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Fixed mesh shape reduces variability in codend size selection

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Abstract

Diamond-mesh codends are the most commonly used in demersal trawls. However, mesh geometry tends to vary in these codends during fishing, which leads to a less well-defined size selection process. This leaves one questioning the rationality of regulating exploitation patterns based on mesh size when size selection and/or variation between hauls is highly variable. While it has been speculated and theoretically investigated how much the variability in mesh geometry may contribute to the variability in size selection, it remained to be quantified experimentally. Therefore, we conducted field test comparing the size selectivity of a simple diamond-mesh codend, where meshes are subjected to variation in geometry, with a rigid diamond-mesh codend, where the geometry of the meshes were kept constant. For Atlantic cod (*Gadus morhua*) the simple diamond-mesh codend was found to have 45% more variation in size selection than the codend with fixed mesh geometry. This confirms theoretical predictions and may guide research towards codend designs with more well-defined size selection properties.

Keywords: Size Selection, Variability, Codend, Diamond-mesh, Mesh geometry

Introduction

Selectivity in towed gears as defined by Wileman et al. (1996) is *"the probability of a fish of a given species and size being retained by a gear once it has encountered it".* The majority of the selection process occurs in the codend, i.e., the end of the trawl where the catch accumulates (Wileman et al. 1996). Diamond-mesh codends are the most widely applied designs and have traditionally been used in the majority of demersal trawl fisheries due to their simple structure and ease of operation (He, 2007; Wienbeck et al. 2011; Sistiaga et al. 2021). However, multiple studies have shown that diamond-mesh codends do not maintain a constant mesh openness while trawling, due to their flexibility (e.g., Robertson and Stewart, 1988; Reeves et al. 1992; Herrmann, 2005). As the catch accumulates the openness of the meshes along the length of the codend becomes more heterogeneous, whereby meshes close to the catch build-up zone become more open and meshes further forward in the codend become more elongated (i.e., closed) (e.g., Jones, 1963; Herrmann, 2005; Herrmann and O'Neill, 2005). Since codend size selectivity is largely determined by the openness of the meshes (Jones, 1963; Herrmann et al. 2009), the variations in the openness occurring during the catching process have been associated to the variation of the size selection properties of the codend either at haul level (Herrmann, 2005) or between-hauls (Fryer, 1991; Herrmann and O'Neill, 2005). This applies especially to roundfish, which have a better chance of escaping when the opening angle (OA) is closer to 90° (e.g., Atlantic cod (*Gadus morhua*); Herrmann et al. 2009).

Codend size selection is often described by a sigmoid selection curve as a function of length of the fish (Wileman et al. 1996). The desired selection curve would have a knife-edged shape with the critical length at the point above which all fish are retained, and below which all fish are released. However, this is rarely the case as there are several factors (e.g., towing speed, and weight of the catch) that determine whether individuals escape (Roda et al. 2019). A measure for the sharpness of the size selection is the selection range (SR). The selection range is the difference in length between fish with a 75% probability of retention (L75) and the length of fish with a 25% probability of retention (L25) (Wileman et al. 1996). Herrmann (2005) and Herrmann and O'Neill (2005) theorized that variations in the geometry of diamond meshes that result from catch accumulation, impacts the SR obtained. Therefore, if the hypothesis arising from these theoretical studies is true, the more variation in mesh geometry, the larger the SR. Conversely, with more constant mesh openness during fishing, the sharper the resulting selection curve will be.

From a management point of view a knife-edged shape selection curve that corresponds to the minimum landing size is desired since it ensures unwanted catches are limited and economic yields are maximized (Andersen, 2019). However, this is rarely the case for fisheries whose exploitation patterns are defined by the size selectivity of diamond-mesh codends, probably due to the variability in mesh geometry impacting on the SR of the codend. Therefore, the geometric variability of codend meshes challenges the management of the exploited fish stocks, as the selection becomes less sharp (i.e., the retention of undersized, and the loss of legal sized individuals is greater). As a result of the suboptimal size selection by the codend alone, some fisheries have supplemented this with additional selective devices to achieve a sharper selection curve such as the grid systems 'Flexigrid' commonly used in the Barents Sea demersal trawl fishery or square mesh panels like BACOMA used in Baltic Sea (Sistiaga et al. 2010 and Wienbeck et al. 2014). However, a better approach could be to stabilize the selection process in the codend, thus avoiding the need for additional selection devices as they often require more handling and increase the cost (Sistiaga et al. 2021).

The benefit of stabilizing mesh OA has been speculated on theoretically in the past (e.g., Herrmann, 2005), but has never been tested experimentally. In this study we aimed at quantifying experimentally the effect of OA variability on the sharpness of codend size selection. Therefore, we developed and tested a rigid codend structure, that allowed the mesh OA to be kept constant. This experimental codend was tested in the Baltic Sea and size-selectivity data were collected for cod (*Gadus morhua*). For the first time, to our knowledge, the assumption was tested for proof of concept at sea.

