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The capability of square-meshes and fixed-shape meshes to control codend size selection

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ABSTRACT

Trawl codends are commonly made of diamond-mesh netting. However, diamond-mesh codends vary in mesh geometry along its length and during fishing due to catch build up. This introduces variability in the size selection process. This phenomenon compromises the rationality of regulating exploitation patterns in trawl fisheries through adjustments in codend mesh size. One technical solution often applied to achieve more well-defined size selection is turning the codend netting 45 degrees (square-mesh). However, there is a lack of evidence that square-mesh codends result in more constant size selectivity. Therefore, we aimed at quantifying the variability in size selection in square-mesh codends. We tested the size selectivity of three codends; a standard square-mesh codend, and two rigid codends where mesh geometries were fixed in diamond shape with an opening angle of 60° and square shape, respectively. The two rigid codends were used to establish baselines with limited variability in size selection. The size selectivity of these codends was compared to results - previously obtained for a standard diamond-mesh codend. Using Atlantic cod (*Gadus morhua*) as a case study, we demonstrated that the standard square-mesh codend had significantly larger variability in size selection compared to the fixed diamond-mesh codend. Moreover, we found no evidence that the standard square-mesh codend had lower variability in size selection than a standard diamond-mesh codend with same mesh size. These results demonstrate that the use of standard square-mesh codends is not sufficient to reduce variability in codend size selection. Additionally, we demonstrate that the sizes of fish retained is strongly dependent on mesh shape and openness. We conclude that a profound re-thinking over codend designs is required in order to achieve better control of size selection in trawl fisheries.

1. Introduction

Defined as "*the probability of a fish of a given species and size being retained by a gear once it has encountered it*" (Wileman et al., 1996), the selectivity of fishing gears is a keystone in the aim for sustainable fisheries (Vasilakopoulos et al., 2015). In towed fishing gears, the majority of the selection often occurs in the codend (Wileman et al., 1996). Selection across length-classes (size selection) is often described by an s-shaped curve, where the retention probability is described as a function of length. The steepness of this curve is determining the capability of the codend to discriminate fish by size. - Selection Range (SR) is used to measure this steepness and is defined as the difference in length between fish with a 75% probability of being retained (L75) and the length of fish with a 25% probability of being retained (L25). To distinguish between fish sizes retained in the codends the length of a fish with 50% probability to be retained is used. In fisheries managed by a referent size, the ideal size selection curve would be knife-edged (SR=0) and with L50 thereby resulting in the release of all individuals below this size, and the retention of all individuals equal to or above it. The advantage of controlled size selection in commercial fisheries is that it ensures economic yields are maximized and bycatch of undersized fish are minimized (Macher et al., 2008). However, a controlled selection in towed fishing gear is rarely the reality as many factors can affect the selection process and the openness of the meshes, for example towing

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speed and size of the catch (Roda et al., 2019).

Multiple studies have concluded that diamond-mesh codends do not maintain a constant mesh openness during trawling, which can affect the size selection (e.g., Robertson and Stewart, 1988; Reeves et al., 1992; Herrmann, 2005; Bak-Jensen et al., 2022). As the catch accumulates in the codend during fishing, the codend shape becomes bulbous and the mesh openness becomes more heterogeneous (Robertson and Stewart, 1988). Meshes close to the catch accumulation become more open while meshes further forward in the codend become more elongated and thereby closed (Jones, 1963; Herrmann, 2005; Herrmann and O'Neill, 2005). These variations in mesh openness have been associated to variations in codend size selection, as fish of the same size may not meet the same escape possibilities during the fishing process often linked to unsatisfactory exploitation patterns in commercial fisheries (Fryer, 1991; Herrmann and O'Neill, 2005; Herrmann, 2005; Krag et al., 2011). Especially size selection of roundfish as cod (*Gadus morhua*) is largely affected by the mesh openness (Herrmann et al., 2009). According to the design guide for cod presented in Herrmann et al. (2009) the difference in L50 for a 110 mm diamond-mesh size would be 18 cm between an opening angle (OA) of 20–60°. This variability in openness can negate the effect of gear modifications to reduce unwanted catches, such as increasing mesh size. Thereby, it can be questioned how well mesh size works as a regulating tool for management (Wileman et al., 1996; Andersen, 2019).

The capture, and subsequent mortality of unwanted species and sizes has negative implications on ecosystems and the economic viability of fisheries (Greenstreet et al., 1999; Uhlmann et al., 2019). Therefore, a fishing gear that has a relatively constant size selection, and hence predictable and constant properties, is desirable. One alternative often adopted in an attempt to reduce variability in mesh openness is the use of square meshes. Compared to diamond-mesh codends that become elongated under tension longitudinal (along the length of the codend), square-mesh codends have bars that are parallel to both transversal (along the circumference of the codend) and the longitudinal direction (Priour et al., 2009). Robertson and Stewart (1988) stated that the parallel bars should keep the meshes more uniform and open as the tension from the drag forces in the mesh bars does not close the meshes which is not the case for diamond meshes. Therefore, the variability in size selection is expected to be lower for square-mesh codends because the possibility for fish of the same size to escape through the codend meshes while towing would be more stable than for diamond-mesh codends (Krag et al., 2011). Experimental trials have corroborated lower variability in size selectivity using square-mesh compared to diamond-mesh (e.g. Robertson and Stewart, 1988; Broadhurst et al., 2003). However, several studies have shown that the variation in selectivity of square-mesh codends may be larger than expected (e.g. Krag et al., 2011; Wienbeck et al., 2014; Herrmann et al., 2016), raising concerns regarding the efficacy of square-mesh codends as an alternative to diamond-mesh codends. Krag et al. (2011) argues that the tension in the bars in square-mesh is mainly in longitudinal, while the two remaining bars (transversal) may well be slack and deformable. This can result in larger fish being able to escape through square-meshes than desirable, increasing the variability in size selection (Herrmann et al., 2016). The opposite where small unwanted individuals are retained is also a possibility, if the longitudinal bars become closer, and as consequence the mesh openness is reduced (Herrmann et al., 2016).

