gillnets, longlines, and trawls. Trawls are one of the most widely used gears to harvest Greenland halibut. In Norway, for example, 39% of the Greenland halibut captured in 2011 was captured as bycatch in the demersal trawl fishery (Fiskeridirektoratet, 2012). Selectivity studies for this species and these gears can be found in the literature (Boje et al., 1997; Woll et al., 1998; Huse et al., 1999; Lisovsky et al., 2004).

In the Northeast Atlantic, sorting grids have been used in combination with diamond mesh codends as a selection measure for the bottom trawl fisheries since the mid 1990s (Larsen and Isaksen, 1993).

Traditionally the size selectivity of sorting grids and codends was investigated solely based on sea trials. In recent years the experimentally based methods have been supplemented by theoretical methods.

FISHSELECT is such a method that can be applied to investigate the basic size selective properties of sorting grids and meshes of different shapes and sizes for individual fish species (Herrmann et al., 2009). The methodology is based on fish morphology data and computer simulations and has been applied in the North Atlantic for *Nephrops* and a variety of roundfish species, including redfish (*Sebastes* spp.), cod (*Gadus morhua*), and haddock (*Melanogrammus aeglefinus*) (Herrmann et al., 2009, 2012; Frandsen et al., 2011; Krag et al., 2011; Sistiaga et al., 2011). However, FISHSELECT has not been applied previously to flatfish species, and therefore the method was specifically developed further to this end. The body shape of roundfishes and flatfishes has different characteristics that have potential implications for the selectivity of these species. Therefore, a morphological-based analysis that relates the characteristics of a

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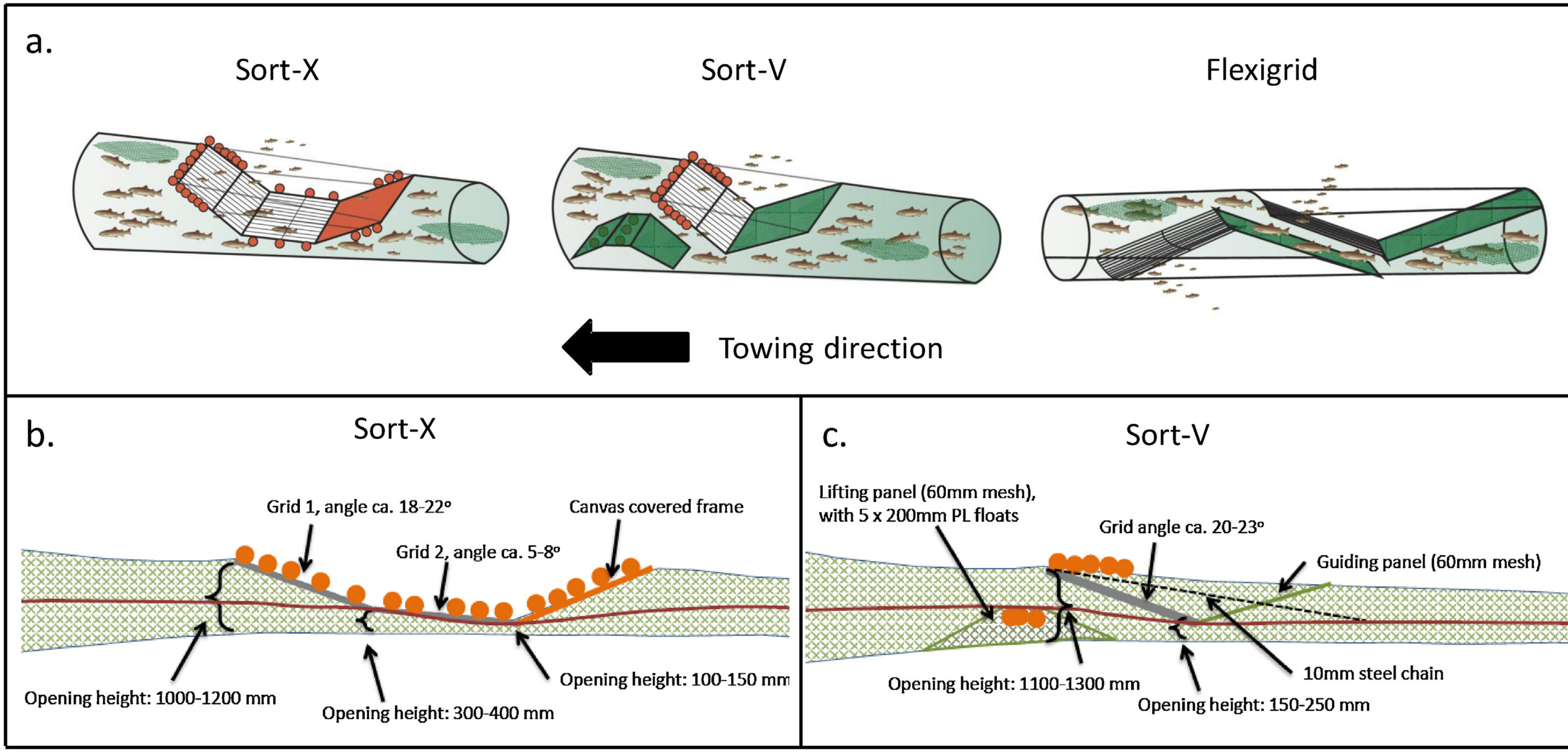

Fig. 1. Design of the three sorting grid systems used in the Barents Sea today (a). Details about the Sort-X grid (b). Details about the Sort-V grid (c).

Table 1
Selectivity results for Greenland halibut obtained with different diamond mesh size codends.

Year	Author	Country	Publication type	Sampling method	Mesh size (mm)	L50 (cm)	SR (cm)	No. hauls	Comments
1981	Chumakov et al.	Russia	NAFO SCR Doc. 81/IX/89	Covered codend	133.0	40.50	8.35[a]	?	Results checked on raw data
1997	de Cárdenas et al.	Spain	NAFO SCS 30, 21–25	Covered codend	129.2	38.70	7.40	4	
1997	de Cárdenas et al.	Spain	NAFO SCS 30, 21–25	Covered codend	129.2	37.70	11.80	4	
1999	Huse et al.	Norway	Fisheries Research 44, 75–93	Paired gear (trouser trawl)	136.0	42.00	9.60	4	
2000	Walsh et al.	Canada	NAFO SCR Doc. 00/66	Paired gear (trouser trawl)	144	47.70	7.41	14	
2000	Walsh and Hickey	Canada	NAFO SCR Doc. 00/49	Paired gear (trouser trawl)	145	47.20	7.00	15	
2001	Brothers and Duthie	Canada	Project Report EACT-7.2001.DFO	Alternate haul method	145	40.20	20.44	10	
2001	Brothers and Duthie	Canada	Project Report EACT-7.2001.DFO	Paired gear (trouser trawl)	145	47.16	6.98	18	
2001	Brothers and Duthie	Canada	Project Report EACT-7.2001.DFO	Alternate haul method	145	46.45	20.39	10	
2001	Lisovsky et al.	Russia	NAFO SCR Doc. 01/30	Covered codend	121.0	33.50	7.30	7	Results checked on raw data
2001	Lisovsky et al.	Russia	NAFO SCR Doc. 01/30	Covered codend	121.0	35.50	6.50	7	Results checked on raw data
2001	Lisovsky et al.	Russia	NAFO SCR Doc. 01/30	Covered codend	130.0	38.50	7.10	7	Results checked on raw data
2001	Lisovsky et al.	Russia	NAFO SCR Doc. 01/30	Covered codend	132.0	40.00	10.50	8	Results checked on raw data
2002	Brothers G.	Canada	Project Report EACT-5.2002.DFO	Twin trawl method	147.0	45.06	14.47	13	
2002	Brothers G.	Canada	Project Report EACT-5.2002.DFO	Twin trawl method	147.0	45.23	8.85	9	
2002	Lisovsky et al.	Russia	NAFO SCR Doc. 02/29	Covered codend	130.8	41.70	6.10	10	Results checked on raw data
2002	Lisovsky et al.	Russia	NAFO SCR Doc. 02/29	Covered codend	145.2	45.20	7.10	10	Results checked on raw data
2002	Lisovsky et al.	Russia	NAFO SCR Doc. 02/29	Covered codend	150.2	46.70	8.40	4	Results checked on raw data
2003	Lisovsky et al.	Russia	NAFO SCR Doc. 03/28	Covered codend	130.3	40.30	9.60	10	
2003	Lisovsky et al.	Russia	NAFO SCR Doc. 03/28	Covered codend	135.2	43.80	10.00	10	
2003	Lisovsky et al.	Russia	NAFO SCR Doc. 03/28	Covered codend	135.8	45.30	7.90	10	
2003	Lisovsky et al.	Russia	NAFO SCR Doc. 03/28	Covered codend	145.4	46.20	6.30	10	
2003	Lisovsky et al.	Russia	NAFO SCR Doc. 03/28	Covered codend	149.8	48.70	6.90	10	
2004	Lisovsky et al.	Russia	NAFO SCR Doc. 04/6	Covered codend	152.2	42.80	14.80	10	
2004	Lisovsky et al.	Russia	NAFO SCR Doc. 04/6	Covered codend	162.6	47.40	14.90	10	
2004	Lisovsky et al.	Russia	NAFO SCR Doc. 04/6	Covered codend	173.0	48.40	15.40	10	

[a] Data not provided by the original authors.

flatfish species to the size selective properties of diamond meshes and grids is relevant for the evaluation of selectivity devices within trawls.