Materials and methods

2.1 Fishing gears

The covered codend method according to Wilemann et al. (1996) was applied. A TV300/60 bottom trawl was used, in conjunction with two Thyboron Type 2 (1.78 m^2) trawl doors and 100 m sweeps. A rigid steel frame was constructed with the dimensions 2 x 0.75 x 0.75 m (length, width and height, respectively; 1.125 m^3). The length of the frame was kept short to make handling easier. The frame was made using square profile pipes of 40 mm x 40 mm x 4 mm steel (height x width x thickness). The four rectangular surfaces were covered with a 5 mm euroline single twine diamond mesh netting of fixed opening angles. The desired 40° opening angle was achieved by attaching the netting with a specific hanging ratio and controlled with an angle measure. The angle of 40° was chosen as it is in the middle of the normal range of the opening angles in a standard flexible codend (Herrmann et al. 2009). Twenty meshes were randomly chosen for each panel from photographs and the OA was estimated after the fishing trials using the software FISHSELECT (Herrmann et al. 2009). Specifically, individual meshes were digitized and a diamond shape model was fitted to obtain values for OA by use of image analysis facilities in the FISHSELECT software. The closing end of the codend and the 4-meter extension piece (measured as stretch length) ahead of the frame were constructed out of diamond meshes with a nominal mesh size of 50 mm to ensure that the selection process would only occur through the larger meshes mounted on the sides of the rigid codend. Therefore, the total length of the extension piece and the rigid codend was 6 m. The frame was lifted by six floats attached to the longitudinal upper bars of the frame to make sure it was free from the seabed and the codend cover (Figure 1). This codend will from this point forward be denoted as "*fixed mesh codend*".

Figure 1. Picture of the rigid frame with the fixed meshes (Fixed mesh codend).

The standard diamond mesh codend (hereafter referred to as the "*flexible mesh codend*") was made of two panels with a circumference of 86 open meshes. The mesh sizes in the codends were measured using an OMEGA-gauge with 125 N stretching force for 20 meshes (dry conditions). The mesh size of the fixed mesh codend, measured in the aft end where there were some loose meshes, was 111.5 mm ±2.14 mm (mean ± standard deviation). The mesh size of the flexible mesh codend was 112.4 mm ± 2.72 mm (mean ± standard deviation). The cover (cc) was made of single 2.5 mm-PE twine with a nominal mesh size of 55 mm. It had a stretched length of ~16 m (2.6 x the length of the extension piece and rigid codend combined) and a diameter of ~3 m. To prevent the cover from masking the selectivity of the codend, a total of seven kites were attached to the cover. Five kites were attached to the forward section and the remaining two were attached to each side of the cover.

2.2 Experimental fishing and data collection

The experimental fishing trials were conducted in the Baltic Sea onboard the German *FRV Solea* (42.40 m LOA, 1780 kW), during the 16^{th} to the 27^{th} of September 2021. The experimental hauls conducted were spatially distributed across German and Danish fishing grounds between ICES Subdivisions 22 and 25. The experimental codends were tested one at a time for a number of hauls. Individuals escaping from the experimental codends (cd) were collected using a cover surrounding the entire codend (Wienbeck et al. 2011, 2014). The catches obtained at haul level were treated for each compartment separately. The fish retained in the codend and the escapees in the cover were kept separate and sampled one after another. The total length of all cod individuals were measured and rounded down to the centimeter below using measuring boards.

2.3 Estimation of codend selectivity

The size selection data obtained by each of the experimental codends was analyzed using the methodology described in Wileman et al. (1996). With this methodology, it is assumed that (a) the proportion of the fish retained in the codend is determined by the ability of the fish to pass through the codend meshes, and (b), that such ability is determined mostly by the morphology and size of the fish, and the geometry and size of the meshes. These basic assumptions allow modeling the codend retention probability *r(l)* by simple mathematical functions with parametric structures leading to non-decreasing, s-shaped selectivity curve asymptotically restricted to values between [0.0, 1.0] (Wileman et al. 1996). The *logistic*, *probit*, *gompertz*, and *Richards* selectivity models were considered as candidates:

$$r(l,\boldsymbol{v}) = \begin{cases} logistic(l, L50, SR) = \dfrac{exp(\frac{ln\,(9)}{SR} \times\ (l - \text{L50}\,))}{1.0 +\ exp(\frac{ln\,(9)}{SR}\ \times\ (l - \text{L50}))} \\ Probit(l,\text{L50},SR) \approx \Phi\left(\frac{1.349}{SR} \times (l - \text{L50})\right) \\ Gompertz(l,\text{L50},SR) \approx\ \exp\left(\ -\exp\left(\ -\left(0.3665 +\ \frac{1.573}{SR} \times (l - \text{L50})\right)\right)\right) \\ Richards(l,\ \text{L50},SR,\delta) = \left(\dfrac{exp\left(Logit(0.5^{\delta}) +\ \left(\frac{Logit(0.75^{\delta}) -\ Logit(0.25^{\delta})}{SR}\right)(l -\ \text{L50}\right)}{1.0 + exp\left(Logit(0.5^{\delta}) +\ \left(\frac{Logit(0.75^{\delta}) -\ Logit(0.25^{\delta})}{SR}\right)(l -\ \text{L50}\right)}\right)^{1/\delta} \\ where \\ Logit(r) = ln\left(\frac{r}{1.0 - r}\right) \end{cases}$$