The effect of variability in mesh openness on the steepness of codend size selection curves was first quantified experimentally by Bak-Jensen et al. (2022). The study found a significant difference in SR for Atlantic cod between a diamond mesh codend where mesh openness was kept constant and a standard diamond-mesh codend where mesh openness was flexible.". This study left questions about the size selectivity using square-mesh, which we in the present study addresses. We experimentally investigated the selectivity of three alternative codends; a standard square-mesh codend, a rigid square-mesh codend where meshes were fixed and a rigid diamond-mesh codend with mesh openings fixed at 60°. By comparing the selectivity properties of these three codends and the selectivity properties of the standard diamond-mesh codend from Bak-Jensen et al. (2022), we aimed to answer the following research questions:

- Does fixing mesh openness reduce the variability in size selection compared to a standard square-mesh codend?
- Which mesh shape, diamond-mesh or square-mesh, provides the lowest variability in size selection with fixed or flexible mesh openness?
- How is the L50 affected by the shape and flexibility of the mesh?

2. Materials and methods

2.1. Test codends and trawl gear

All codends were constructed using high density polyethylene (HDPE) 5-mm single twine netting (Euroline®). Codend mesh size was measured with an OMEGA-gauge with 125 N stretching force. For each codend 20 meshes were measured in dry conditions as suggested by Fonteyne et al. (2007), albeit limited free meshes in the fixed mesh codends reduced the possibility of gauging control measures. The mesh size of the fixed mesh codends were measured at a section of loose meshes located between the aft end of the frame and the codline.

The standard square-mesh codend, hereafter referred to as Standard Square Codend, (Fig. 1, left) was made from two panels of netting where the meshes were turned 45° relative to the standard netting configuration of the diamond-mesh codend used by Bak-Jensen et al. (2022). The panels were 49.5 meshes long and 24 open meshes wide (Table 1). The two experimental fixed mesh codends consisted of a rigid steel frame covered with the same type of netting as the Standard Square Codend (Fig. 1). The dimensions of the frames were 2.00 × 0.75 × 0.75 m (length, width, and height, respectively; 1.125 m^3), defined on the basis of handling limitations when setting and retrieving the trawls. The frames were made of square profile pipes of 40 × 40 x 4 mm steel (height, width, thickness, respectively). The netting was mounted one panel per side to the surfaces of the frame with fixed opening angle of either 60°or orientated 90° (square). The angle of the mesh opening was measured by using a protractor. The angle of 60° was chosen as it is in the upper end of the OAs of the diamond meshes according to the design guide in Herrmann et al. (2009), and would still be different when comparing to square meshes. This codend is hereafter referred to as "Fixed Diamond Codend". The only difference between the Fixed Diamond Codend and the second fixed mesh codend tested is the opening angle of the meshes, where the meshes were turned 45° and fixed to achieve a square-mesh configuration. This codend is hereafter referred to as "Fixed Square Codend". The trawl gear used was a TV300/60 trawl, spread by Thyboron Type 2 (1.78 m^2) trawl doors and 75-m long sweeps.

For comparative purposes, we reuse the data published by Bak-Jensen et al. (2022) for the standard diamond-mesh codend. This codend is hereafter referred to as "Standard Diamond Codend". The netting for this codend was the same as used for the three experimental codends tested.

2.1.1. Experimental fishing and data collection

Fishing trials were conducted onboard the German Fishery Research Vessel "Solea" (42.40 m length overall, 1780 kW), during June 14th to 26th 2022. The trials took place in the Western Baltic Sea (Fig. 2). Selectivity data were collected using the covered codend method (Wileman et al., 1996). The cover was made of single 2.5 mm-PE twine with a nominal diamond mesh size of 55 mm. The stretched length was ~16 m and the diameter ~3 m. To prevent the cover from masking the codend meshes, seven kites were attached to the cover. Five out of the seven kites were attached to the forward section of the cover, 46.5 meshes from the attachment to the trawl. Four out of the five forward-positioned kites were attached to the sides (2 kites per side) and