In the fishing grounds of the Barents Sea, three different grid types: Sort-X, Sort-V and Flexigrid, are legal (all of them with 55 mm bar spacing) (Fig. 1). These grids have different designs, but all three are installed in the extension piece in front of the codend.

When designing a sorting grid, it is important to develop a system that ensures that most fish come into contact with the grid and thereby have a chance to escape through it. Devices such as the lifting panel in some grid sections were introduced with this purpose (Fig. 1). When estimating the selective properties of a grid, the fraction of the fish that comes in contact with the grid and thus has an actual chance to escape through it must be considered (Sistiaga et al., 2010). Given that a fish contacts the grid, both its shape and orientation relative to the grid bars will determine whether or not it can escape. Because grids used today in the Northeast Atlantic bottom trawl fisheries are constructed with vertical bars, and assuming that a flatfish normally swims with its ventral part towards the seabed, the angle of attack (hereafter referred to as θ) that would maximize the escape possibility for a flatfish would be 90°. For roundfish, this angle would be 0°, meaning that the fish does not need to turn from its natural swimming orientation to maximize its chances to escape. Thus, the larger the difference between a fish's horizontal and vertical dimensions, the more important the fish's orientation (and hence its ability to change its orientation) relative to the grid bars will be for its escapement chances. Flatfishes are an extreme case among finfishes because they are much wider than they are high, and this means that their ability to reorient themselves is a determining factor for size selection.

The main objectives of this study were to (i) estimate the size selectivity of Greenland halibut based on its morphological characteristics and compare these results to new and to historical selectivity data collected with grids and diamond mesh codends; (ii) evaluate the importance of the θ of Greenland halibut on size selectivity of grid-based systems; and (iii) understand to what extent θ can explain the shape of the size selection curves obtained for Greenland halibut in sea trials. This is the first scientific study to quantify the importance of θ on the escape possibilities for fish.

2. Material and methods

2.1. Historical data

The historical selectivity data presented for different bar spacing grids and diamond mesh codends were collected after an extensive literature review, for which a previous review by Dyck et al. (2007) was used as a starting point. Tables 1 and 2 list the available selectivity data from different countries for different diamond mesh sizes and grids with different bar spacing. These data were collected with various gear types (trawl types, codends with different twine thickness, different types of grids) and over a long time span, which potentially could lead to variation in the selectivity estimations. Further, different data analysis methods were used in different studies. In several of the references presented in Table 1, the raw selection data were provided by the authors. Some of these studies were conducted as long as 30 years ago, and we reanalyzed the data to identify possible discrepancies in the results. We fit a standard logistic curve to the data and compared the results with those originally presented by the authors. The small differences (<1 cm for size selection parameters) obtained in the reanalysis of the data with respect to the original results were negligible, and therefore the original results were kept. Chumakov et al. (1981) did not provide the SR value, but raw data and consequently SR was obtained from reanalysis (Table 1).

2.2. Sea trials

2.2.1. Trials onboard the "M/V Hopen"

The sea trials conducted onboard the "M/V Hopen" took place from 7 to 22 November 1994 in the fishing grounds located between of Fugløybanken and Tromsøflaket (70°10′–17°10′ N, 14°44′–17°10′ E). The "M/V Hopen" is a 60.5 m long and 14.0 m wide factory trawler with a 4000 HP (1 HP = 735.5 W) engine, which has the equipment and skilled crew necessary to run scientific trawl selectivity studies. A set of Morgére-R trawl doors (2800 kg), 140 m sweeps, and two nearly identical trawls (a Selstad 444 fishing trawl and an Alfredo Mørenot nr 4) were used during the fishery. A Sort-X sorting grid system (Fig. 1a and b), which consists of two grid sections and a canvas section (see Larsen and Isaksen, 1993 for further information on the grid), was installed in the extension piece in front of the codend. To control the number of fish escaping through the grid, a 52 mm mesh cover was installed over the grid. The design of the cover was identical to the one used by Larsen and Isaksen (1993) (Fig. 2). The mesh size in the codend was 52 mm and the codend was therefore considered to be non-selective.

For each of the four hauls carried out, a Greenland halibut subsample of at least 430 fish from each of the compartments (grid cover, codend) was measured to the nearest centimeter below. The rest of the fish were counted. The measured sample was taken in random subsamples collected at different stages of fish processing to avoid sampling bias. In total was 4600 Greenland halibut measured during the four hauls.

2.2.2. Trials onboard the "M/V Ramoen"

The data collection onboard the "M/V Ramoen" occurred from 19 to 30 October 2011 at the banks of Hopendjupet (between 77°05′–77°15′ N, 28°17′–30°45′ E). The vessel has a length overall of 66.7 m a 5170 HP engine. The experimental setup included a pair of "Scorpion injector" bottom trawl doors (9.5 m^2 and 4400 kg each), 80 m sweeps, and a "Vonin bacalao" trawl. The sorting grid section used was a 55 mm Sort-V grid system (see Jørgensen et al., 2006 for more details; Fig. 1a–c), which was combined with a 135 mm (nominal mesh size) codend constructed entirely of 10 mm PE "Ultra cross" knotless netting. The codend was 160 meshes long and 120 meshes around and was blinded by a 55 mm inner net. A similar construction was also used for the cover over the grid.

Table 2
Selectivity results for Greenland halibut obtained with different grids and grid bar spacing.

Year	Author	Country	Publication type	Sampling method	Bar spacing (mm)	L50 (cm)	SR (cm)	No. hauls
1992	Isaksen et al.	Norway	Fisheries Research 13, 335–352	Grid cover	19	15.00	?	?
1996	Lisovsky et al.	Russia	NAFO SCR Doc. 96/37	Grid cover	35	33.00	3.60	2
1996	Lisovsky et al.	Russia	NAFO SCR Doc. 96/37	Grid cover	35	33.80	4.20	8
1996	Lisovsky et al.	Russia	NAFO SCR Doc. 96/37	Grid cover	40	33.80	12.90	2
2005	Grimaldo and Larsen	Norway	Fisheries Research 76, 187–197	Grid cover	19	19.52	6.04	3
2005	Grimaldo and Larsen	Norway	Fisheries Research 76, 187–198	Grid cover	19	20.19	4.56	6
2006	Grimaldo	Norway	Fisheries Research 77, 53–59	Grid cover	19	20.22	5.43	22

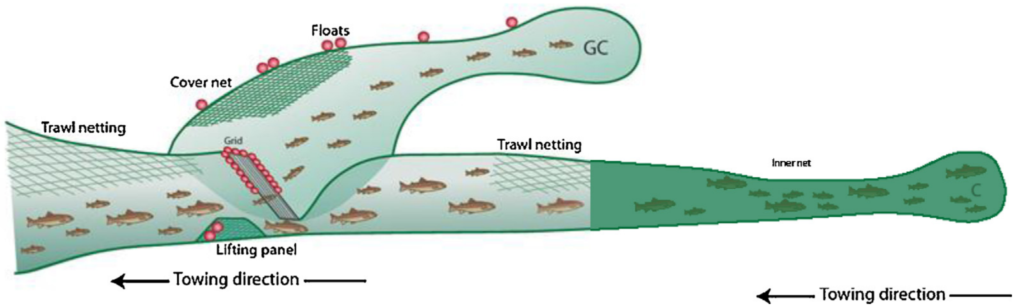

Fig. 2. Illustration of a sampling setup for which the sorting grid (here a Sort-V grid) is covered with a small mesh cover that retains the fish escaping through the grid. Note that the codend is blinded so that only the selectivity of the grid is estimated.

Once the fish were onboard, the sampling procedure was the same as that used onboard the "M/V Hopen". At least 250 Greenland halibut per compartment (grid cover, codend) were measured during each of the six hauls conducted in the cruise. A total of 5700 Greenland halibut were measured during the six hauls.

2.3. Analysis of experimental data for the grid-based selectivity systems

The experimental designs applied onboard the "M/V Hopen" and "M/V Ramoen" (Fig. 2) enabled analysis of the collected catch data as two-compartment data (binominal data; the fish were either retained by the cover over the grid or by the codend behind the grid) to estimate the size selection in the grid (i.e., length-dependent grid rejection likelihood). The two-compartment data analysis (compartment C vs. compartment GC in Fig. 2) meant that for each haul (j) we had the number for fish of each length class l collected in compartment C (nC_{jl}) and in compartment GC (nGC_{jl}), respectively. The likelihood of finding a fish with length l in compartment GC in haul j given that it is found in one of the compartments is expressed by the function $r_j(l)$, which quantifies the length-dependent grid rejection likelihood. The purpose of the analysis is to estimate the values of this function for all relevant sizes of Greenland halibut. The values of $r_j(l)$ can be expected to vary between hauls (Fryer, 1991), although this variation was of no specific interest for this study. Instead, we were interested in the length-dependent values of $r(l)$ averaged over hauls because this would provide information about the average consequences for the size selection process of applying the grid to a fishery. Thus, we assumed that the size selective performance of the grid for the group of hauls conducted was representative of how the grid would perform in a commercial fishery (Millar, 1993; Sistiaga et al., 2010).