(1)

The term Φ in the probit function refers to the cumulative distribution function of a standard normal distribution. $\boldsymbol{v}$ = (L50, SR) are the parameters that control the shape of the selection curve. Note that the *Richards* model involves an additional parameter δ which adds flexibility to the selection curve. The expected number of fish retained in the codend (ncd_l) and the number of escapees collected in the cover codend (ncc_l) can be directly related to the total number of fish entering the codend n_l and the selection curve:

$$\begin{aligned} ncd_l &= n_l \times r(l,\boldsymbol{v}) \\ ncc_l &= n_l \times (1.0 - r(l,\boldsymbol{v})) \end{aligned} \qquad (2)$$

Under the assumption that the retained and escaped fractions are determined by the size selection of the codend, the selection curves described in Eq. 1 and associated selectivity parameters can be estimated via Maximum Likelihood, by minimizing the negative of the log-likelihood function derived from the binomial probability mass function:

$$LogLik = -\sum_{i=1}^{m}\sum_{l}\{ncd_{il} \times ln(r(l,\boldsymbol{v})) + ncc_{il} \times ln(1.0 - r(l,\boldsymbol{v}))\} \qquad (3)$$

The log-likelihood function (Eq. 3) include a summation over hauls $h \in \{i=1,\dots,m\}$, with ncd_{il} and ncc_{il} being the number of cod sampled in haul *i* belonging to length class *l*. Thus, assuming that the *m* hauls were randomly drawn from all possible hauls that could be conducted, Eq. 3 returns an estimate of the population-average selectivity properties of the codend tested.
The four models described in Eq. 1 were estimated and ranked by AIC (Akaike, 1974), and the model with lowest AIC was picked for further analysis.

To account for potential variability within and between hauls of the size-selection process, we used the double bootstrap method (Efron, 1979; Millar, 1993; Sistiaga et al. 2010) as follows:

a) Based on the observed hauls, $H = h_{i=1},\dots,h_m$, a random sample of hauls $H^* = h_{i=1^*},\dots,h_{m^*}$ is generated by non-parametric resampling. In other words, after selecting haul *i*, this is replaced in the original sample so that it can be resampled. This outer resampling scheme emulates the between-haul variation in the size selectivity data.
b) A second, inner resampling scheme is applied to the length distribution of the measured fish, separately for each haul drawn in Step (a) and within the haul. For cover-codend data, this step generates bootstrap distributions of lengths of measured fish in the codend (ncd^*_{il}) and cover ($ncc^*_{il,}$) by resampling the data in each length class independently. Once this step is concluded, a new sample $H^{**} = h_{i=1^{**}},\dots,h_{m^{**}}$ is generated from the original data.
c) Selectivity estimates from the bootstrap data generated in the two previous steps are obtained using Maximum Likelihood (Eq. 3), resulting in a selectivity curve $r^*(l, \boldsymbol{v}^*)$ *and* associated parameters $\boldsymbol{v}^* = (L50^*, SR^*, (\delta^*))$.
d) Steps (a)–(c) *B* are repeated B=10.000 times, so that a bootstrap population of selectivity curves $r^{*b}(l)$, and associated selectivity parameters ($L50^{*b}$, $SR^{*b}(\delta^{*b})$) are generated ($b=1,\dots,B$).

The distributions of the average selectivity curve and associated parameters estimated in Equation 3 are approximated by the histogram based on the population of size *B* generated in Step (d), from which 95% confidence intervals are obtained using the percentile method (Efron, 1979).

2.4 Evaluation of differences in selectivity among tested codends

Assuming that the variation in the geometry of the codend meshes is a major contributor for the variability of the size selection of the codend and that such variability is reflected on the value of the SR (Herrmann, 2005, Herrmann and O'Neill 2005), then the average SR value estimated by pooling the *m* hauls conducted with a given codend should contain the variation of the size selection caused by mesh geometry variations occurring at haul level and across hauls (Fryer 1991; Herrmann and O'Neill 2005). Thus, the larger the SR the larger the combined within-and-between haul variability and the reduced steepness of the selection curve. By testing the selective properties of a simple diamond mesh codend with flexible meshes and an experimental codend with the geometry of the meshes fixed, the contribution of geometric mesh variation to selectivity variability is quantified by the following statistics:

