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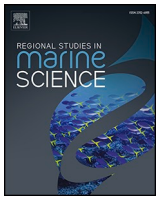

Size selecting for flatfish while avoiding cod

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ABSTRACT

Optimizing exploitation patterns for multiple species in trawl fisheries simultaneously presents both technological and managemental challenges. In the Baltic Sea demersal trawl fisheries targeting flatfish, fishers must avoid catching cod (*Gadus morhua*) due to its critical stock status. This study investigates the selectivity performance of a codend with large and rigid square-meshes (LRSM) optimized for size selection of plaice (*Pleuronectes platessa*). The expectation was that the LRSM would effectively release cod and other non-target species while providing an optimal exploitation pattern for the targeted flatfish species. For plaice 85 % of the target sizes were retained and 92 % of the unwanted sizes were released with the LRSM. The LRSM significantly reduced the capture of undersized plaice and flounder (*Platichthys flesus*) by 49 % and 30 %, respectively compared to a square-mesh codend (SMC125) implemented in the Baltic Sea to protect cod stocks. For target-sized flatfish species, there was no significant difference in retention probability. The LRSM retained only 3 % of the cod that entered the codend, representing a significant reduction of 31 % compared to the SMC125. However, the results also demonstrated that cod and flounder did not fully utilize the release potential of the LRSM, which needs to be addressed to achieve the full benefit of the LRSM.

1. Introduction

Demersal trawl fisheries are most often multi-species and among the world fisheries of greatest concern in terms of unwanted bycatch issues (He et al., 2021; Pérez Roda et al., 2019). Unwanted bycatch includes unwanted species and undersized individuals of target species. According to the EU landing obligation, all quoted species and sizes must be landed and counted against quota, but only the fraction of catch above a given reference size will be allowed to be marketed for human consumption (European Parliament, 2013; ICES, 2024a; Pohlmann et al., 2016). The aim of this legislation is to incentivize fishers to fish more selective, for example by adjusting the selectivity of the fishing gear (Melli, 2018). Adjustments of gear selectivity to avoid bycatch often involve adding bycatch reduction devices (e.g. sorting grids and square-mesh panels), able to provide escape possibilities for bycatch species before entering the trawl codend (Kennelly and Broadhurst, 2021). However, these bycatch reduction devices are often implemented without exploring the limits of codend design to address the primary bycatch issue (Herrmann et al., 2024; Jørgensen et al., 2006). Depending on the bycatch problem being addressed, proper optimization of codend selectivity from a multispecies perspective may render the use of additional bycatch reduction devices unnecessary.

One case where bycatch issues might be largely solved by codend optimization is in Baltic Sea demersal trawl fisheries. Historically, demersal fisheries in the Baltic Sea focused on targeting cod (*Gadus morhua*), with bycatch of flatfish, namely plaice (*Pleuronectes platessa*), flounder (*Platichthys flesus)*, and dab (*Limanda limanda*) (Eero et al., 2020, Santos, 2021). However, the severe depletion of the Baltic cod stocks over the last decade (Eero et al., 2020; ICES, 2019), has led to drastic management measures by the EU, including a zero-quota policy for cod. Subjected to the landing obligation for quoted species in the EU, cod is no longer considered a target species and only flatfish can be

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targeted. Therefore, cod may ultimately become a choke species for the emerging flatfish-directed fisheries in the Baltic Sea (ICES, 2019). To address this issue, the EU has adopted new technical measures including codends that should provide better escape possibilities for cod compared to the traditional T90 and Bacoma codends (European Parliament, 2019; Wienbeck et al., 2014). These two traditional codends were developed when the fisheries in the Baltic Sea were targeting cod and therefore not optimized for the current intended exploitation pattern aiming at capturing flatfish at certain sizes while avoiding cod of all sizes (Santos, 2021; Santos et al., 2022). One new design aiming at meeting the current exploitation goal is a square-mesh codend constructed out of knotless netting with a minimum mesh size of 125 mm (SMC125) (European Commission, 2024a). It has been demonstrated that the SMC125 improves escape possibilities of cod compared to former codend designs (Madsen et al., 2021; Wienbeck et al., 2014). However, according to the size-selection properties of the SMC125 (Wienbeck et al.; 2014), it is expected that this codend will provide little or no escape possibilities to large cod individuals. To reduce the risk of bycatch of these individuals, fishers need to mount an additional selection device named ROOFLESS (Santos et al., 2022) ahead of the SMC125, to provide an escape path to large individuals before they enter the codend (European Commission, 2024b; Santos et al., 2022). Further, according to previously obtained results for full square-mesh codends, adoption of the SMC125 will not solve the issue of unsustainable exploitation patterns of flatfish species related to the former Bacoma codend (Wienbeck et al., 2014; Madsen et al., 2021). Specifically, the cross-section shape of flatfish matches poorly the shape of the square-meshes, hindering juveniles from escaping unless the mesh size is sufficiently large (Bak-Georgsen et al., 2025; Fonteyne and M'rabet, 1992, Herrmann et al., 2013).