Estimation of the average size selection over hauls $r_{av}(l)$ involves the pooling of raised (in case of subsampling) data from the different hauls. According to Fryer (1991), simply pooling data over hauls could lead to underestimation of the uncertainties in the size selection process due to the potential between-haul variation. We mitigated this problem by using a double bootstrapping technique that accounts for both within- and between-haul variation in the selection process. For each case analyzed, 2000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Efron, 1982; Chernick, 2007). Because this technique is similar to the one applied by Sistiaga et al. (2010), Eigaard et al. (2011), Herrmann et al. (2012), and Madsen et al. (2012), it is not described further here. Because we tested different parametric models for $r_{av}(l)$, we write $r_{av}(l,\boldsymbol{v})$, where $\boldsymbol{v}$ is a vector consisting of the parameters of the model. The purpose of the analysis is to estimate the values of the parameter $\boldsymbol{v}$ that make experimental data averaged over hauls most likely to be observed assuming that the model is able to describe the data sufficiently well. Thus, function (1) was minimized, which is equivalent to maximizing the likelihood for the observed data:

$$-\sum_{j}\sum_{l}\left\{\frac{nGC_{jl}}{qGC_j}\times\ln(r_{av}(l,\boldsymbol{v}))+\frac{nC_{jl}}{qC_j}\times\ln(1.0-r_{av}(l,\boldsymbol{v}))\right\} \quad (1)$$

where the summations are over hauls j and length classes l, and qGC_j and qC_j are the length-independent subsampling rates for haul j for the grid cover and the codend inner net, respectively.

Evaluation of the ability of a model to describe the data sufficiently well based on (1) is based on calculation of the corresponding p-value, which expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this p-value should not be below 0.05. Model deviance vs. degree of freedom also can be applied in the model evaluation (Wileman et al., 1996). To calculate the fit statistics (p-value, model deviance), data were pooled without raising them to avoid making data look stronger than they are. Selection of the best model among those with acceptable p-values is based on comparing the AIC values for the models. The selected model is the one with the lowest AIC value (Akaike, 1974). If the model with the lowest AIC value does not produce an acceptable p-value, it could be due to the model's inability to describe the length-based structure of the data or to overdispersion in the data. Residual plots can be used to discriminate between overdispersion and structural problems in a model's ability to describe experimental data (Wileman et al., 1996; Madsen et al., 2012).

Size selectivity was analyzed using the software tool SELNET following the methodological recommendations in Wileman et al. (1996) and Fryer (1991). SELNET offers a variety of additional models and methods for analysis, including the double bootstrap technique described above. SELNET was developed by the first author of the study reported here, and additional information about the software can be obtained from him or by consulting Sistiaga et al. (2010), Eigaard et al. (2011), Frandsen et al. (2011), Wienbeck et al. (2011), Madsen et al. (2012), and Herrmann et al. (2012).

Initial inspection of the shape of the size selection curve for the experimental grid retention data for Greenland halibut (Section 2.2) indicated that a traditional *logit* model may not be able to adequately model the length-dependent grid rejection likelihood for this species. Therefore, we applied a more flexible family of models to model the grid rejection likelihood for Greenland halibut:

$$r_{av}(l,\boldsymbol{v})=\frac{\exp(f(l,\boldsymbol{v}))}{1+\exp(f(l,\boldsymbol{v}))} \quad (2)$$

where f is a polynomial of order m with the coefficients v_0 to v_m. We applied (2) with f of the following form:

$$f(l,\boldsymbol{v})=\sum_{i=0}^{m}v_i\times\left(\frac{l}{100.0}\right)^i \quad (3)$$

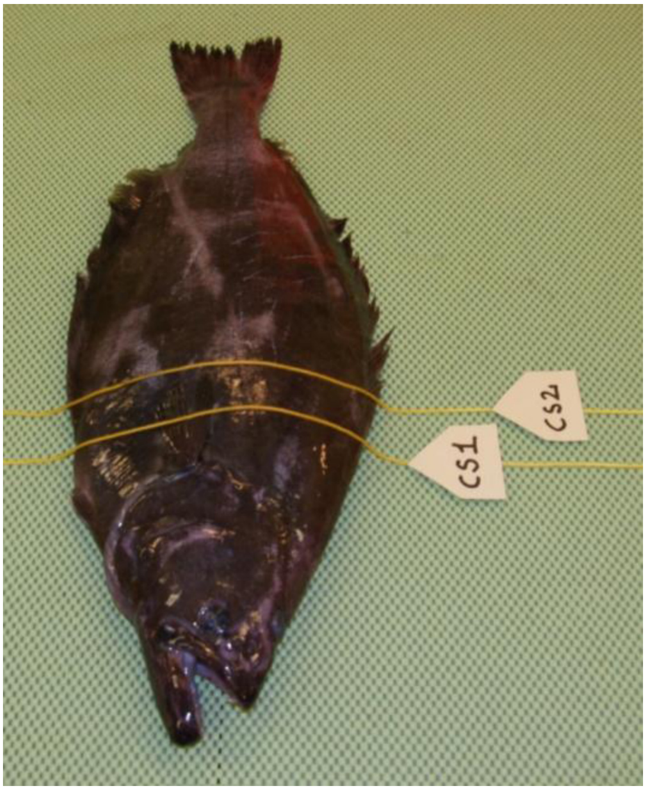

Fig. 3. Position of the cross-sections measured for all Greenland halibut included in the study.

where we considered the orders $m \leq 3$. Leaving out one or more of the parameters v_0 to v_3 led to 15 additional models that needed to be considered as potential models for the size selection of Greenland halibut in the grids. The traditional *logit* model is a special case of (3) where $m = 1$. When estimating the uncertainty of the size selection, we took the uncertainty related to model selection (Katsanevakis, 2006) into account by incorporating automatic model selection into each of the bootstrap iterations carried out in the estimation procedure.

To estimate the traditional selectivity parameters L50 and SR, we used a numerical method implemented in SELNET, as we could not derive analytical expressions for them based on formulas (2) and (3). We used the definition for L50 as the length at which $r_{av}(l,\boldsymbol{v}) = 0.5$ (50% likelihood of being retained). We used the obtained values for the parameter vector $\boldsymbol{v} = (v_0 \ldots v_3)$ and numerically solved $r_{av}(l,\boldsymbol{v}) = 0.5$. The length l that fulfilled this condition then was set equal to L50. We used a similar approach for SR, defined as the difference between L75 and L25.

2.4. The FISHSELECT methodology

A short description of the methodology is given in the introduction (see Herrmann et al., 2009 for further information). The FISHSELECT method can be divided into four main steps (Sections 2.4.2–2.4.5) that enable size selectivity predictions to be made (Section 2.5).

2.4.1. FISHSELECT data collection

The data necessary to run the FISHSELECT methodology were collected onboard the "R/V Jan Mayen" (63.8 m length overall and 4080 HP) from 1 to 10 December 2008 off the coast of Troms and Finnmark (north of Norway). The fishing operations were conducted using a bottom trawl normally used for this type of fishery in the Barents Sea. During the cruise we had constant access to newly harvested fish, which were not subjected to dehydration, rigor mortis, or other similar processes that could affect fish morphology. It is very important that the data included in the FISHSELECT measurements are representative for the conditions of live fish. The aim of FISHSELECT is to predict the size selective properties of different selective devices. Therefore, it is convenient that the sample of Greenland halibuts selected for the FISHSELECT measurements covers the largest possible size range. The fish included in the study were handpicked from the trawl catch. Apart from the condition of the fish, the only other selection criterion was the need to cover the widest possible size range of Greenland halibut.

2.4.2. FISHSELECT step 1: morphological data

The first step in the FISHSELECT methodology involves measuring the total length of the fish and its morphology at different cross sections (CSs). CSs were chosen based on earlier experiences as the positions likely to determine if a fish will be able to escape through meshes or grids of different sizes and shapes. The position and number of CSs considered adequate vary between species. For Greenland halibut, we chose two CSs: a transversal section of the fish starting from the papilla at the highest point (CS1) and a transversal section at the widest point of the fish (CS2) (Fig. 3). A morphometer specially constructed for this study allowed us to measure flatfish up to 40 cm wide and 8 cm high. The morphometer consists of an aluminum frame and 164 measuring aluminum sticks (2.5 mm wide) that can be shifted vertically and fixed at a desirable position (Fig. 4).

The shape formed in the morphometer of the Greenland halibut CS (Fig. 4) was afterwards converted into a digital image using a flatbed scanner and digitized using the image analysis tools

Fig. 4. (a)–(c) Illustrate the use of the morphometer to register the shape of each fish in each cross-section.