$$\Delta SR[cm] = (SR_{D2} - SR_{D1})$$

$$\Delta SR[\%] = 100 \times \frac{(SR_{D2} - SR_{D1})}{SR_{D1}} \qquad (5)$$

Where SR_{D2} is the selection range estimated for the flexible mesh codend and SR_{D1} is the selection range estimated for the fixed mesh codend and used as baseline. Therefore, ΔSR quantifies the contribution of the mesh geometric variability in absolute (cm) and percentage (%) terms. A value of $\Delta SR \sim 0$ would imply that the variation in selectivity obtained experimentally could not related to the flexible nature of the codend meshes. Conversely, the larger the value of ΔSR the larger the contribution of geometric mesh variation to the overall selectivity variation. To assess if the value of ΔSR is significantly different from zero (either in absolute or percentage terms), the 95% confidence intervals are estimated from a bootstrap distribution of ΔSR derived from the previously estimated bootstrap distributions for SR_{D1} and SR_{D2} (Larsen et al. 2018; Herrmann et al. 2018). Thus, significant differences would be found when the 95% confidence intervals around ΔSR do not overlap the value associated to the null hypothesis H_o: $\Delta SR = 0.0$. This procedure is equivalent to methodologies often applied to assess differences between selectivity and catch comparison curves (Herrmann et al. 2018; Larsen et al. 2018; Melli et al. 2020).

Results

3.1. Description of fishing operations and catches

A total of 55 hauls were conducted of which 32 hauls were made with the fixed mesh codend and 23 hauls with the flexible mesh codend. Of these, 27 hauls (12 and 15 for the fixed mesh codend and flexible mesh codend, respectively) were considered valid and used in the statistical analysis, as they contained more than 20 cod in total (Table 1). The depth varied between 19 and 46 m and the haul duration varied between 20 and 60 min (Table 1).

Table 1. Overview of the operational data from each haul used in the analysis. *Denotes missing values

Trawl configuration	**Date and time (yyyy/mm/dd hh:mm UTC)**	**Towing time (min)**	**Depth (m)**	**Towing speed (kt)**	**Number of cod**		**Total catch cd (kg)**
					ncd	ncc	
Fixed mesh codend	2021/09/19 06:43	20	18	4	12	12	24.09
	2021/09/19 12:08	35	18	4	20	9	15.18
	2021/09/20 05:35	35	18	4	19	11	34.84
	2021/09/20 07:04	60	21	3	5	56	124.46
	2021/09/20 10:09	45	18	4	12	8	48.00
	2021/09/20 11:21	50	18	4	13	12	78.50
	2021/09/20 12:36	50	19	4	102	22	104.81
	2021/09/28 05:35	40	18	4	12	41	161.95
	2021/09/28 07:14	60	17	4	1	19	48.73
	2021/09/28 10:10	50	18	4	8	21	133.44
	2021/09/29 04:56	50	19	4	8	177	78.06
	2021/09/29 06:10	50	18	4	7	43	*
Flexible mesh codend	2021/09/21 05:35	50	20	4	4	25	210.05
	2021/09/21 07:08	50	22	4	5	16	170.87
	2021/09/21 10:10	50	19	4	4	57	117.8
	2021/09/21 11:36	50	18	4	20	29	98.96
	2021/09/22 12:02	30	19	4	0	26	108.23
	2021/09/25 13:16	20	33	4	0	20	108.13
	2021/09/25 14:11	20	40	4	10	36	254.18
	2021/09/26 05:33	20	18	4	9	31	69.61
	2021/09/26 06:23	40	20	5	0	43	123.26
	2021/09/26 10:10	50	22	4	4	40	318.93
	2021/09/26 12:06	50	20	4	4	32	190.04
	2021/09/27 05:34	50	26	4	8	18	199.65
	2021/09/27 07:19	50	19	3	4	22	311.07
	2021/09/27 10:10	50	23	4	2	73	153.81
	2021/09/27 11:23	50	18	4	7	17	163.97

The number of cod used in the analysis and the length range represented in the data for the fixed mesh codend and flexible mesh codend, respectively, is shown in Table 2.

Table 2. Overview of the number of cod caught in the codend and the cover and in total used in the analysis for the fixed mesh codend and flexible mesh codend respectively.

	Number of cod			**Length Range (cm)**	
	cd	cc	Total	cd	cc
Fixed mesh codend	219	431	650	9 - 48	9 - 33
Flexible mesh codend	81	485	566	9 - 57	8 - 44

The OA for the fixed mesh codend was estimated to 39.1° with a standard deviation of 2.4°. The OA varied from 32.7° to 45.5°.