The morphology determines whether a fish can physically pass through a mesh opening (Herrmann et al., 2009). Therefore, prior to testing at sea, it is advisable to incorporate systematic procedures to evaluate mesh sizes and mesh geometries that could lead to the best possible trade-off between retention of marketable sizes and release of unwanted bycatch. (Brčić et al., 2018; Herrmann et al., 2013; Sistiaga et al., 2011). To design a codend that retains commercially sized flatfish while enabling cod to escape, the most effective approach is to utilize the morphological differences between the species. As a roundfish, cod is morphologically better shaped for escaping through a square-mesh than a diamond-mesh (Herrmann et al., 2009). Contrary, the compressed shape of flatfish provides better opportunities for escaping through diamond-meshes (Bak-Georgsen et al., 2025). However, the potential slack bars perpendicular to the drag force on the netting in a square-mesh codend during fishing can enhance escape opportunities for larger flatfish (Bak-Jensen et al., 2024), while retaining smaller sized cod (Bak-Jensen et al., 2023; Krag et al., 2011). Therefore, the stability and openness of the codend meshes is important for ensuring well-defined escape opportunities (Bak-Jensen et al., 2023, 2022). Considering the shape variability of the meshes, selecting the appropriate mesh size for a rigid square-mesh should ideally retain commercially viable sizes of flatfish while allowing the release of undersized flatfish and a wide range of cod sizes (Bak-Georgsen et al., 2025; Bak-Jensen et al., 2024, 2023). Therefore, this study aims to investigate whether the multi-species challenge in the Baltic Sea trawl fisheries targeting flatfish can be addressed by using a codend with large rigid square-meshes (LRSM). Specifically, the following research questions are investigated:

1. How is the size selection and catch patterns provided by the experimental LRSM codend for the targeted flatfish species and how is this performance compared to the mandatory SMC125?
2. How is the size selection and catch patterns provided by the experimental LRSM codend for the unwanted cod and how is this performance compared to for the mandatory SMC125?
3. Is the optimization of mesh size and shape a sufficient technical strategy to fully utilize the potential of codend selectivity to achieve a satisfactory catch pattern of targeted flatfish species while minimizing cod bycatch?

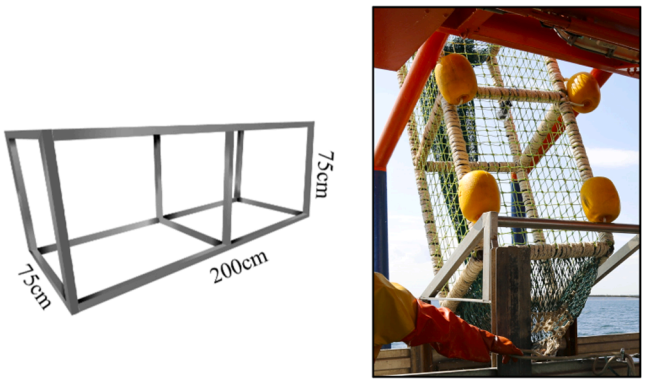

Fig. 1. Left: the frame dimensions of LRSM. Right: LRSM in use.

Table 1
Technical details of the experimental LRSM and the mandatory SMC125 codends. Standard deviation is presented in parentheses.