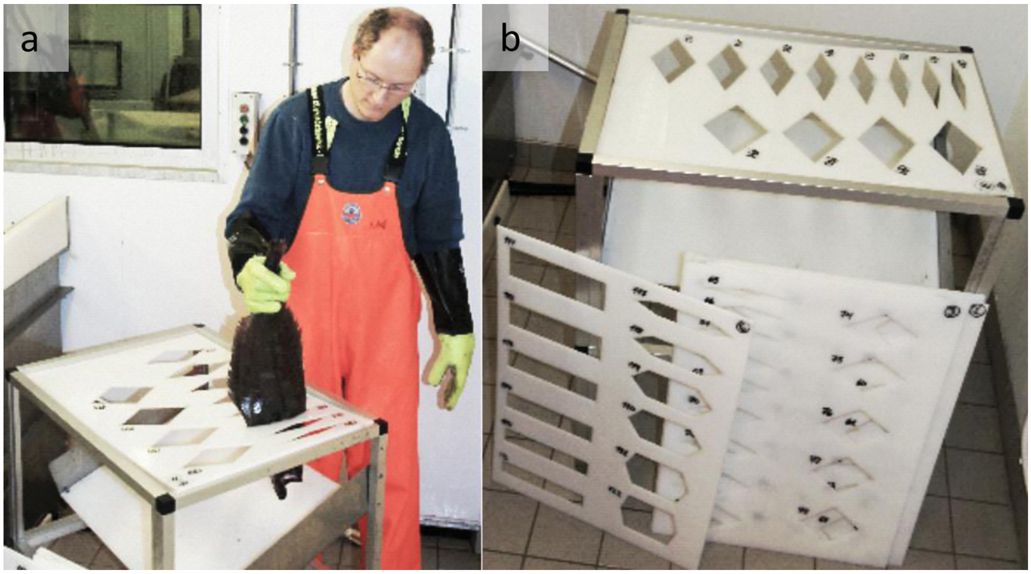

Fig. 5. (a) The fall-through experiments and (b) some of the plates with different mesh sizes and shapes used during the exercise.

implemented in the FISHSELECT software tool (see Herrmann et al., 2009 on details of this procedure).

2.4.3. FISHSELECT step 2: fall-through experiments

Fall-through experiments are used to determine if a fish can physically pass through a certain rigid shape (pressed by the force of gravity). One hundred fish were each tested for 191 different shapes built in 5 mm thick solid nylon plates (see Herrmann et al., 2009 for further information) (Fig. 5). The shapes tested included diamonds, hexagons, and rectangles that respectively varied from 280 to 840 mm, 240 to 800 mm, and 240 to 2000 mm in circumference.

2.4.4. FISHSELECT step 3: cross-section modeling

The CS shapes registered with the morphometer were modeled for further analysis in FISHSELECT. Four different shapes were tested for each CS as candidates to model the shapes of Greenland halibut: half ellipse, symmetric trapezoid, asymmetric trapezoid, and flex hill (Fig. 6a–d; Appendix). Each of the models was tested on each of the two CSs registered for each fish and the model with the lowest AIC (Akaike, 1974) was chosen for further analysis in FISHSELECT. The parameters defining the CSs were related to the individual's length, which in turn facilitated the production of virtual populations with defined CSs.

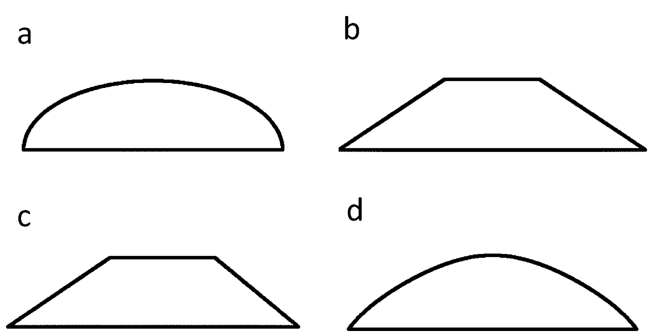

Fig. 6. The four different shapes tested to describe the Greenland halibut cross-section: (a) half ellipse, (b) symmetric trapezoid, (c) asymmetric trapezoid, and (d) flex hill.

2.4.5. FISHSELECT step 4: search for penetration model

We simulated the penetration of each of the modeled CSs of each of the 100 fish included in the sample through the 191 different shapes included in the fall-through trials. As fish can be compressed both dorsoventral and lateral, different compression models were tested for each CS in order to establish an optimal penetration model for Greenland halibut. A new family of models, used for the first time in this study, was tested on Greenland halibut. These models take into consideration that flatfish are deformable around the dorsal fin and anal fin. In these models, the width was first cut off when the height was below a specific fraction α of the maximum height, followed by an overall reduction in height to fraction β of the original height (Fig. 7). Different models of this type were simulated for CS1 and CS2 individually (using free pass for the other). For every combination where α and β individually varied between 0.5 and 1.0 in steps of 0.1, a penetration model was constructed. This resulted in $51 \times 51 = 2601$ penetration models for each cross-section individually. Besides inspecting the performance of the models based on each of the CSs, models based on the combination of CS1 and CS2 ($2601 \times 2601 = 6{,}765{,}201$ models) were tested against the experimental fall-through results.

The penetration results obtained from these simulations were compared with the fall-through results (Section 2.4.2), and maximization of the degree of agreement (DA) between simulated and experimental fall through results was then used to choose an optimal penetration model (see Herrmann et al., 2009; Sistiaga et al., 2011 for the mathematical expression and further information about DA).

2.5. Simulation-based predictions and comparisons to sea trial results

2.5.1. Simulation-based predictions of size selectivity

Given virtual populations with the desired population structure and defined CSs and a defined penetration model, the size selective properties of a range of mesh shapes and sizes can be predicted in FISHSELECT by simulation. The virtual populations used had 2000 individuals uniformly distributed between 5 and 110 cm. The outcome of the method consists of L50 and SR estimations for all of the included mesh sizes, shapes, and opening angles (OAs).

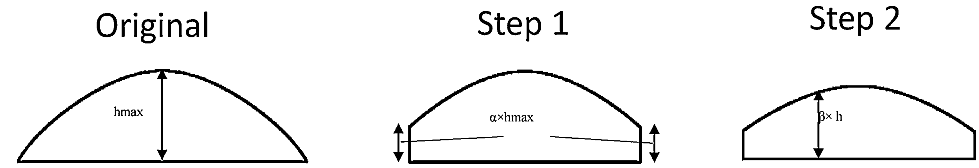

Fig. 7. The two-step compression model used to search for the optimal penetration model for Greenland halibut.

2.5.2. Prediction of codend size selection and comparison to historical sea trial results

Sistiaga et al. (2011) demonstrated that the mesh shapes in the knotted codends normally used in the gadoid fishery are better described as a hexagonal rather than a perfect diamond shape. Because these codends are normally the ones used to fish Greenland halibut in the North Atlantic, we assumed that the shape of the meshes in the codends historically used to harvest Greenland halibut is well described as hexagonal. Sistiaga et al. (2011) also estimated that the parameter K in a hexagonal mesh constructed with an 8 mm twine is 27.2 mm (Fig. 8), and this value was used for the codend mesh selectivity predictions made in this study.

Herrmann et al. (2007) stated that mesh OAs between 30° and 60° are realistic for diamond meshes depending on catch size in the codend during fishing. Based on underwater recordings, Sistiaga et al. (2011) also concluded that OAs in this range are realistic for diamond mesh codends used in the Barents Sea gadoid fishery (Fig. 8). Based on the findings in these two studies, we assumed an OA of between 30° and 60° to compare the historical diamond mesh size selectivity results obtained for Greenland halibut with the predictions estimated from FISHSELECT in this study. Thus, we estimated the selectivity parameters for hexagonal meshes with a fixed K value of 27.2 mm for meshes between 100 and 200 mm in mesh size and OAs between 30° and 60°.

In addition to the calculations carried out to compare the simulation results with the historical data, a design guide (DG) (see Herrmann et al., 2009) that shows the L50 predictions for Greenland halibut captured with diamond mesh codends (hexagonal meshes; K = 27.2 mm) was created. This DG covers the predictions for meshes from 100 to 200 mm in mesh size with OAs from 0° to 180°.

2.5.3. Prediction of grid size selection and comparison to historical and new sea trial results

The FISHSELECT models for mesh size selection can be applied to make predictions about the size selective potential for grids with different bar spacing. This is done by using the penetration model and the virtual Greenland halibut population applied for codend size selection (see Section 2.4.5) and applying a list of rectangular meshes. Thus, the potential size selection for each of the listed rectangular meshes represents the potential size selection of grids with different bar spacing. Following this approach, we simulated the size selective potential for Greenland halibut of grids with bar spacing between 15 and 70 mm in steps of 5 mm The results obtained were compared to historical sea trial results and results from the cruises carried out onboard the “M/V Hopen” and “M/V Ramoen”.

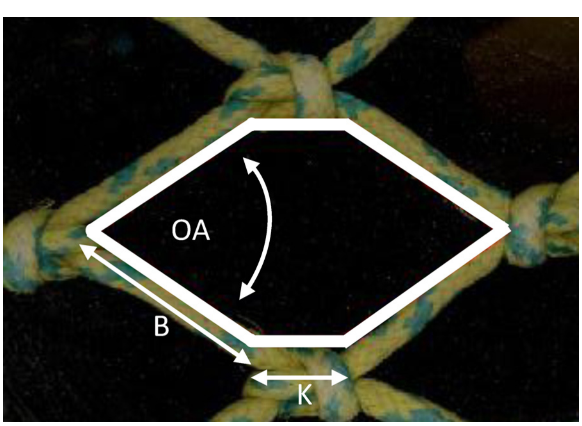

Fig. 8. The shape of the meshes in the codends normally used in the Barents Sea codfish (Gadidae) fishery (Sistiaga et al., 2011). The lengths of K and B and the OA define the shape of the mesh.

2.5.4. The importance of θ on the potential escapement through sorting grids

In previous studies carried out using FISHSELECT to predict size selection through a codend, it was assumed that a fish will have multiple chances to escape, especially when it swims just ahead of the catch built up in the codend. Therefore, earlier FISHSELECT analyses assumed that each fish is optimally orientated when attempting to pass through the codend meshes. However, this assumption is not necessarily valid when predicting the size selectivity of grids (such as the Sort-X and the Sort-V) placed in the extension piece ahead of the codend. For such systems, Greenland halibut likely have limited time in the area from which escapement through the grid is possible, and therefore the number of escapement attempts will be limited. Thus, it could be expected that the θ for the fish with the grid could vary from fish to fish and that the fish on average would not be able to attack the grid at an optimal orientation (Fig. 9). If this is the case, the standard FISHSELECT approach would overestimate the size selective potential of the grids because the simulations assume that all fish are optimally orientated when they seek escapement through the grid.