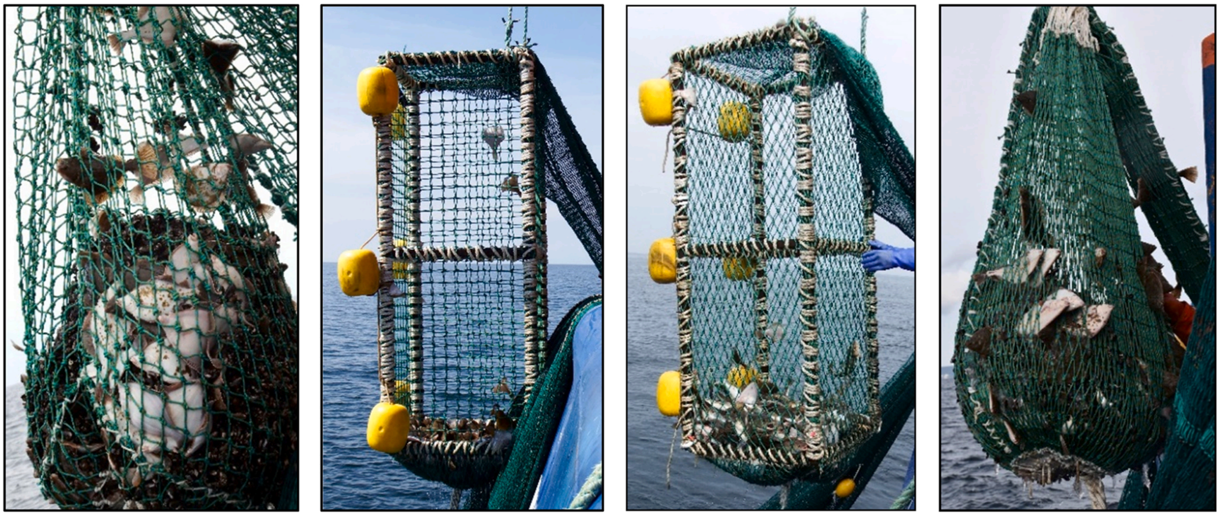

Fig. 1. The four codends. From left Standard Square Codend, Fixed Square Codend, Fixed Diamond Codend (OA 60°), and Standard Diamond Codend (from Bak-Jensen et al., 2022).

Table 1
Average measured mesh sizes with std. deviations (in brackets) and construction details of the netting from the tested codends.

	Standard Square Codend	Fixed Square Codend	Fixed Diamond Codend	Standard Diamond Codend
Mesh size [cm]	110.4 (4.0)	111.9 (1.9)	113.9 (2.1)	112.4 (2.7)
No. of panels	2	4	4	2
Panel width (No. of meshes)	24	10	11	24
Panel length (No. of meshes)	49.5	30	17	49.5

the fifth was mounted on top -. The two remaining kites were attached to the lateral sides of the mid-section of the cover, 125 meshes from the attachment to the trawl.

The codends were tested in consecutive series, and only when preliminary analysis revealed the data to be sufficiently strong was the series with the next codend started. The catches obtained in the codend and cover during each haul were sorted and measured separately for each compartment. Only hauls containing a total catch of more than 20 individuals were used in the analysis (Bak-Jensen et al., 2022). The total length of all individuals was measured and rounded down to the nearest centimeter.

2.1.2. Codend selectivity analysis

The size selection data obtained for each of the three experimental codends were analyzed in SELNET using the methodology described in Wileman et al. (1996). This methodology assumes that the retained proportion of fish in the codend is determined by the fish's ability to pass through the codend meshes, and that this ability is determined mostly by the size and morphology of the fish compared to the geometry and size of the meshes. Consequently, the larger the fish the more difficult for it to escape through a mesh of specific size and shape, and beyond a certain size it will not have any chance of escaping. These basic assumptions allow modeling the codend retention probability *r(l)* by simple mathematical functions with parametric structures leading to a non-decreasing s-shaped selectivity curve asymptotically restricted to values between 0.0 and 1.0 (Wileman et al., 1996). The *Logistic*, *Probit*, *Gompertz*, and *Richards* selectivity models were considered as candidates. Mathematical descriptions of the models can be found in Bak-Jensen et al. (2022). The four models were estimated and ranked by Akaike Information Criterion (AIC) (Akaike, 1974), and the model with lowest AIC was chosen for further analysis. The Efron 95% confidence intervals (CIs) for the selection curve and parameters were obtained by using a double bootstrap method with 1000 repetitions following the same procedure as described in Bak-Jensen et al. (2022).

2.1.3. Inference of difference in variability in size selection between codends

The selective properties of the codends were compared pairwise, where one codend was used as baseline and the other codend as treatment. The comparison used the SR values predicted for each codend to evaluate whether the geometry of the meshes influences the variability in the size selection process. Assuming that the variation in the geometry of the codend meshes is a major source of variability in codend size selection, and that such variability is reflected in the SR values (Herrmann, 2005; Herrmann and O'Neill, 2005; Bak-Jensen et al., 2022), then the average SR values estimated by pooling the *m* hauls conducted with a given codend should contain the variation of the size selection caused by geometric mesh variation occurring at haul level and across hauls (Fryer, 1991; Herrmann and O'Neill, 2005; Bak-Jensen et al., 2022). The difference in variability in selectivity between the treatment and baseline codends is quantified by the following statistics:

$$\Delta SR[\%] = 100 \times \frac{(SR_T - SR_B)}{SR_B} \quad (1)$$

Where SR_B is the SR estimated for the baseline codend and SR_T is the SR estimated for the treatment codend. The larger the value of ΔSR, the larger the difference in variation will be. When evaluating if ΔSR was significantly different from zero, 95% Efron CIs were estimated from a bootstrap distribution of ΔSR obtained from a previously estimated bootstrap distributions for SR_B and SR_T (Efron, 1979; Larsen et al., 2018; Herrmann et al., 2018). Thus, significant differences would be found when the 95% confidence intervals around ΔSR did not overlap the values associated to the null hypothesis H_0: $\Delta SR = 0.0$. 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).