	LRSM	SMC125
Mesh size (mm)	141.3 (0.94)	125.6 (1.17)
Number of panels	4	2
Number of free bars around	32	50
Number of free bars in length	22	84

2. Materials and methods

2.1. Codends

The LRSM codend consists of a rigid 2 m long steel frame made of 40 mm× 40 mm x4 mm (height x width x thickness) square profile pipes with netting mounted on the outside (Fig. 1). The four rectangular surfaces of the frame were covered with ~140 mm single twine, 3.5 mm Euroline© Premium netting. This mesh size was chosen based on previous laboratory experiments for predicting flatfish selectivity using different mesh sizes and shapes (Bak-Georgsen et al., 2025). Specifically, the model by Bak-Georgsen et al. (2025) predicted that a square-mesh codend with 140 mm mesh size and the meshes fully open provide a 50 % retention probability (*L50*, Wileman et al., 1996) for plaice close to the Minimum Conservation Reference Size (MCRS) at 25 cm, while *L50* for flounder and dab would both be approximately 26 cm. The SMC125 codend was made by Ultra Cross© knotless square-mesh with 5 mm twine thickness. The mesh sizes in the codends were measured using an OMEGA-gauge, whereby 20 meshes (dry conditions) were measured with a stretching force of 125 N (Table 1).

2.2. Experimental design and data collection

The selective properties of the experimental LRSM and the mandatory SMC125 codends were tested during experimental fishing trials conducted in the Baltic Sea onboard the German FRV *Solea* (42.40 m LOA, 950 kW main engine power), between June 14th and 20th 2023. The codends were mounted one at a time to a bottom trawl type TV300/60, spread by Thyboron Type 2 (1.78 m2) doors and 100 m sweeps. The haul duration was fixed to 30 min for all hauls using both codends. Size selectivity catch-data was collected at haul level using the covered codend method (Wileman et al., 1996). The codend cover was made of single 2.5 mm-PE twine with a nominal mesh size of 55 mm (further details can be found in Bak-Jensen et al. 2022). Catches obtained in the codend and cover were processed and sampled separately. Catches were sorted by species except mussels (*Mytilus* sp.) and starfish (*Asterias sp.*).

The number of individuals of each species was counted, and the total weight was noted. When individuals were broken e.g. jellyfish or mussels, the broken tissue was compiled into what could be assumed to be one individual. All cod, plaice, flounder and dab caught were length-measured using measuring boards. Individual measurements were rounded to the centimeter below.

2.3. stimation of codend size selectivity

The data obtained in the cover and codend when fishing with each of the experimental codends was analyzed using the methodology described in Wileman et al. (1996). This methodology estimates a size selection curve. This size selection curve, *r(l)*, quantifies the probability for a fish of length *l* entering in the codend to be retained in it. The curve can be modeled using different non-decreasing functions confined in the range of retention probabilities between 0.0 and 1.0. The four basic models described in Wileman et al. (1996) *Logistic*, *Probit*, *Gompertz* and *Richards* were initially fitted to the data. All the basic models are parameterized by the selection parameters *L50* and *SR*, where *SR* is the selection range, which is defined as the range of lengths between the lengths associated to 75 % and 25 % retention probabilities (Wileman et al., 1996). The structure of the basic models described above assume that all the fish entering the codend will be subjected to the same selection process. However, in some cases only a fraction of the fish will contact the mesh opening and therefore only this fraction will be subject to a size selection process. To account for this, we considered four additional models which parametric structure assumes that only a fraction C of the fish entering the codend will be subjected to the length-dependent selection of the codend. These models are referred to as *CLogistic*, *CProbit*, *CGompertz*, and *CRichards* (Bak-Jensen et al., 2024; Cuende et al., 2020). In addition, a ninth model, the *DLogistic*, accounting for more than one selection process was also considered. The *DLogistic* model can describe a dual selection process assuming that a fraction of the fish entering the codend is subjected to one logistic size selection process whereas the remaining fraction is subjected to another logistic size selection process (Herrmann et al., 2024, Bak-Jensen et al., 2023). The first fraction C_1 is described by the parameters $L50_1 and SR_1$ whereas the second fraction is described by the parameters $L50_2 and SR_2$ (More about the *DLogistic* model can be found in Bak-Jensen et al. (2024). All models are listed in Eq. 1:

$$
\mathrm{r}(l,\boldsymbol{v}) = \begin{cases}
Logistic(l, L50, SR) = \dfrac{\exp((l - L50) \times \frac{\ln(9)}{SR})}{1 + \exp((l - L50) \times \frac{\ln(9)}{SR})} \\
Probit(l, L50, SR) \approx \Phi\left(\dfrac{1.349}{SR} \times l - L50\right) \\
Gompertz(l, L50, SR) \approx \exp\left(-\exp\left(-\left(0.3665 + \dfrac{1.573}{SR} \times (l - L50)\right)\right)\right) \\
Richards(l, L50, SR, \delta) = \left(\dfrac{\exp\left(Logit(0.5^{\delta}) + \left(\frac{Logit(0.75^{\delta}) - Logit(0.25^{\delta})}{SR}\right) \times (l - L50)\right)}{1.0 + \exp\left(Logit(0.5^{\delta}) + \left(\frac{Logit(0.75^{\delta}) - Logit(0.25^{\delta})}{SR}\right) \times (l - L50)\right)}\right)^{\frac{1}{\delta}} \\
CLogistic\left(l, C, L50_g, SR_g\right) = 1.0 - C + C \times Logistic\left(l, L50_g, SR_g\right) \\
CProbit\left(l, C, L50_g, SR_g\right) = 1.0 - C + C \times Probit\left(l, L50_g, SR_g\right) \\
CGompertz\left(l, C, L50_g, SR_g\right) = 1.0 - C + C \times Gompertz\left(l, L50_g, SR_g\right) \\
CRichards\left(l, L50_g, SR_g, 1/\delta_g\right) = 1.0 - C + C \times Richards\left(l, L50_g, SR_g, 1/\delta_g\right) \\
DLogistic(l, C_1, L50_1, SR_1, L50_2, SR_2) = C_1 \times Logistic(l, L50_1, SR_1) + (1.0 - C_1) \times Logistic(l, L50_2, SR_2) \\
\text{where} \\
\Phi(x) \text{is the cumulative distribution forastandard normal distribution and } Logit(r) = \ln\left(\dfrac{r}{1.0 - r}\right)
\end{cases} \tag{1}
$$

The size selection curves described in Eq. 1 and associated selectivity parameters $\boldsymbol{v}$ were estimated via Maximum Likelihood (Wileman et al., 1996) for each codend and species separately summed across hauls conducted with the specific codend. The model with the lowest AIC was chosen to model the size selection for each codend and species separately (Akaike, 1974). The ability of the chosen model to describe the trend in the experimentally collected size selection data was evaluated based on the p-value obtained from a Pearson's Chi-squared test (Lomeli et al., 2020; Wileman et al., 1996). This p-value quantifies the probability of obtaining at least as big a discrepancy between modelled and experimental retention rates by coincidence (Wileman et al., 1996). The overall selectivity parameters *L50* and *SR* for the size selection curve are obtained using the numerical technique described by Sistiaga et al. (2010). Uncertainties for the modelled size selection curve and the associated parameters were described by 95 % Efron percentile confidence intervals (CIs) (Efron, 1979) obtained by the bootstrapping procedure described in Herrmann et al. (2012) based on 1000 resamples.

To quantify the difference in size selectivity between the two codends, the Δ approach was used. The Δ retention, $\Delta r(l)$, can be found by subtracting the two selection curves from each other (Bak-Jensen et al., 2022):

$$\Delta r(l) = r(l)_{LRSM} - r(l)_{SMC125} \tag{2}$$

95 % Efron confidence intervals were estimated from a bootstrap distribution of $\Delta r(l)$ obtained from the previously estimated bootstrap distributions for the two codends (Herrmann et al., 2018; Larsen et al., 2018). Significant difference is found when the CIs does not include 0.0.

2.4. Predicting codend design exploitation pattern indicators

To predict how the LRSM and SMC125 affected the harvesting patterns through the change in size selectivity, the values of two exploitation pattern indicators are estimated (Mašanović et al., 2023; Melli et al., 2020; Wienbeck et al., 2014; Yu et al., 2024). The values for the indicators are based on size selection curves for the two codends and the size structure of the catch in the codend and cover combined obtained by considering the hauls for both codends:

$$\begin{aligned} nP_{-} &= 100 \times \frac{\sum_{l<RS}\{r(l,\boldsymbol{v}) \times nPop_l\}}{\sum_{l<RS}\{nPop_l\}} \\ nP_{+} &= 100 \times \frac{\sum_{l\geq RS}\{r(l,\boldsymbol{v}) \times nPop_l\}}{\sum_{l\geq RS}\{nPop_l\}} \end{aligned} \tag{3}$$