To investigate the potential effect of the fish not being optimally oriented relative to the grid, the FISHSELECT software tool was further developed to enable simulation of the size selectivity for different fixed values of θ. We used this facility to predict the size selection for θ between 0° and 90° in steps of 5° for grids with bar spacing between 15 and 70 mm in steps by 5 mm. To investigate whether there is any experimental evidence sub-optimal θ for the Sort-X and the Sort-V grids (see Fig. 1b and c), we plotted the FISHSELECT predictions against the historical grid selection results and the experimental results from the trial data analyzed in this study.

2.5.5. Predicting frequency of θ values for the data collected onboard the “M/V Hopen” and “M/V Ramoen”

Using experimental retention values for L05–L95 (length of fish with retention likelihood between 5% and 95%) obtained from the two cruises and the simulation function in FISHSELECT, we investigated the extent to which we could explain the experimentally obtained size selection curves assuming that Greenland halibuts were seeking escape through the grid with different θ (including the assumption that some did not come into contact with the grid). The procedure estimated the size selection data for a virtual population of Greenland halibut corresponding to the data collected on each cruise and assuming that the fish that hit the grid do so at different θs (angles 0°, 5°, 10°, 15°, . . ., 80°, 85°, 90°, no contact with the grid). A function was developed in FISHSELECT to provide the relative contributions of the different θ that would best be able to reproduce the experimentally obtained selection curves based on

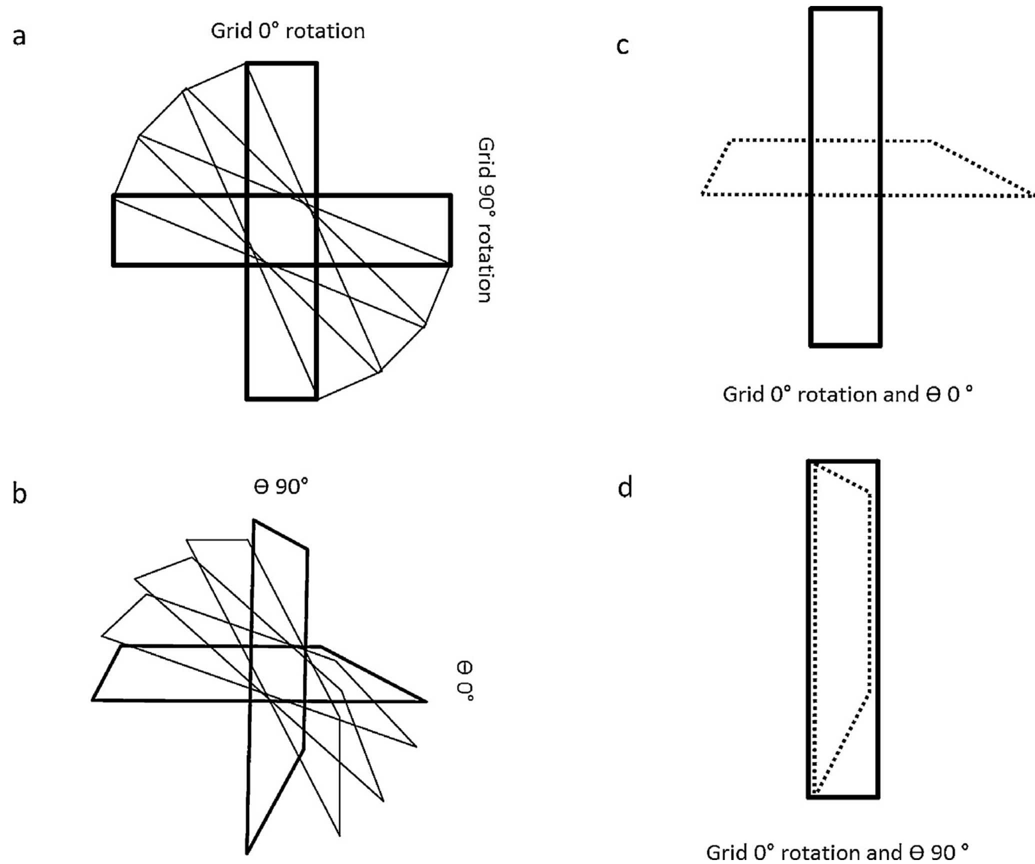

Fig. 9. The influence of θ on the potential for escape. Panel (a) shows different grid rotation. Panel (b) shows different fish orientations. Panels (c) and (d) show the difference in escapement possibility for a flatfish (represented as an asymmetric trapezoid cross-section) swimming in its horizontal swimming position and a 90° orientated position, respectively.

L05–L95. This involved estimation of the relative contributions of 20 θs plus one for no contact, hence estimating the most likely 21 parameter combination and representing the predicted frequency of each. To do this we used an optimization method implemented in FISHSELECT, which is based on the Powell algorithm (Press et al., 1992). This method requires a penalty function to minimize. We used the following formula (4):

$$f(w_0, \ldots, w_{90}, w_{none}) = \sqrt{\sum_i (L_i - LF(w_0, \ldots, w_{90}, w_{none})_i)^2},$$

$$i \in \{5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95\} \quad (4)$$

where $w_0, \ldots, w_{90}$ are the frequencies of the different θ values; w_{none} represents the frequency for no grid contact; L_i are the experimentally obtained retentions lengths; and LF_i are the parallel FISHSELECT results obtained based on the specific contributions of the different values for θ and for the fish that do not contact the grid. The *LF* values are estimated automatically in FISHSELECT using a nonparametric method as part of the algorithm, from the resulting selection data, and by combining the FISHSELECT selection data for each of the θ values with the frequencies based on the values of the 21 parameters estimated.

2.5.6. Use of established frequencies for θs to predict grid size selection

Using FISHSELECT, we explored the extent to which we could explain the experimental grid size selectivity results shown in Table 2 based on the frequencies for θs established from the experimental results from the cruises onboard the "M/V Hopen" and "M/V Ramoen". This was done by simulating selection data for bar spacing between 15 and 70 mm with different θs, generating combined selection data based on the relative contributions for the different θs from the estimated frequencies from the cruises, and finally estimating the size selection for each of the bar spacings.

3. Results

3.1. Greenland halibut morphology and penetration model

The selectivity results estimated in FISHSELECT are based on the morphological characteristics of 100 Greenland halibut. All individuals ranged between 33 and 73 cm in total length and were approximately evenly distributed between these limits.

3.1.1. Cross-section shape

The analysis of the CS shapes obtained from the morphometer showed, according to the procedure outlined in Section 2.4.4, that for CS1 the asymmetric trapezoid was the model that best fit the registered shapes (AIC = 916.28; Table 3), whereas for CS2 the flex hill shape resulted in the lowest AIC value (AIC = 899.23) (Fig. 10). The choice of these two models was supported by high R^2 values (0.988 and 0.992, respectively).

The asymmetric trapezoid chosen to represent CS1 is a four parameter model (C1, C2, C3, and C4), whereas the flex hill shape chosen to represent CS2 can be defined with three parameters (C1, C2, and C3) (see Appendix). The relationship between these parameters and fish length was used to generate virtual fish populations.

Table 3
R^2 and AIC values for the four shapes tested on CS1 and CS2.

Model	CS1		CS2	
	R^2	AIC	R^2	AIC
Half ellipse	0.960	1167.440	0.967	1226.060
Symmetric trapezoid	0.978	1064.990	0.989	993.020
Asymmetric trapezoid	0.988	916.280	0.993	915.790
Flex hill shape	0.983	981.630	0.992	899.230

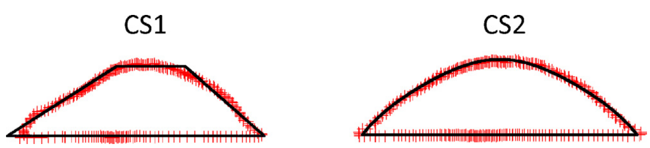

Fig. 10. Fit of an asymmetric trapezoid and a flex hill shape to the CS1 and CS2 (red crosses) of a Greenland halibut randomly picked from the FISHSELECT trials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

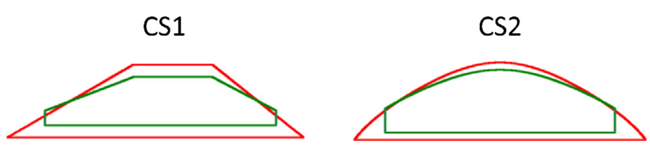

Fig. 11. Shape of the optimal penetration model overlapped on the original shape modeled from the morphometer.