3.2 Covered codend analysis

The logistic model described in Eq. 1 was fitted to the data for both codends (Figure 2) as this resulted in the lowest AIC value in both cases (Table 3). The fit statistics are reported in Table 4. The SR was found to be 8.75 cm and 6.04 cm for the flexible mesh codend and the fixed mesh codend respectively (Figure 3). The cumulative probability is shown in Figure 4 for the SR in percentage. Eq. 5 was used to calculate the difference in SR at 2.7 cm or 44.8 % (Table 5). Thereby, 44.8 % more variation in the size selection was found in the flexible mesh codend compared to the fixed mesh codend. The L50 was larger for the flexible mesh codend than the fixed mesh codend (27.79cm and 23.42cm, respectively).

Table 3. Overview of the AIC values for flexible mesh and fixed mesh codend respectively. The lowest AIC value is marked in bold

	AIC value	
	Fixed mesh codend	Flexible mesh codend
Logistic	**290.50**	**273.14**
Probit	293.25	274.95
Gompertz	296.45	275.87
Richards	290.71	274.11

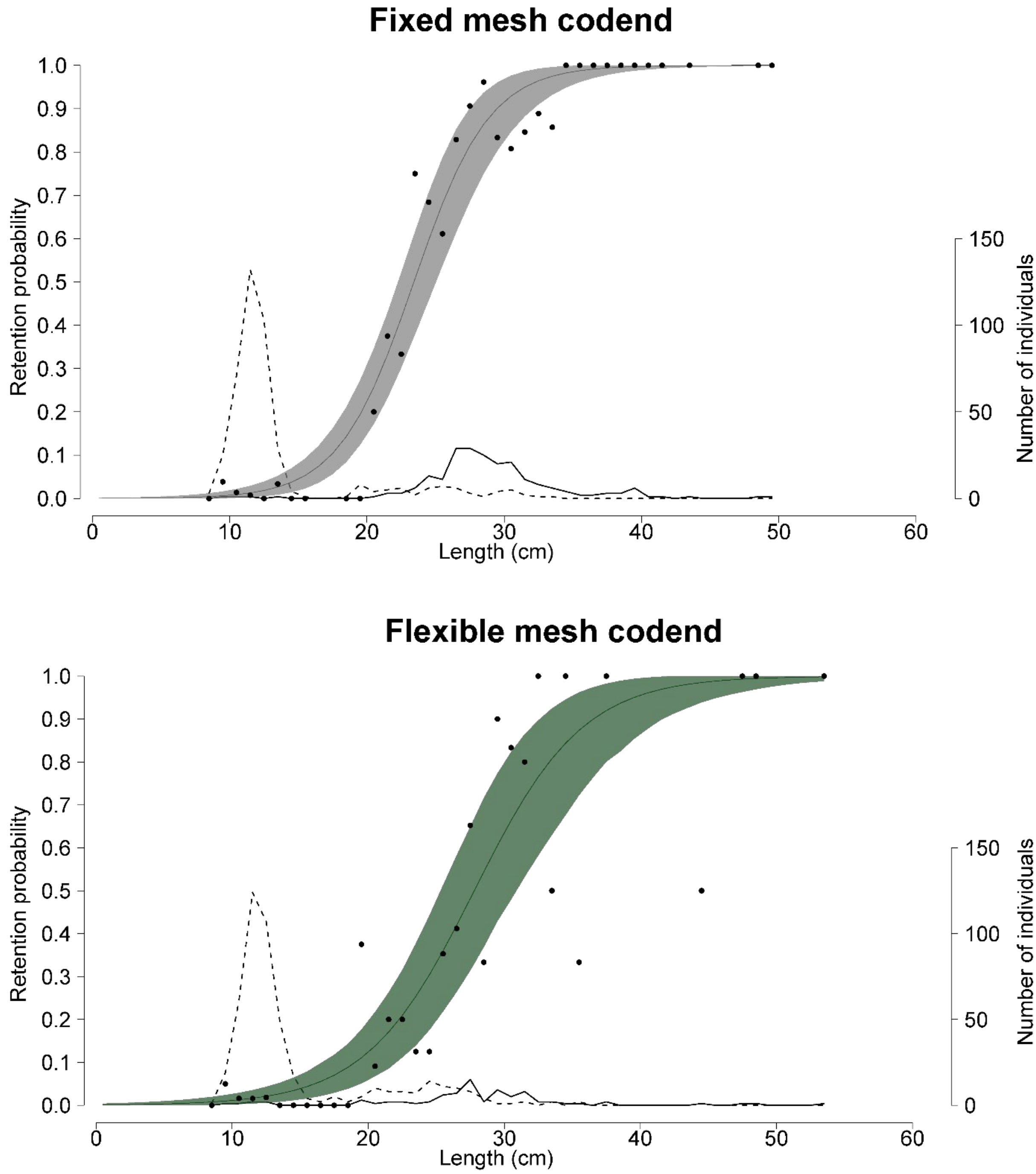

Figure 2. Length-dependent probabilities of escape in the fixed mesh and flexible mesh codend respectively. The solid curves represent the models fitted to the data (points) with the 95% CIs (shaded area). The frequency curves represent the number of fish caught in each length class in the codend (solid) and cover (dashed).