For each species analyzed, $nPop_l$ refers to the number of individuals in class size l of the population that entered the codend (codend + cover). The indicator nP_{-} quantifies the capture efficiency on the fraction of the fished population below a species-specific reference size (RS). For plaice and flounder, the RS corresponds to the MCRS in the area (ICES SD22, SD24) at 25 cm and 23 cm, respectively (European Parliament, 2019). As there is no official RS set for dab in the case area, the length of maturity is used, counting all individuals below this length as unwanted catch. The average length of first maturity is set to 22.5 cm for females in the western Baltic Sea (ICES, 2010). nP_{+} quantifies the capture efficiency for the population fraction equal or greater the species RS. nP_{-} and nP_{+} were estimated with using the distributions of $r(l,\boldsymbol{v})$ and $nPop_l$ obtained from the bootstrap resamples. Specifically, by calculating the values for the indicators based on the result of each bootstrap resample for $r(l,\boldsymbol{v})$ and $nPop_l$ to obtain a bootstrap set for the indicator values. Efron 95 % CIs were estimated for each of the indicators based on the resulting bootstrap set by the procedure described in Melli et al. (2020) and Herrmann et al. (2018).

The percentage differences in capture efficiency were quantified as follows:

Fig. 2. Photo of the fall through experiment performed on the meshes of the LRSM.

$$\Delta nP_{-}\% = 100 \times \frac{(nP_{-LRSM} - nP_{-SMC125})}{nP_{-SMC125}} \tag{4}$$

$$\Delta nP_{+}\% = 100 \times \frac{(nP_{+LRSM} - nP_{+SMC125})}{nP_{+SMC125}}$$

95 % Efron confidence intervals were estimated from a bootstrap distribution of $\Delta nP_{-}\%$ and $\Delta nP_{+}\%$ obtained from the previously estimated bootstrap distributions for the two codends (Herrmann et al., 2018; Larsen et al., 2018). Significant differences are observed when the CIs do not include 0.0.

Since, all sizes of cod were considered unwanted the $\Delta nP_{-}\%$ were applied for all sizes. Technically, this was achieved by specifying the RS to a value above the length of the largest cod captured. For flatfish, the catch efficiency was quantified both fractions below and above the species-specific RS.

2.5. Species dominance analysis

To obtain a more holistic evaluation of the effect of applying the codends in the fishery, a catch composition and species dominance assessment was performed following the procedure outlined in several published works (Cerbule et al., 2022; Madhu et al., 2023; Mytilineou et al., 2022; Petetta et al., 2023). When analyzing community species structures or catch structures, cumulative species dominance curves are often used (Clarke, 1990). The most common species in the community is also known in ecology as the dominant species (Krebs, 2014). The dominance curves can then be used to evaluate if a large part of the catch is dominated by species that are normally not considered when evaluating fishing performance and exploitation patterns. Species dominance

Table 2
Number of hauls and measured fish by catch compartment (test codend and cover) used in the analysis.

		Number of hauls and aggregated catches (No. fish)	
		LRSM	**SMC125**
Cod	No. hauls	20	14
	Fish in codend	305	345
	Fish in cover	11360	5825
Plaice	No. hauls	21	17
	Fish in codend	2143	2208
	Fish in cover	5408	5621
Flounder	No. hauls	16	14
	Fish in codend	2195	1081
	Fish in cover	547	189
Dab	No. hauls	21	17
	Fish in codend	316	469
	Fish in cover	1413	1760

Table 3
The AIC values for the different models for the different species and codend. The model with the lowest AIC is noted with *.

		Cod	**Plaice**	**Flounder**	**Dab**
LRSM	***Logistic***	1741.80	3998.68	1794.51	861.87
	Probit	1781.47	4088.81	1788.62*	902.40
	Gompertz	1741.80	4637.48	1814.03	993.20
	Richards	1740.77	3993.20	1795.12	851.05
	CLogistic	1770.97	3984.46	1796.49	833.92
	CProbit	1755.36	3992.68	1790.81	843.38
	CGompertz	1758.13	4039.23	1841.03	844.38
	CRichards	1758.34	3988.63	1797.43	835.89
	DLogistic	1725.87*	3975.50*	1791.58	830.65*
		Cod	**Plaice**	**Flounder**	**Dab**
SMC125	***Logistic***	1643.18	4653.58	810.50	1558.95
	Probit	1682.66	4688.42	807.66*	1587.21
	Gompertz	1768.30	4927.75	815.67	1673.59
	Richards	1638.12	4649.70*	809.80	1550.70
	CLogistic	1622.84	4654.43	811.74	1541.94
	CProbit	1613.16*	4650.88	809.68	1539.37*
	CGompertz	1620.74	47.07.87	814.91	1551.64
	CRichards	1618.69	4656.10	811.85	1543.91
	DLogistic	1623.98	4652.01	811.49	1545.92