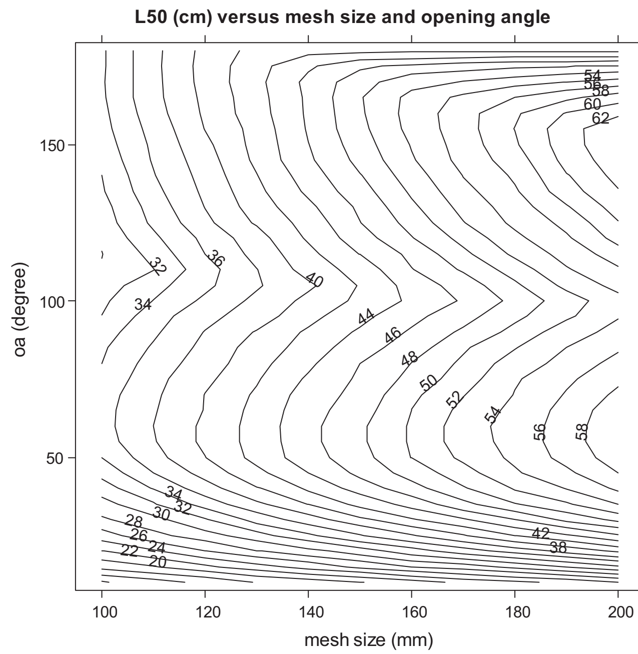

Fig. 12. Design guide showing the variation in L50 for Greenland halibut with varying mesh size and OA for hexagonal meshes (with a fixed K at 27.2 mm).

The parameter values for the regression models (C1–C4 for CS1 and C1–C3 for CS2) are shown in Table 4.

3.1.2. Choice of penetration model

Comparison of the penetration model results obtained from the FISHSELECT simulations with the empirical fall-through results resulted in a maximal DA value of 96.76% when considering CS1 only (see Section 2.4.5. for explaining the DA value). When only CS2 was considered, a maximum DA value of 97.57% was achieved. Combining both CS models led to the model with the highest DA value of 97.75%. While the combined model added complexity to the analysis, the gain in DA justified the use of this model.

The penetration model applied for CS1 implied cutting of lateral sections from the points at which the height of the fish was lower than 30% ($\alpha = 0.3$) of the maximum height of the fish at that CS, followed by a downscaling in height to 66% ($\beta = 0.66$) of the original height of the fish (Fig. 11). The same process was applied to CS2, but in this case the lateral cuts were made at the point at which the height of the fish was lower than 38% ($\alpha = 0.38$) and the following downscaling was to 81% ($\beta = 0.81$) of the original height of the fish.

3.2. Codend size selection

The design guide (DG) created from the estimations in FISHSELECT shows that L50 is very dependent on the OA of hexagonal meshes, especially for OAs between 0° and 50° (Fig. 12). Considering that codends have been observed to have OAs of between 30° and 60° when operating (Herrmann et al., 2007; Sistiaga et al., 2011), adjustments that can influence the OA of the codend, even just by a few degrees, can have a considerable effect on the size selectivity of the codend.

To test how well the FISHSELECT estimations fit with the historical data collected for Greenland halibut using diamond mesh (hexagonal) codends (Table 1), we plotted L50 values for the historical data together with predictions based on FISHSELECT for OAs at 30°, 40°, and 60°. The results show that apart from four data points that are just above the range estimated in FISHSELECT, the remainder of the historical selectivity results for Greenland halibut fall well within the L50 range estimated for OAs of 30–60° for the species in FISHSELECT (Fig. 13).

3.3. Grid size selection

The grid selectivity data collected onboard the “M/V Ramoen” and “M/V Hopen” are restricted to fish above 30 cm because fish below this size were not abundant in the trial areas. The grids employed in the cruises onboard both vessels had the same bar spacing (55 mm). However, the selectivity results for the cruises onboard the two vessels differed substantially, especially for the L50 values. The confidence intervals reflect significant differences between both cruises for this parameter (Table 5). The SR values estimated for both cruises also seem to differ (with approximately 6.2 cm), but this difference is not significant since the confidence intervals for this parameter overlap (Table 5). The p-value of the fit statistics for the “M/V Hopen” data shows that we cannot rule

Table 4
Relationship between the four parameters used to define CS1 (asymmetric trapezoid) and the three parameters used to define CS2 (flex hill) with fish length.

	CS1: asymmetric trapezoid				CS2: flex hill		
	C1 vs. length	C2 vs. length	C3 vs. length	C4 vs. length	C1 vs. length	C2 vs. length	C3 vs. length
a	0.019	0.065	0.001	0.010	0.061	0.019	0.388
SD a	0.001	0.004	0.000	0.002	0.003	0.001	0.086
b	1.220	1.250	1.680	1.400	1.150	1.230	0.600
R^2	0.937	0.949	0.687	0.633	0.948	0.947	0.197

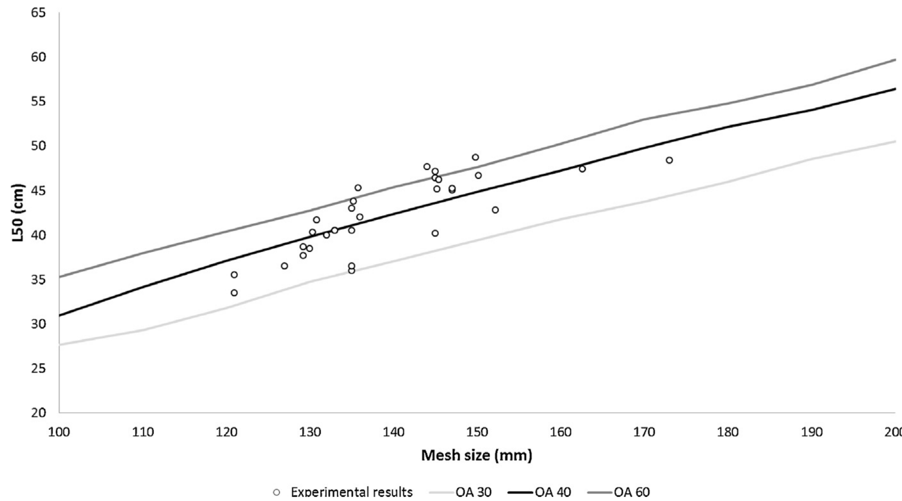

Fig. 13. Historical data for Greenland halibut codend selectivity (Table 1) plotted together with FISHSELECT estimations for OA values of 30°, 40°, and 60°.

Table 5
Greenland halibut mean selectivity parameters for grids (55 mm) for the cruises carried out onboard the "M/V Hopen" and "M/V Ramoen". Confidence intervals are given in ( ). See Eqs. (2) and (3) for explaining parameters V_0–V_3.

	"M/V Hopen"	"M/V Ramoen"
L50	46.28 (42.08–55.61)	62.48 (59.03–66.54)
SR	18.47 (13.60–24.78)	25.55(20.29–55.22)
V_0	−39.36 (−89.67 to −1.90)	−10.82 (−24.24 to 0.96)
V_1	20.46 (0.00–50.85)	5.02 (−1.35 to 12.26)
V_2	−3.60 (−9.64 to 0.17)	−0.93 (−2.22 to 0.22)
V_3	0.22 (−001 to 0.61)	0.06 (0.00–0.14)
Dof	40	61
Deviance	54.730	109.100
p-Value	0.060	0.002

out the possibility that the discrepancy found between the model and the data is a coincidence. Conversely, a first inspection of the fit statistics for the "M/V Ramoen" data shows that the chosen model is not acceptable ($p = 0.002$). However, further investigation shows that there is no structure in the residuals. Hence, we can regard the discrepancy between the model and the data as a simple case of overdispersion.

The size selective properties of the fishing gear used during the two cruises differ significantly for length classes from approximately 48–77 cm, and the confidence limits do not overlap in this range (Fig. 14). This size range covers approximately half of the Greenland halibut population (i.e., the bigger fish) available during the two cruises, implying that the bigger fish were selected significantly differently during the two cruises.

The curves from both cruises look very different from the traditional *logit* curve. The experimental retention data for both datasets were better described by the flexible model described by Eqs. (2) and (3), which is implemented in SELNET. This curve was therefore applied to model the experimental data using automatic model selection between the 16 different models belonging to this family of models. The size selection for both experimental data sets is much poorer than what would be expected based on FISHSELECT if every fish seeks escapement through the 55 mm grid with an optimal θ (light gray curve in Fig. 14). This result indicates that a substantial proportion of the fish entering the grid section does not contact the grid at all or at least does not contact it with a θ that would maximize their chances of escape.

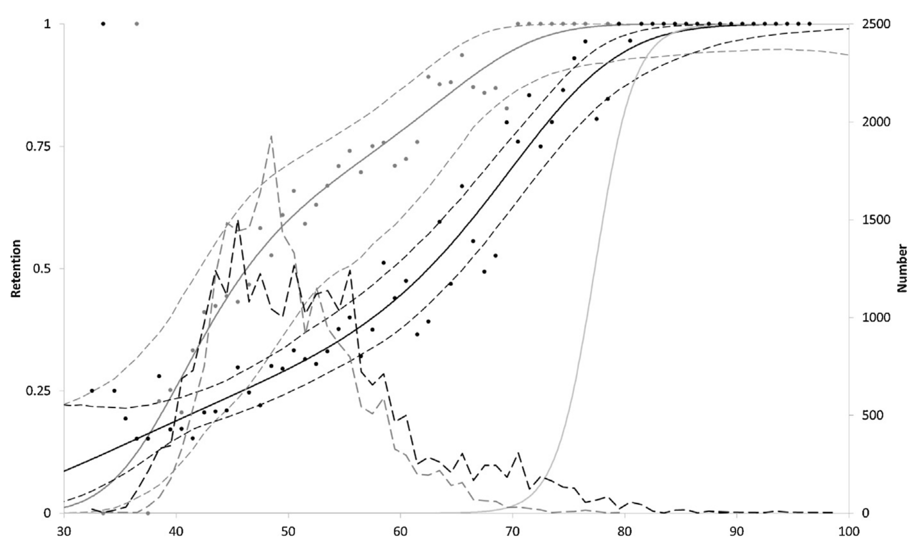

Fig. 14. Size distribution of fish in the fishing area, retention points, and mean selection curves with confidence intervals for the cruises carried out onboard the "M/V Hopen" (gray curve) and "M/V Ramoen" (black curve). The light gray curve to the right shows the optimal selection curve estimated from FISHSELECT that assumes optimal θ for all individuals.