Table 4. Fit statistics obtained from the covered codend analysis showing the L50 and SR for the two different trawl configurations tested. Values in parentheses represent 95% CI's. The fit statistics in terms of the p-value, deviance, and DOF.

	Flexible mesh codend	**Fixed mesh codend**

L50 (cm)	27.79 (25.21-30.70)	23.42(22.30-25.07)
SR (cm)	8.75 (6.80-11.62)	6.04(4.74-7.48)
P-value	0.17	0.58
Deviance	38.56	30.82
DOF	31	33

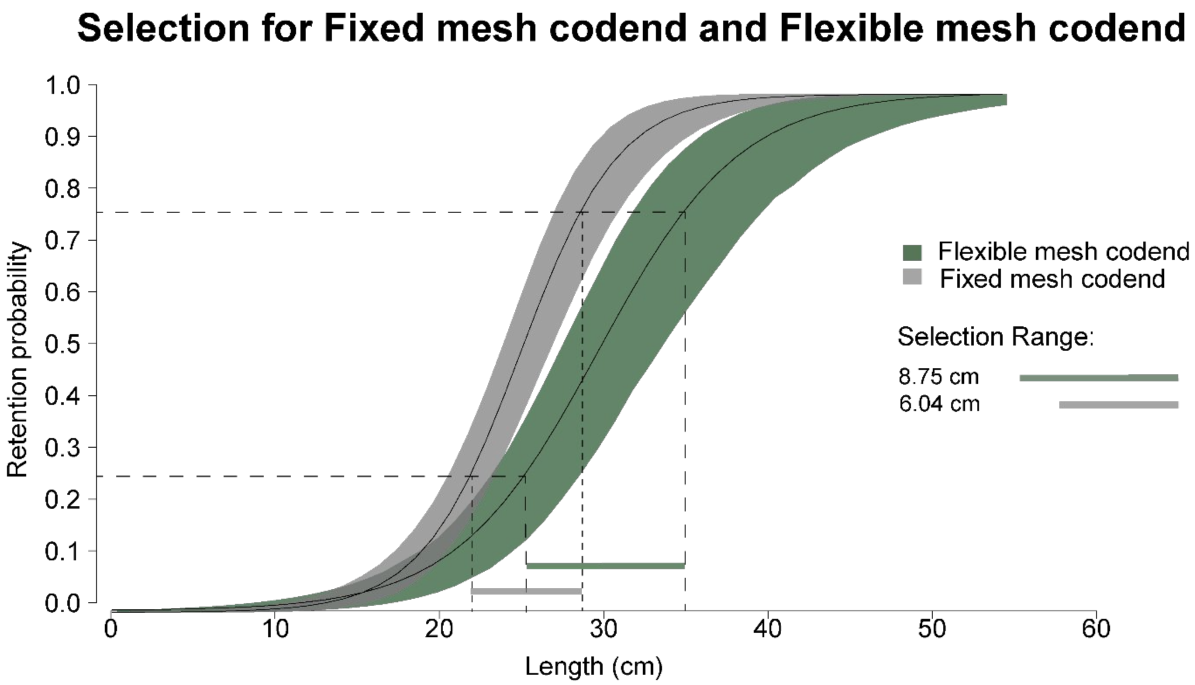

Figure 3. Comparison of the estimated length-dependent probabilities of retention for the two codend configurations tested. Dashed lines denote the selection range with results shown in the right side of the figure. Shaded areas represent the 95% CIs.