curves are often used to quantify information about the relative species abundances for a given sample (Petetta et al., 2023). The dominance curves are based on the ranking of species (Warwick et al., 2019). This ranking in fisheries typically lists the target species first, followed by valuable bycatch species, species with no commercial interest and lastly, species of concern (Cerbule et al., 2022; Madhu et al., 2023; Petetta et al., 2023). The species that were caught in the codend or codend cover in either the LRSM or the SMC125 were used to make a ranked list of all species caught.

The cumulative dominance Dn_I curves were estimated as follows:

$$Dn_I = \frac{\sum_{j=1}^{h}\sum_{i}^{I} n_{ij}}{\sum_{j=1}^{h}\sum_{i}^{s} n_{ij}} with 1 \le I \le S \quad (5)$$

where I is the species rank summed up in the nominator. j represents the haul and i is the species rank previously defined. n_{ij} is the number of individuals of the species i being counted in haul j. S is the total number of species considered, whereas h is the total number of hauls conducted with the specific codend. Efron percentile 95 % CIs were used to quantify uncertainty using the bootstrap method described in (Herrmann et al., 2022).

Table 4
Selectivity parameters and fit statistics obtained for the two codends and the four species analyzed. Values in parentheses represent 95 % CIs for the selectivity parameters.

		Cod	**Plaice**	**Flounder**	**Dab**
LRSM	**Model**	*DLogistic*	*DLogistic*	*Probit*	*DLogistic*
	L50 **[cm]**	42.40 (41.41; 43.35)	24.89 (24.44; 25.41)	23.79 (23.45; 24.13)	25.92 (25.41; 26.38)
	SR **[cm]**	6.84 (4.97; 9.18)	2.33 (1.85; 2.47)	3.48 (3.12; 3.91)	1.62 (1.26; 2.05)
	$L50_1$ **[cm]**	30.80 (28.32; 44.06)	24.89 (24.50; 57.20)	-	26.57 (25.45; 57.76)
	SR_1 **[cm]**	2.39 (1.00; 7.85)	2.30 (1.00; 50.00)	-	11.60 (1.00; 50.00)
	C_1	0.89 (0.61; 0.99)	0.99 (0.01:0.99)	-	0.07 (0.03; 0.99)
	$L50_2$ **[cm]**	42.63 (28.43; 44.13)	23.70 (1.00: 25.40)	-	25.91 (15.40; 26.26)
	SR_2 **[cm]**	6.52 (1.00; 7.74)	29.19 (1.00; 50.00)	-	1.50 (1.00:50.00)
	D	-	-	-	-
	p-value	0.59	0.43	0.99	0.38
	Deviance	39.29	30.76	9.20	19.18
	DOF	42	30	23	18
		Cod	**Plaice**	**Flounder**	**Dab**
SMC125	**Model**	*CProbit*	*Richards*	*Probit*	*CProbit*
	L50 **[cm]**	40.73 (39.66; 41.98)	24.12 (22.96;25.20)	22.20 (21.43; 22.88)	25.63 (24.64; 26.23)
	SR **[cm]**	7.63 (6.64; 8 93)	3.34 (2.79; 3.93)	4.60 (3.81; 5.45)	3.33 (2.78; 3.88)
	$L50_1$ **[cm]**	40.80 (39.74; 42.10)	-	-	25.68 (24.69; 26.28)
	SR_1 **[cm]**	7.54 (6.48; 8.81)	-	-	3.26 (2.74; 3.76)
	C_1	0.99 (0.98; 0.99)	-	-	0.98 (0.95; 0.99)
	$L50_2$ **[cm]**	-	-	-	-
	SR_2 **[cm]**	-	-	-	-
	D	-	0.75 (0.44; 1.21)	-	-
	p-value	0.52	0.94	0.99	0.89
	Deviance	47.77	22.05	8.06	13.54
	DOF	49	34	23	21