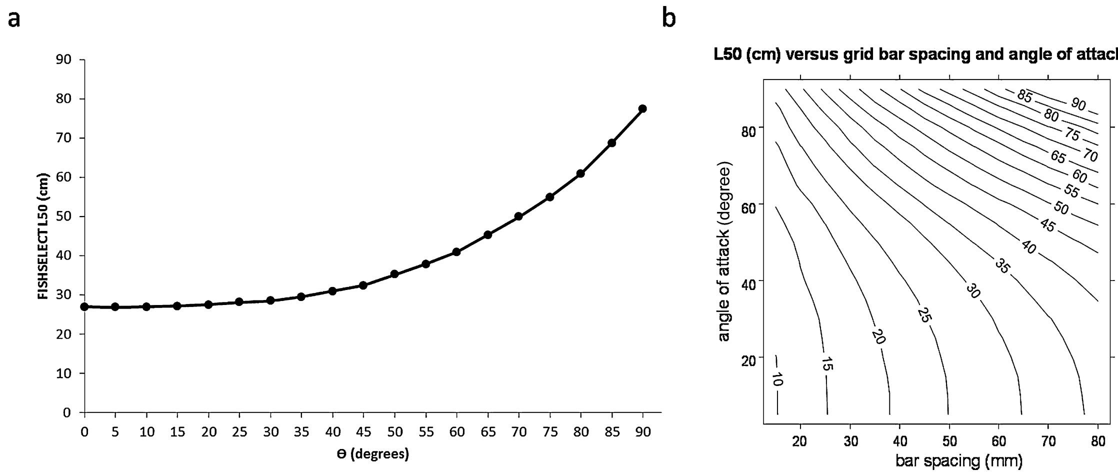

Fig. 15. (a) L50 estimated in FISHSELECT for a 55 mm grid and different θs. (b) The evolution of the iso-L50 lines with varying θ and bar spacing.

3.4. Size selection in grids and the influence of attack angle (θ)

The results estimated in FISHSELECT show that the optimal θ for a Greenland halibut to pass through a grid constructed with vertical bars is 90° (Fig. 15a). This result agrees well with what was expected taking into consideration the anatomical characteristics of flatfish (Fig. 9). L50 increases with increased θ from 0° to 90°. Hence, the closer the rotation angle is to 90° relative to the grid, the higher the chances for a given fish to pass through. The results indicate a progressive increase in L50 with increasing angle. The L50 value increases little as θ increases from 0° to 45–50°, whereas it increases much faster as θ increases from 45–50° to 90°.

Fig. 15b shows how the predicted L50 values depend on grid bar spacing (*x*-axis) and θ (*y*-axis).

3.4.1. Predicting frequency of θs for the "M/V Hopen" and "M/V Ramoen" data

Using the simulation tools in the FISHSELECT software, which include the possibility of specifying the contribution of different θs to a selection curve, we tried to reproduce the experimental data curve obtained for the trials onboard the "M/V Hopen" and "M/V Ramoen". The results of these simulations indicate that it is indeed possible to reproduce a size selection curve that looks reasonably similar to the experimentally obtained results (Fig. 16). Thus, we can assume that the contribution of the different θs represents a potential explanation for the shape of the experimental curves obtained for the "M/V Hopen" and "M/V Ramoen" data.

The results from the FISHSELECT simulations show that it is possible to reproduce the size selection curves obtained during the sea trials with fair precision. Therefore, we assumed that we would be able to use the estimated frequencies for θ values as the relative occurrence of the different θs during the two experimental fishing trials. In this manner, the estimated occurrences would explain the difference in size selectivity observed between the cruises in terms of differences in the relative occurrences of the different θs. The results obtained indicate that a higher proportion of the fish collected during the cruise onboard the "M/V Hopen" had a $\theta > 45°$ relative to the grid compared to the fish collected during the "M/V Ramoen" cruise (Table 6). However, only about 3% of the "M/V Hopen" fish were estimated to meet the grid optimally orientated ($\theta = 90°$), and nearly no fish met the grid with an angle less than 45°, as nearly 99% of the cumulative frequency had a θ between 45° and 90°. During this cruise, only about 1% of the fish was estimated to not contact the grid. The results from the cruise onboard the "M/V Ramoen" indicate that almost 4% of the Greenland halibut did not meet the grid at all. However, during this cruise over 90% of the fish had a θ greater than 45°, and it was estimated that 21% of the fish met the grid with the optimal 90° angle.

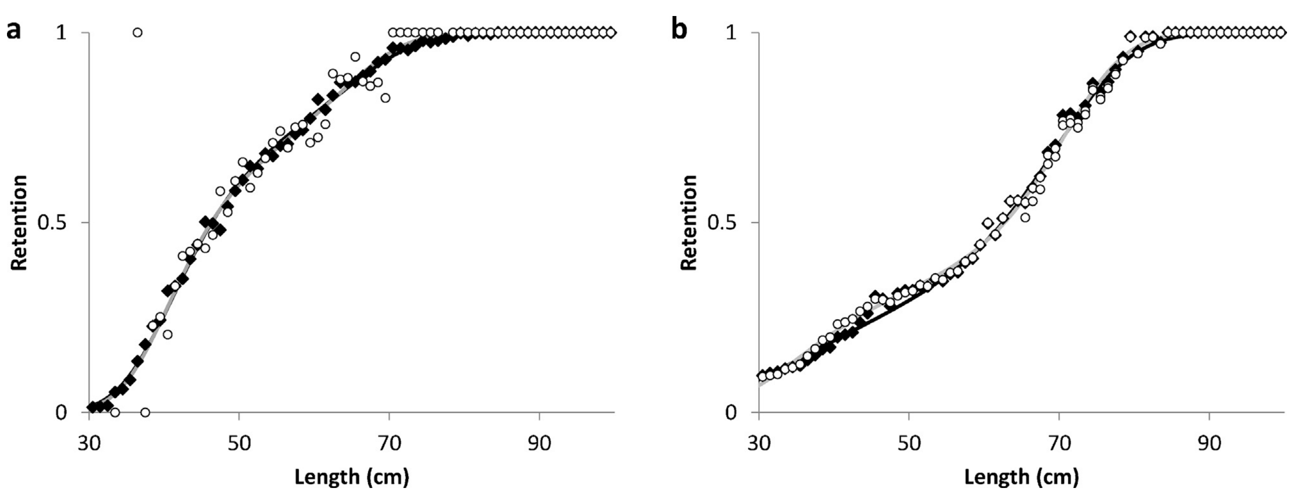

Fig. 16. Selection curves estimated in SELNET for the cruises carried out onboard the (a) "M/V Hopen" and (b) "M/V Ramoen" (black diamonds and lines) and the corresponding curves simulated in FISHSELECT for each of the trials based on the contribution estimated for each θ (white circles and gray line, respectively).

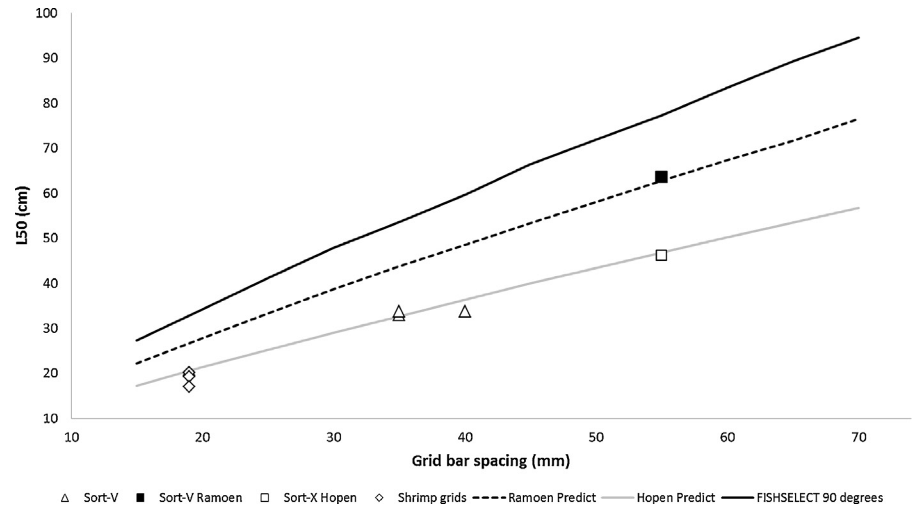

Fig. 17. Selectivity predictions with optimal θ (90° for Greenland halibut, Fig. 9), θ frequencies from the cruise onboard the "M/V Hopen", and θ frequencies from the cruise onboard the "M/V Ramoen". The white diamonds and triangles represent Greenland halibut historical L50 values obtained from various selectivity trials (see Table 2). The squares represent the average L50 values obtained during the cruises onboard the "M/V Ramoen" (black) and "M/V Hopen" (white).