2.1.4. Inference of difference in mean size selection between codends

To evaluate the difference in L50 between the tested codends we adapted the statistic Eq. 1 to L50:

$$\Delta L50[\%] = 100 \times \frac{(L50_T - L50_B)}{L50_B} \quad (2)$$

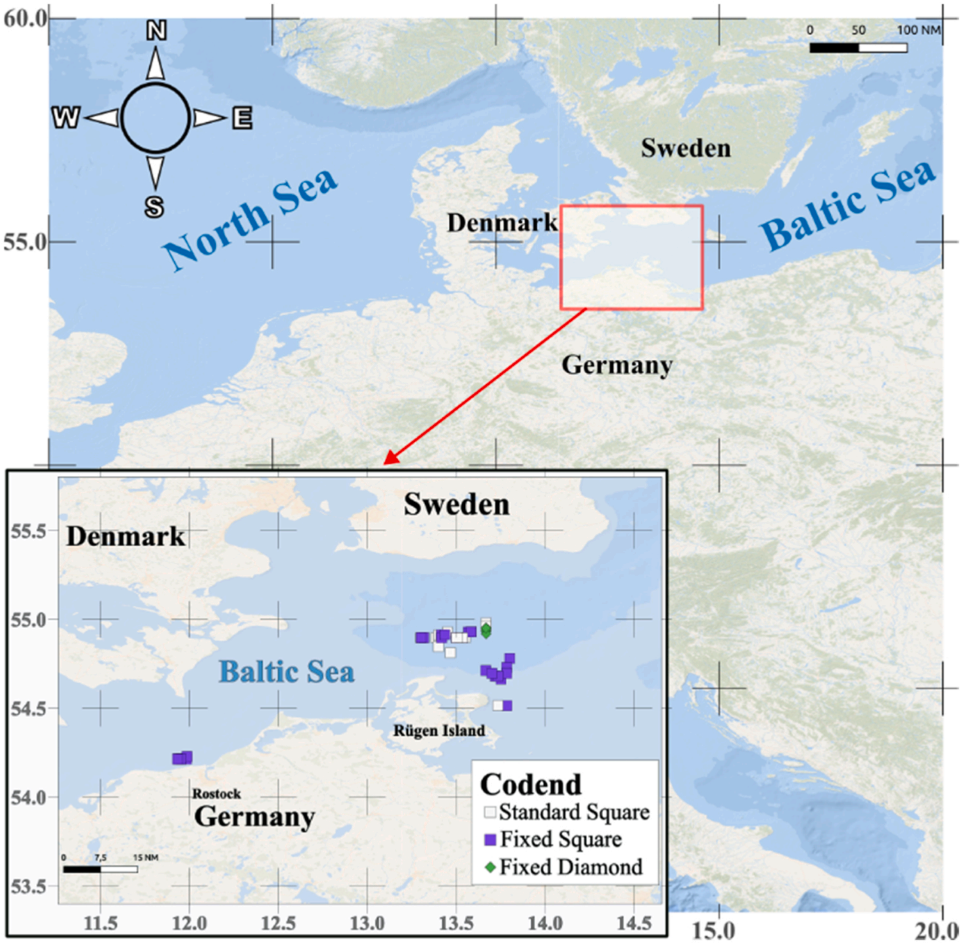

Fig. 2. The geographical area in which fishing trails were conducted for the three different codends.

The $\Delta L50$ values for the pairwise comparisons between codends is used to quantify the effect of mesh shape and flexibility on mean codend size selection.

Furthermore, the difference in the mean L50 estimated for fixed codends and the theoretical predictions for cod at the same mesh size and OA presented in Herrmann et al. (2009) is estimated by:

$$\Delta L50[\mathrm{cm}] = L50_{OAT} - L50_{OAB} \quad (3)$$

where $L50_{OAT}$ is the mean L50 value obtained for any of the tested codends with the mesh openings fixed to a specific OA (60 or 90°), and $L50_{OAB}$ is the L50 value theoretically predicted in Herrmann (2009) for the same OA as in the tested codend evaluated.

3. Results

A total of 50 hauls were conducted (For detailed catch information see supplementary materials Table S1). The average fishing depth was 40.5 m, with a maximum depth of 48 m and a minimum of 15 m (Supplementary: Table S1). The average duration of the hauls was 23 min ranging from 15 min to 50 min. For the Standard Square Codend 14 out of the 18 hauls conducted were used in the analysis as these contained more individuals than the specified minimum (Table 2). For the Fixed Square Codend, 21 out of 26 hauls were used and for the Fixed Diamond Codend all 6 hauls were used. In addition, 15 out of 27 hauls with the Standard Diamond Codend from Bak-Jensen et al. (2022) were used. The total numbers of cod used for the analysis retained in the three codends was 2036 individuals and 8484 individuals retained in the cover (Table 2).

Table 2
Fit statistics obtained from the covered codend analysis showing the L50 and SR for the four different codend configurations tested for cod. Values in parentheses represent 95% CIs. The fit statistics in terms of the p-value, deviance, and DOF. Number of hauls and number of fish used in the analysis are listed last.

	Standard Square Codend	Fixed Square Codend	Fixed Diamond Codend	Standard Diamond Codend
Model	Richards	Richards	Richards	Logistic
L50 [cm]	38.25 (37.56;39.28)	36.81 (35.87;37.99)	33.57 (33.03;34.12)	27.79 (25.21;30.70)
SR [cm]	7.42 (6.35;8.70)	6.38 (5.30;7.48)	5.51 (4.97;6.12)	8.75 (6.80;11.62)
***p*-value**	0.86	0.57	0.98	0.17
Deviance	35.66	40.83	28.64	38.56
DOF	46	43	46	31
No. hauls	14	21	6	15
No. cod total	3937	2954	3629	566
No. cod cover	3409	2661	2414	485

3.1. Codend selectivity analysis

The models considered for analysis in section 2.3 were successfully fitted to the selectivity data, albeit a few outlier points can be noted in the graphics of Standard Square Codend, Fixed Square Codend above 40 cm (Fig. 3). Based on AIC, the *Richards* model was in all cases picked as the best candidate to describe the size selection and for further analysis except for the Standard Diamond Codend where the *Logistic*