2.6. Release size limits

To obtain an estimate of the morphological release limit of cod in the LRSM, a fall-through experiment was conducted. Fall-through experiments determine whether a fish can physically pass through a mesh (Sistiaga et al., 2011). Freshly caught cod were used to avoid using fish with rigor mortis which could affect the outcome. The cod were measured using a measuring board and the length was rounded to the centimeter below. The fish were afterward exposed to a mesh in the LRSM to observe if they could pass through subjected to gravity only. Specifically, the fish was orientated optimally for mesh passage and held by the tail through the entire passage process. If a fish passed through the meshes, it was registered as released and if the fish could not pass through the meshes it was registered as retained. This procedure is used

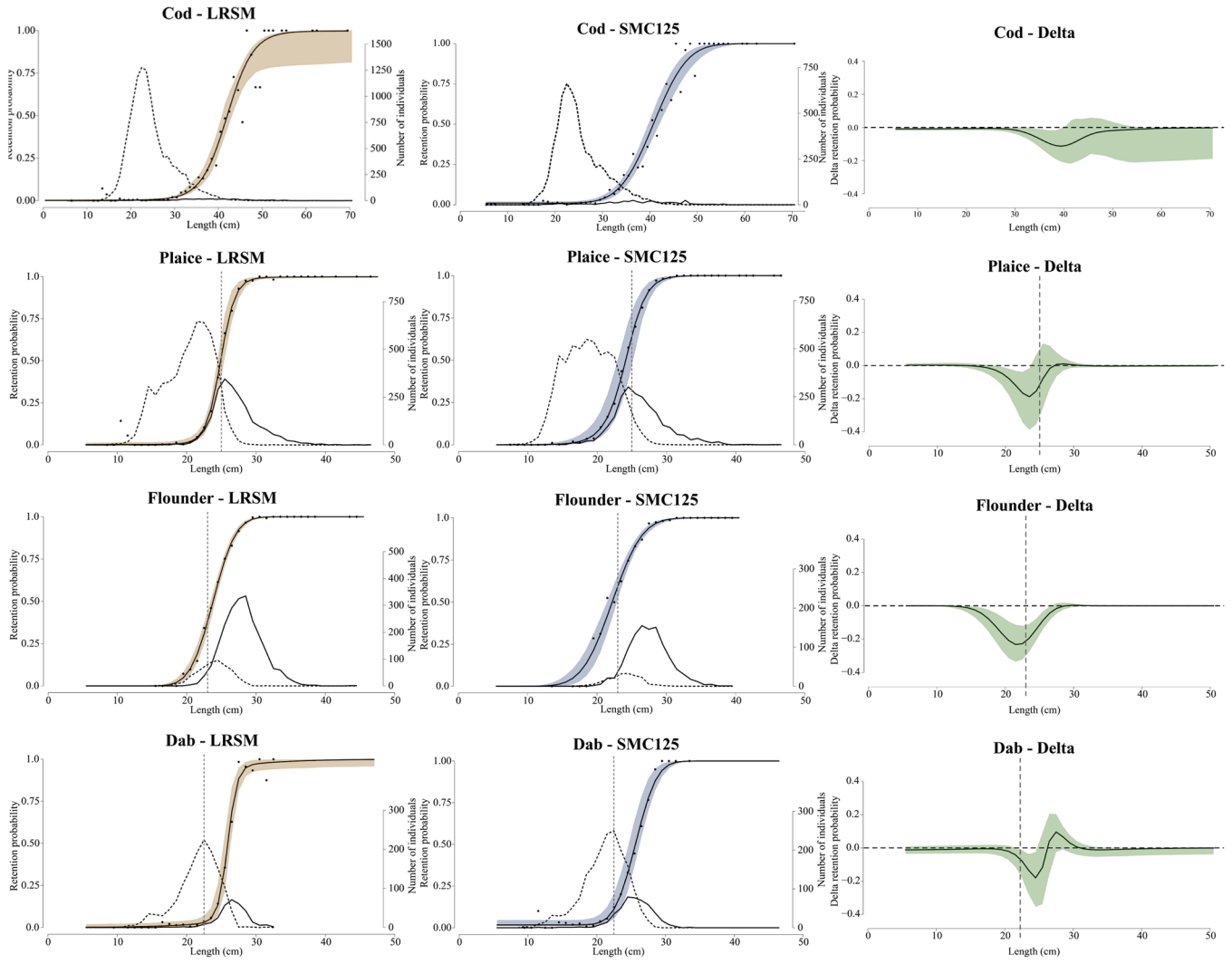

Fig. 3. Column to the left and middle: Retention curves for the LRSM and SMC125 respectively. The solid curves represent the models fitted to the selectivity data (points) with the 95 % CIs (shaded area). The polygons at the bottom of each plot represent the number of fish caught in each length class in the codend (solid line) and cover (dashed line). Column to the right: Δ plots for the comparison of the two codends with the SMC125 used as baseline. The solid curve represents the change in retention probability of the LRSM to the SMC 125 at each length. Δ values above 0.0 represent an increase in retention probability by the LRSM, and the opposite for Δ values below 0.0. The shaded green area represents the 95 % CIs associated with the Δ curve. The dashed horizontal line denotes the zero-difference value. The dashed vertical line denotes the RS.