3.4.2. Prediction of grid size selection based on experimentally obtained θ frequencies and comparison with historical results

A comparison of the results obtained in FISHSELECT (where the size selectivity of the fish is predicted based on only a θ value of 90° (i.e., all with optimal θ)) with the historical results obtained with grids for Greenland halibut (Table 2) and the cruises onboard "M/V Ramoen" and "M/V Hopen" shows that in all cases, the sea trial results were below the FISHSELECT 90° estimations (Fig. 17). This indicates that during all of these cruises, a proportion of the Greenland halibut entering the grid section either did not contact the grid or contacted it at a sub-optimal angle. The bigger the distance between the line representing the FISHSELECT results and the sea trial results, the further the θ has been from the optimal (this includes the possibility that no grid contact occurred).

Based on θ frequencies estimated for the size selectivity curves obtained from the cruises onboard the "M/V Ramoen" and "M/V Hopen", FISHSELECT estimations were performed for grid bar spacing between 15° and 70°. This was done by first simulating selection data for bar spacing between 15 and 70 mm under different θ values and then generating combined selection data based on the relative contributions of the different θs using the estimated frequencies from the "M/V Ramoen" and "M/V Hopen" data, respectively, and estimating the resulting size selection for each bar spacing. The results obtained were then compared to the historical sea trial results and the FISHSELECT optimal estimations (Fig. 17).

The FISHSELECT predictions based on the "M/V Hopen" data are in fairly good agreement with historical grid results, but the results for the "M/V Ramoen" data clearly deviate from the rest of the results.

Table 6
Frequency and cumulative frequency for θ in steps of 5° for the experiments carried out onboard the "M/V Hopen" and "M/V Ramoen".

θ (°)	"M/V Hopen"		"M/V Ramoen"	
	Freq.	Cum. freq.	Freq.	Cum. freq.
90	3.15	3.15	21.092	21.09
85	9.80	12.95	23.623	44.72
80	13.33	26.28	15.342	60.06
75	8.01	34.29	7.158	67.22
70	13.62	47.90	2.251	69.47
65	13.63	61.53	4.496	73.96
60	13.02	74.55	5.413	79.38
55	12.34	86.89	6.493	85.87
50	10.50	97.39	3.559	89.43
45	1.50	98.89	0.82	90.25
40	0.02	98.91	0.736	90.98
35	0.01	98.92	0.024	91.01
30	0.00	98.92	0.01	91.02
25	0.00	98.93	0.00	91.02
20	0.01	98.93	0.002	91.02
15	0.00	98.93	0.01	91.03
10	0.00	98.93	0.061	91.09
5	0.01	98.94	0.451	91.54
0	0.05	98.99	4.523	96.06
No contact	1.01		3.935	

4. Discussion

As expected, the results obtained from the application of FISHSELECT to Greenland halibut and the comparison of these with results from earlier studies conducted on roundfish show that the morphological differences between flatfish and roundfish are considerable. Earlier studies of cod and haddock (e.g., Herrmann et al., 2009; Sistiaga et al., 2011) showed that an ellipse is a good shape to describe the cross-sections of this type of fish. In contrast, trapezoid like shapes, best fit the cross-sections of Greenland halibut. The penetration models applied in this study also differ substantially from the penetration models applied in earlier FISHSELECT-based studies that focused on roundfish. The fins and the soft tissue along the sides of the flatfish caused us to apply a model with a lateral cut (Section 2.4.5). This is likely also relevant for other flatfish species. The high DA values obtained from the analysis prove that the penetration models applied in this study adequately describe Greenland halibut. The differences in the cross-section shapes and penetration models applied to Greenland halibut and roundfish demonstrate the need to evaluate the properties of size selection devices separately for flatfish and roundfish. The present study is the first in which the morphology of a flatfish was analyzed in FISHSELECT in order to evaluate its size selective properties.

The FISHSELECT mesh (codend) selectivity results obtained for Greenland halibut in this study fit well with the historical results obtained for diamond mesh codends for this species. Most earlier results fell between the FISHSELECT prediction lines for different mesh sizes with OAs of 30° and 60°, which supports the estimations for codend mesh OAs while fishing (Herrmann et al., 2007; Sistiaga et al., 2011). Further, considering that the FISHSELECT predictions are based on hexagonal meshes with a fixed knot size of 27.2 mm and that the historical results fit the predictions well, the assumptions of a 27.2 mm knot size seems to be adequate. This knot size was estimated by Sistiaga et al. (2011) for meshes constructed with 8 mm twine. The normal alternative to this construction for Greenland halibut fisheries is a 4 mm double twine construction, which would have a similar knot size (Herrmann et al., 2012).

The fact that the historical codend selectivity data fit well with the FISHSELECT estimations demonstrates the value and relevance of creating a DG for Greenland halibut codend selection, which can be used to estimate size selective properties of diamond mesh codends (modeled by hexagonal shapes) for Greenland halibut. As reflected in the available published studies (Tables 1 and 2), research on the size selectivity of Greenland halibut in towed fishing gears has been focused more on codend selectivity than on grid selectivity (Figs. 13 and 17). In this study, we performed selectivity analysis of two sea trials carried out using a Sort-X grid and a Sort-V grid, respectively. Although these grid designs are quite different (Fig. 1), they nevertheless have similar size selective properties for cod and haddock (Isaksen et al., 1996, 1998). However, our analysis of the data from these two trials suggests significant differences in the size selective properties for Greenland halibut between these grid types (i.e., no overlap of the CI of the curves between 48 and 77 cm; Fig. 14). This significant difference contrasts with the good agreement between earlier results obtained with different types of grids, which in turn also agree with the FISHSELECT predictions based on the Sort-X grid and the "M/V Hopen" cruise data (Fig. 17).

There is no obvious explanation for the disagreement between the results obtained from the cruise onboard the "M/V Ramoen" and the results obtained on the rest of the cruises with different grids (Table 2 and cruise onboard "M/V Hopen"). However, this difference may be related to the different θs of Greenland halibut when encountering these two grids during these two cruises. The fact that the selection curves obtained from both cruises had high SR values and do not look like the more traditional *logit* curves most often used in selectivity analysis support the hypothesis that the fish may not have contacted the grid with an adequate θ.

None of the studies that have specifically studied Greenland halibut grid size selectivity have quantified the effect of θ of the fish towards the grid. Using simulation tools in FISHSELECT specifically developed for this purpose, we successfully reproduced and later analyzed the selection curves obtained from the cruises onboard the "M/V Hopen" and "M/V Ramoen". We identified which angles of attack and which proportion of fish not contacting the grid could lead to the selection curves obtained from the analysis of the cruise data. For the first time we demonstrated and analyzed how differences in θ can create considerable differences in the selective properties of a gear. Further, we demonstrated that the differences in the selectivity parameters found between the cruise onboard the "M/V Hopen" and "M/V Ramoen" can potentially be explained solely by the fact that the fish in the "M/V Ramoen" experiment on average were more optimally oriented when seeking escapement through the grid. The results of this study indicate that poor contact is not the only reason for Greenland halibut having a poorer selection than that predicted by FISHSELECT for optimal θ (Fig. 17). On the one hand, the results indicate that only 1.01% and 3.94% of the Greenland halibut were unable to contact the grid for all of the cruises conducted onboard the "M/V Hopen" and "M/V Ramoen", respectively (Table 6).

This proportion of fish not contacting the grids is unlikely to produce the difference observed between the FISHSELECT results and the selection results obtained from the cruise. On the other hand, we observed that the selectivity results obtained from the shrimp trawl studies (data for bar spacing 19 mm in Table 2 and Fig. 17) also fell well below the FISHSELECT optimal values. Due to the design and selection principle of the shrimp grid sections used in the North Atlantic (e.g., Grimaldo and Larsen, 2005), all Greenland halibut in this type of grid contact the grid. Therefore, the most likely explanation for the difference between the FISHSELECT predictions and the cruise-based results is the poor θ of the fish when contacting the grid.

Differences in θ can be created by many factors, such as different towing speeds (which allow more or less time for the fish to attempt an escape), the mounting of a lifting panel, and densities of fish entering the grid section. Many of these factors are not easy to control at sea and can affect the ability of the fish to contact the grid or to turn enough to actually have a good chance to escape through the grid. Our results indicate that the chances that a fish can escape through the grid increase drastically for each 5° the fish can turn after it has first turned 45° (Fig. 15). If the conditions inside the grid section are such that the fish has a limited turning capacity (i.e., it can only turn between 0° and 45°), its chance of escape is limited.

Considering the characteristics of the grids used in the North Atlantic today (e.g., these grids are composed of vertical bars), the ability of Greenland halibut to turn determines their chance of escape. Greenland halibut can swim up in the water column and are able to swim vertically (i.e., rotated 90° relative to the most natural swimming orientation of flatfishes) (Huse et al., 1999). However, when the swimming performance needs to be maximized and the fish swims in bursts, as the fish would do inside a trawl net, Greenland halibut swim with the ventral part of the body towards the seabed (as is most natural for flatfish) (Albert et al., 2003).

The results of this study show the importance of considering the θ of fish when evaluating the size selectivity properties of a device. If a sorting grid provides unsatisfactory size selection, it is important to identify why the device is not working properly in order to improve its performance. There can be different reasons for poor grid performance, such as inadequate bar spacing, a low contact rate between the fish and the grid, and fish not contacting the grid at an adequate θ.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2013.04.004.

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