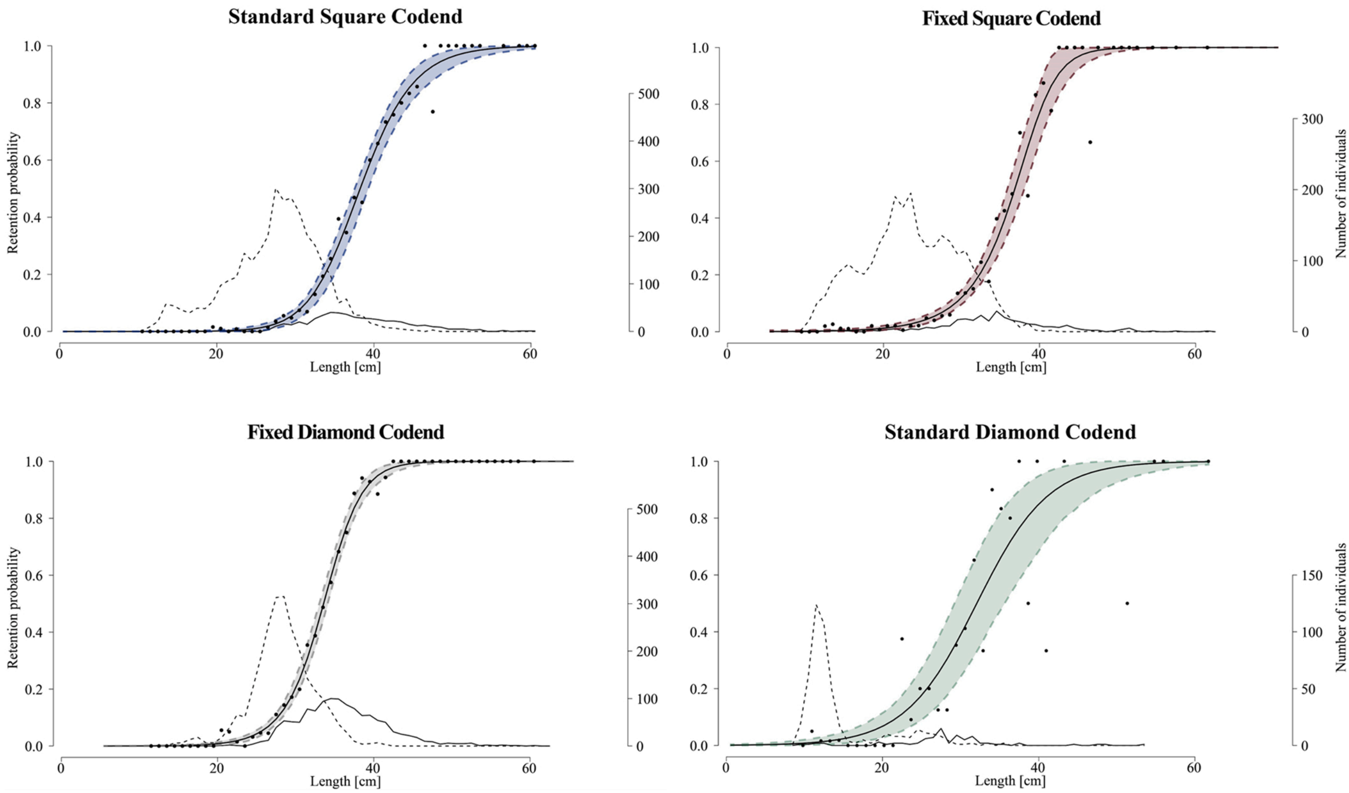

Fig. 3. Length-dependent retention probabilities for the Standard Square Codend, Fixed Square Codend, Fixed Diamond Codend and Standard Diamond Codend, respectively. Points represent the length-dependent experimental retention proportions; the predicted selectivity curves are represented by solid black curves and the associated 95% CIs are represented as shaded areas outlined by the dashed lines. Solid and dotted lines at the bottom of the plots represent the number of fish caught in each length class in the test codend and cover, respectively.

model was chosen (Table 2). The fit statistics for the selected models showed that the deviation between the experimental data and the modelled curve was on an acceptable level (p-value >0.05) This showed that the deviation between the experimental data and the modelled curve could be coincidental and, therefore, the model could be used to describe the trends in the data (Table 2).

L50 was lowest for the Standard Diamond Codend and highest for the Standard Square Codend (Fig. 4), with average values of 27.79 cm and 38.25 cm, respectively. SR values were found to be lowest for both fixed mesh codends, with the Fixed Diamond Codend having the lowest SR of 5.51 cm. The Standard Diamond Codend had the largest SR of the four codends of 8.75 cm.

3.2. *Evaluation of differences in size selection variability between codends*

The pairwise comparisons of the different codends tested in the present study were conducted according to the delta method described in the section "*Inference of difference in variability in size selection between*