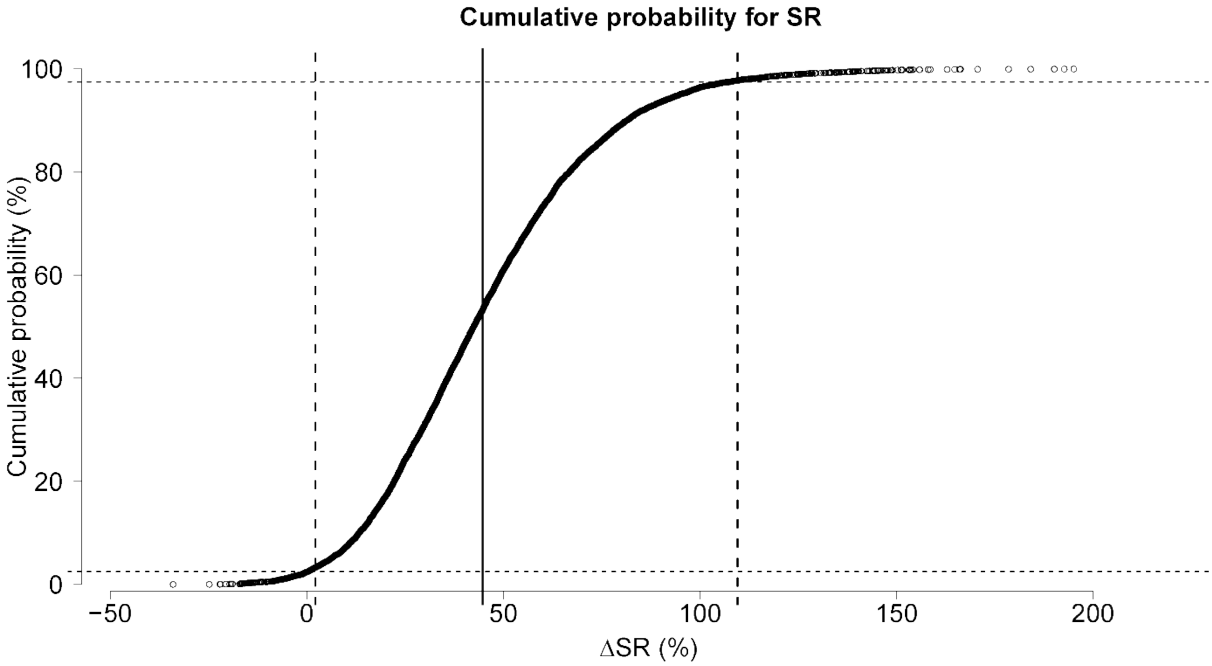

Figure 4. Comparison of the SR for the two tested configurations in percentage. Vertical stippled lines represent the 95% CIs and the solid line the mean, and the dashed horizontal lines denote the quantile (0.025 and 0.975).

Table 5. Difference in the selection range between the two different codend configurations. Values in parentheses represent 95% CIs.

ΔSR (cm)	2.7 (0.2-5.9)
ΔSR (%)	44.8 (2.2-109.6)

Discussion

We developed and tested a construction that ensured mesh openness remained constant, making it possible to quantify how much variation in mesh geometry influences the ability for fish to escape. This was, to our knowledge, the first time this has been experimentally tested. Our results show that the flexible mesh codend had a much higher variation when compared to the fixed mesh codend. It is important to notice that, while the rigid frame allowed us to successfully demonstrate the effect of mesh openness variation on SR for diamond mesh codend, it is not a commercially or practically viable design.

Due to the manufacturing process, i.e., variation in mesh size, it was not possible to keep the OA completely uniform, as it varied between individual meshes from 32.7° to 45.5°. With the OA still subjected to variation, it might be possible to further reduce the SR if the OA can be kept completely constant. Furthermore, catch weights were in general small and did not vary considerably. Bigger and more variable catches could be expected to lead to a higher SR for both codends. However, due to that higher catch weights will result in more variation in mesh openness for a flexible mesh codend (Herrmann et al. 2005; Herrmann and O'Neill, 2005), it is expected that SR for this codend is more affected by catch weight than the fixed mesh codend consequently resulting in a bigger difference in SR between the two codends with increase in catch weights. Therefore, our estimate of the differences in SR between the two codends is likely at the lower limit. With larger catches, the setup might reach operational challenges as the length of the selective part of the fixed mesh codend would be too short.

The L50 was higher for the flexible mesh codend compared to the fixed mesh codend. However, that was expected as an OA of approximately 40° prevents meshes from reaching maximum stretched openness and thereby the chance for escape for larger fish is less in the fixed mesh codend. With the theoretical estimates of the OA (avg: 39.1°, min: 32.7° and max: 45.5°) and the measured mesh size (avg: 111.5mm, max: 116mm and min: 105mm), the L50 was found to vary from 26 cm to 35 cm according to the design guide presented by Herrmann et al. (2009) (Figure 5).