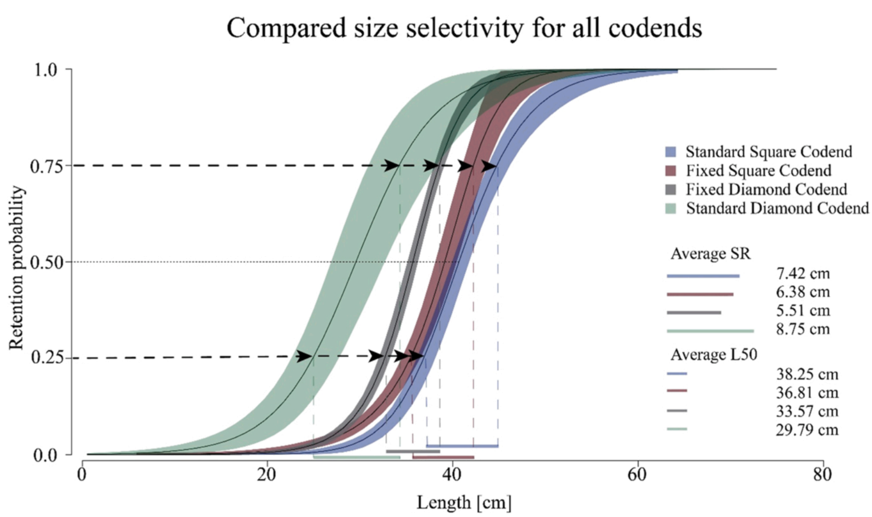

Fig. 4. Comparison of selectivity curves of Standard Square Codend, Fixed Square Codend, Fixed Diamond Codend, and Standard Diamond Codend. The predicted selectivity curves are represented by solid black curves and the associated 95% CIs are represented as shaded areas. The horizontal dashed lines mark the points for the L25 and L75 which marks the interval for the SR (showed with dashed vertical lines from the predicted average curve to the x-axis). The dotted line marks L50.

codends" (Fig. 5). The pairwise comparison between the Standard Square Codend and the Fixed Square Codend indicated, albeit not significantly, that the SR for Fixed Square Codend was about 14% lower. The comparison between the Standard Square Codend and the Fixed Diamond Codend revealed a significant difference of approximately 26% less variability for the latter codend (Table 3). The comparison between Standard Square Codend and Standard Diamond Codend revealed no significant difference, though the average showed higher variability for the latter. The comparison between the Fixed Square Codend and Fixed Diamond Codend, albeit not significant, yielded a difference in SR of about 14%. The comparison between the Standard Diamond Codend and Fixed Diamond Codend resulted in a 59% significant higher variability for the former.

3.3. Evaluation of differences in mean size selection between the tested codends

All possible pairwise comparisons between the L50 values obtained for each codend resulted in significant differences (Table 4). The largest difference in L50 was found between Standard Diamond Codend and Standard Square Codend, where the L50 for the Standard Square Codend was approx. 27% larger in average (Fig. 6). The smallest difference was found between Standard Square Codend and Fixed Square Codend, where the Fixed Square Codend was in average approx. 4% smaller than the Standard Square Codend. The L50 for the Fixed Square Codend is 3.26 cm larger on average than the L50 for Fixed Diamond Codend calculated using Eq. 3.

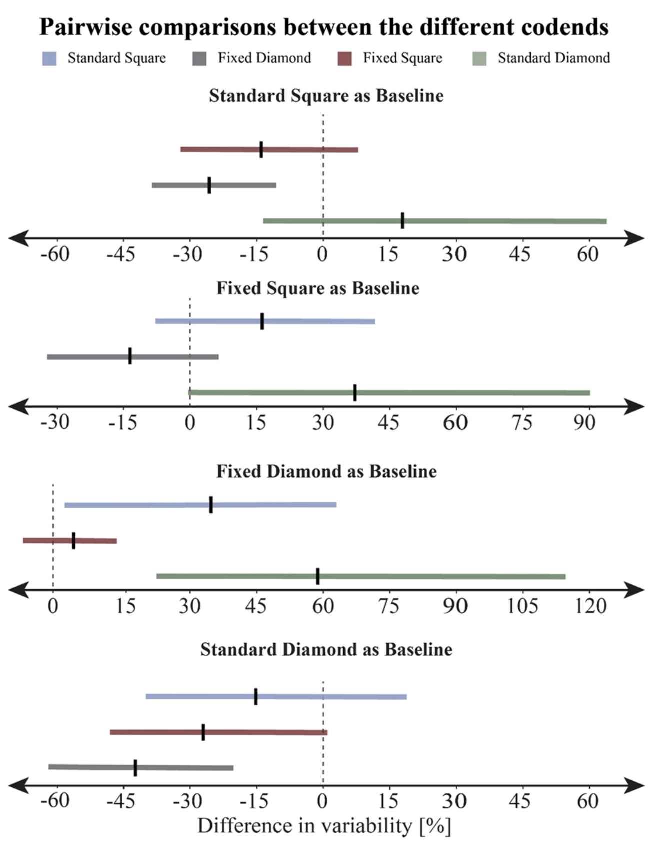

Fig. 5. The difference in variability (%) for the multiple pairwise comparisons between the different codends. Zero difference in variability is marked vertical by the dashed line. The colored horizontal lines show the CIs for the different pairwise comparisons (ΔSR). Vertical black lines mark the average ΔSR. No significance is found if the horizontal lines cross the zero-difference variability line.

4. Discussion

Using Baltic Sea cod caught in the Baltic Sea as a case study, we demonstrated that the Standard Square Codend had significantly larger variability in size selection compared to what was obtained with the Fixed Diamond Codend. Moreover, we found no evidence that the Standard Square Codend had lower variability in size selection than a Standard Diamond with same mesh size. No significance was found between the Standard Square Codend and the Fixed Square Codend.

While square-mesh codends have previously been found to have more constant mesh openness, and consequently better selectivity than diamond-mesh codends (i.e. Robertson and Stewart, 1988; He, 2007), our results demonstrate that fixing mesh openness can be used to control size selectivity further. Despite not been able to prove differences in the size selective variability between the Standard Square Codend and the Fixed Square Codend, we do not reject that fixing the meshes could result in lower variability. Considering fixing the meshes to an opening angle of 60° resulted in a large and significant reduction in variability of the selection compared to the Standard Square Codend, we except that a fixed square mesh would also contribute to less variation. According to our results, using square-mesh codends is not an effective strategy to reduce the variability in size selectivity caused by variations in mesh geometry. Another way to try to reduce variability in codend size selection could be by turning the diamond mesh 90° (T90). Previous work has shown the benefit of using T90 codend design also compared to square-mesh (Einarsson et al., 2021). Actually, T90 codends is one of the legal designs for the Baltic demersal trawl fishery (Wienbeck et al., 2011). How the fixed codend design would perform compared to a T90 codend would be relevant to investigate in a future study.

Both square-mesh codends increased the L50 for cod but did not significantly reduce the variability in codend size selection compared to the Fixed Diamond Codend. When aiming at releasing cod as the situation in the Baltic Sea demands, this means that the square shape releases the largest individuals with the smallest mesh size, which could be beneficial in the ongoing fisheries targeting flatfish. To reduce variability in size selection, fixing mesh geometry to an angle theoretically known to provide best escape probabilities would be preferable.

The data collected for Standard Diamond Codend was not as strong and there seem to be outliers. However, this might be a result of the low number of individuals. Additionally, there also seems to be outliers at 43 cm and 47 cm for the Fixed Square Codend and the Standard Square Codend, respectively (Fig. 3). Looking at the length distribution for the two square codends, the number of large individuals is low, which could imply that the large deviation observed could be coincidental. The outliers, however, could be related to fish in poor condition making them very slim. Atlantic cod in the Baltic Sea have been known to have poor condition for example due to infection of liver parasites (Marnis et al., 2020). Moreover, a loose closure of the codlines was detected during the trials for the two fixed frames (Fig. 7), which might have provided greater escape possibilities for large fish that else would not have been able to escape through the codend meshes. However, for cod to be able to escape through the gap in the codline, it had to be during the initial phase of the haul, before such gap would be eventually blocked by accumulation of catch. Thus, if there was a gap at the codline, it would only have affected the results to a minor extent and therefore, would not evict the overall conclusions.

Our results showed no evidence that the Standard Square Codend had less variation in size selectivity than the Standard Diamond. This could partly be a result of the limited power of the test associated to the ΔSR (Eq. 1) and the low number of cod caught using the Standard Diamond. Square-mesh codends have previously been found to have smaller SRs when compared to diamond mesh codends (e.g. He, 2007). However, even if square-mesh codends were more constant, they only achieve a marginal improvement, while fixing the geometry improves substantially the stability of codend size selection.

Results from this experimental trial support the speculations by Krag

Table 3
ΔSR for baseline codends compared with the treatment codends for all combinations in percent. Bold denotes value with significant difference.

	Baseline				
		Standard Square	Fixed Square	Fixed Diamond	Standard Diamond
Treatment	Standard Square		16.17(−6.37;48.07)	**34.50(12.57;62.71)**	-15.21(−36.83;16.97)
	Fixed Square	-13.96(−32.13;7.85)		15.78(−6.54;39.74)	-27.01(−46.95:1.96)
	Fixed Diamond	**-25.69(−39.67;−10.65)**	-13.63(−29.12;6.32)		**-36.96(−52.75;−16.35)**
	Standard Diamond	17.88(−13.53;63.96)	37.00(−0.54;89.89)	**58.63(22.28;114.38)**	

Table 4
ΔL50 for baseline codends compared with the treatment codends for all combinations in %. Bold denotes value with significant difference.

	Baseline				
		Standard Square	Fixed Square	Fixed Diamond	Standard Diamond
Treatment	Standard Square		**3.93(0.08;8.09)**	**13.94(11.14;17.70)**	**37.65(24.39;51.90)**
	Fixed Square	**-3.77(−7.50;−0.20)**		**9.64(6.30;13.80)**	**32.45(19.11;45.84)**
	Fixed Diamond	**-12.23(−15.04;−9.87)**	**-8.79(−12.11;−5.92)**		**20.81(9.61;33.46)**
	Standard Diamond	**-27.35(−34.55;−20.10)**	**-24.50(−32.12;−16.59)**	**-17.22(−25.38;−9.08)**	

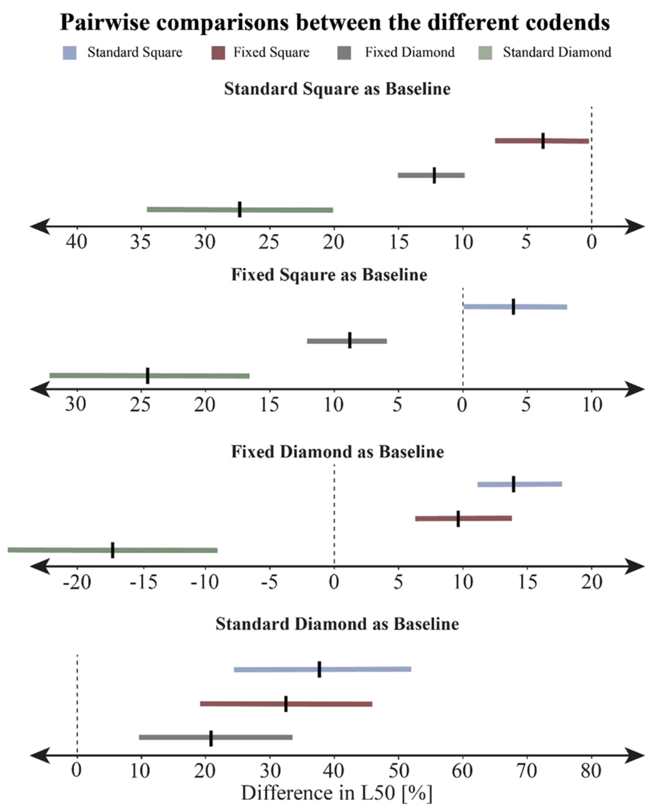

Fig. 6. The difference in L50 (%) for the multiple pairwise comparisons between the different codends. Zero difference in L50 is marked vertical by the dashed line. The colored horizontal lines show the CIs for the different pairwise comparisons (Δ*L50*). Vertical black lines mark the average Δ*L50*. No significance is found, if the horizontal lines cross the zero-difference variability line.