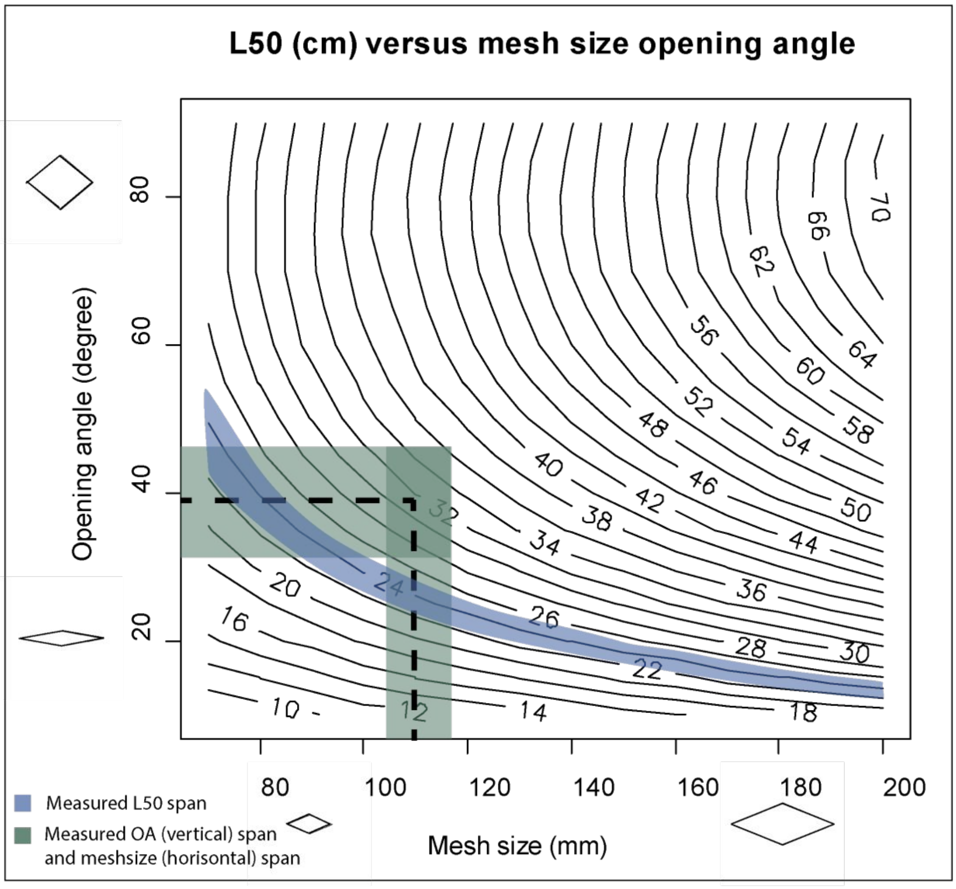

Figure 5. Comparison of the estimated L50 for cod and the design guide represented in Herrmann et al. (2009). The horizontal rectangle represents the interval between the maximum and minimum measured OA from the fixed

mesh codend. The vertical square represents the span between the maximum and minimum mesh size measured on the fixed frame. The overlapping area of the squares represents where the L50 theoretically would be covered. Dashed lines denote the average OA and mesh size. The colored area along the meso lines denotes the span of the measured L50.

The difference between the measured L50 interval between the fixed mesh codend and the calculated mesh opening angle and size was found to align unsatisfactory with the design guide presented by Herrmann et al. (2009) (Figure 5). This could be explained by the way the fish approach and contact the mesh. Mesh penetration has both a mechanical and behavioral component (Glass et al. 1993). Krag et al. (2014) found the contact angle of the individual to the mesh opening and the orientation of it to affect the size selection of Antarctic krill (*Euphausia superba*). The design guide in Figure 5 is based on the fish being orientated optimally for escape and penetrating the mesh perpendicular. However, if the fish contact the mesh at another angle, the mesh will appear smaller and the fish might not be able to escape (Krag et al. 2014; Cuende et al. 2020). Furthermore, the end of the fixed mesh codend is made from a small mesh size that is not permeable for escape, and consequently the likelihood of the fish contacting the mesh opening perpendicularly is, therefore, likely to be less. Cuende et al. (2020) found for blue whiting (*Micromesistius poutassou*) that a non-optimal contact angle and orientation affects the L50 and SR making it lower and higher, respectively. This could indicate that the influence of the constant mesh openness is even higher.

Rather than developing new and more complex gear designs to achieve a sharper selection, our results show that it is possible by simply stabilizing mesh geometry. By testing the influence of variability in OA, we have opened for development towards more rigid codend designs. In contrast to these findings, Vincent et al. (2021) found that deformable meshes may offer greater escape potential than rigid ones. However, despite the escape potential for rigid meshes being less, they offer a more accurate size selection for round fish. Gear specifications that have been found to influence selectivity and subsequently implemented in regulations, such as twine thickness and number of twines, become obsolete with the use of rigid meshes, something that can potentially simplify management regulations. Furthermore, our results open for innovation of new materials and designs, as well as investigation of established approaches such as the flexible grid designs (Lomeli and Wakefield, 2013; Lomeli et al. 2017) that can help maintain a constant escape openness and achieve a sharper size selection.

With more constant mesh openings, fish morphology becomes even more relevant in the selection process. This will be particularly important when dealing with mixed species fisheries, where the mesh shape should account for the retention or escape of multiple shapes and sizes. For the demersal fisheries in the Baltic Sea, the flatfish species are especially important, as the cod stock is at a critically low level (Santos et al. 2022). Therefore, larger mesh opening angles need to be explored as flatfish theoretically would be more likely to be retained by larger mesh openings than roundfish (Herrmann et al. 2013). Furthermore, T90 mesh codends should be investigated for obtaining less variable selection as these codends have previously been indicated to have lower SR values compared to a simple diamond mesh codend due to their assumed higher stability in mesh openness (Wienbeck et al. 2011).

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Competing interests

The authors declare there are no competing interests.

Data availability

Raw data were generated at DTU Aqua. Derived data supporting the findings of this study are available from the corresponding author zitba@aqua.dtu.dk on request.

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