et al. (2011) and Herrmann et al. (2016), that similar to standard diamond-mesh codends, the meshes in standard square-mesh codends are to some degree deformed either in the catch build-up phase or during haul back, which affects the risk of losing valuable catch or increasing the retention of unwanted sizes. The Fixed Diamond Codend had 56% lower variability in selectivity compared to the Standard Diamond. These results are in line with those obtained by Bak-Jensen et al. (2022), where a fixed codend with 40° OA was tested against a standard diamond-mesh codend. The overall lowest variability in size selectivity was found for the Fixed Diamond Codend. However, there was no significant difference between the two fixed mesh codends. As there was no significant difference in size selective variation between the two fixed codends, the opening angle of the meshes should be selected according to the morphology of the fish to achieve best performance, for example, using software capable of identifying the most appropriate opening angle across a wide range of mesh sizes and angles (Herrmann et al., 2009).

Fig. 7. Picture of the gap in the codline detected during the trials.

According to the design guide presented in Herrmann et al. (2009), the L50s for diamond and square-mesh codends for 110 mm mesh size should be approximately 38 cm and 41 cm, respectively. The difference of three centimeters fits well with the difference found between the Fixed Diamond Codend and Fixed Square tested here, which was 3.26 cm. However, the L50 for the Fixed Diamond Codend and Fixed Square were both lower than those found in Herrmann et al. (2009). Alzorriz et al. (2016) also found that experimental data resulted in lower L50 than the L50 obtained when using simulated data. Cuende et al. (2020) proposed that this could be explained by the fish's orientation and angle of attack when contacting the meshes. The design guide in Herrmann et al. (2009) is calculated with the assumption that all individuals have optimal orientation for escape, which would be perpendicular to the mesh opening. Thus, the ability of fish to orientate and contact meshes in an optimal angle is an issue that needs to be addressed in the search for more selective codend designs.

The L50 values for the two diamond codends, Standard and Fixed, were found to be significantly different. Fixed Diamond Codend had a significantly larger L50 than the Standard Diamond, which was expected as 60° is a quite high OA. This difference was expected as 60° is a quite high OA. The fixed diamond-mesh codend with an OA of 40° tested by

Bak-Jensen et al. (2022) was also found to have a significantly different L50 from the Standard Diamond; however, here the fixed-mesh codend had a lower L50 than the Standard Diamond. Standard Diamond resulted possibly from the larger variation in the codend meshes. The variation in the mesh openness could still affect the L50 to be different from an OA of 60°, but in this case we would just expect the L50 to be lower, as we would expect it to be closer to an OA of 40°.

A significantly larger L50 was found for the Standard Square Codend compared to the Fixed Square Codend when calculated by Eq. 2. When looking at Fig. 4 the CIs overlap, which could indicate no significance, however the delta method has more statistical power (Larsen et al., 2018). This difference reveals the same pattern as found in Krag et al. (2011). They proposed that the mesh bars that are parallel to the circumference of the codend become slack allowing for larger individuals to escape. This may explain the larger L50 found for the Standard Square Codend.

Our results show that fixing mesh openness can improve the size selection of cod. Fixed-mesh codends might also benefit species selectivity by including knowledge about species morphology and thereby be a useful tool in many fisheries. Considering both morphology and behavior in the trawl, may allow for designing meshes differently in areas where differences between species in behavior and morphology are known to exist. For example, knowing that flatfish have a preference to the lower half of the codend while some roundfish are known to orientate in the upper half (Winger et al., 2010), designing the codend to facilitate the best possibility for escape for different species in different places might benefit not only size selectivity but also to species selectivity. This has already been tested experimentally to some extent by Frandsen et al. (2011), who aimed at selecting Nephrops (*Nephrops norvegicus)* from fish in a multispecies fishery. However, this have not been explored with in a controlled setup with constant meshes. We propose a change in the way of looking at trawl codend design towards stabilization of the meshes, and potentially the specification of their form aiming at a more controlled size selection.

The construction including a metal frame used in this experimental trial is not feasible for use in commercial fisheries due to health, safety and environment issues and limitations in handling large catch volumes. Therefore, a new and more user-friendly design for commercial use should be designed. The solution requires maintaining constant mesh geometry regardless of the difference in tension, for example caused by different catch sizes and during haul back. However, the design needs to ensure a constant mesh openness while also accounting for the need of handling and storing the gear onboard. Such practical requirements open engineering challenges that might lead to paths towards an alternative paradigm in the design and construction of trawl codends.

CRediT authorship contribution statement

Zita Bak-Jensen: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Data curation, Visualization. **Bent Herrmann:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision. **Juan Santos:** Conceptualization, Methodology, Investigation, Writing – review & editing, Data curation, Visualization, Supervision. **Valentina Melli:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Daniel Stepputtis:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Jordan P. Feekings:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2023.106704.

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