to find the release size limits for a given species and mesh (Grimaldo et al., 2018; Wienbeck et al., 2011). The fall-throughs were performed directly on the meshes of the LRSM (Fig. 2).

The obtained data were treated as "covered codend data" where each fish that passed through the mesh was considered to end up in the cover, while the others were considered to be retained in the codend. A *Logistic* size selection curve (Eq. 1) was subsequently fitted to the data.

2.7. Software

The analyses conducted in 2.3–2.5 were carried out using the software tools SELNET (Herrmann et al., 2012) and FISHSELECT (Herrmann et al., 2009). Plots and graphics were created using R (version 4.5.0).

3. Results

3.1. Description of fishing operations and catches

In June 2023, a total of 38 hauls were conducted, of which 21 hauls were made with LRSM and 17 hauls with the SMC125. For each species only the hauls with more than 20 individuals were used, providing variable number of hauls used in the analyses for each species and codend design (Table 2). The mean catch weight for the total catch for the codend was 59.6 kg (Standard Deviation, SD= 23.4 kg) and 54.6 kg (SD= 16.5 kg) for the LRSM and the SMC125, respectively (For additional information see Table S1 in supplementary materials). Fishing depths varied between 14 m and 49 m.

3.2. Codend selectivity analysis

In three of cases, the *DLogistic* model and in two cases a *CProbit* model (Eq. 1) described the experimental size selection data best (Table 3). The overall *L50*s for plaice for the LRSM was 24.89 cm, a value close to the species' RS (25 cm). Coupling the *L50* and species RS is often a management goal, which was achieved by using the LRSM. *L50*s were 23.79 cm and 25.92 cm for flounder and dab, respectively. For flounder, this matches well with the RS value set at 23 cm while the *L50* value for dab was well above the length of first maturity (22.5 cm). The *SR* values for all flatfish species and both codends were below 5 cm. For plaice and dab, the *SR* was lower in the LRSM compared to the SMC125 (Table 4),

Table 5
Retention efficiency for total catch of cod and below and above RS for flatfish, for the two codends in percentage. In the right column the Δ is marked as significant with a *. < RS corresponds to nP_- and > RS to nP_+ (Eq. 3). Δ quantifies the difference in retention efficiency in percentage (Eq.4). Values in brackets represent 95 % CIs.

Retention efficiency			
Species	LRSM	SMC125	Δ
Cod	3.11 (2.39; 3.90)	4.47 (3.40; 5.90)	−30.43 (−48.58; −11.17)*
Plaice < RS	8.45 (5.33; 13.30)	16.66 (9.49; 26.88)	−49.28 (−71.74; −6.19)*
Plaice > RS	84.84 (78.80; 91.70)	87.01 (79.74; 93.13)	−2.51 (−11.90; 9.34)
Flounder < RS	42.60 (37.70; 47.89)	60.74 (54.20; 67.04)	−29.86 (−39.91; −18.16)*
Flounder > RS	91.57 (89.72; 93.37)	93.91 (92.09; 95.67)	−2.45 (−5.06; 0.22)
Dab < RS	1.58 (0.49; 4.14)	3.45 (1.86; 7.84)	−54.06 (−88.84; 34.37)
Dab > RS	28.36 (22.15; 37.56)	36.74 (29.17; 50.51)	−22.80 (−46.11; 7.43)

confirming the benefit of constant and uniform mesh shape on the sharpness of codend size selection.

The size selectivity curves predicted by the models chosen based on comparing AIC-values represented the trends in the experimental data well (Fig. 3). This is supported by the p-value for the models, with values above the decision threshold of 0.05 in all cases (Table 4), meaning that the differences between the data and the modelled curves could be coincidental. The delta plot for cod showed for a size range, between 30 cm and 40 cm, a significant reduction in retention probability. Further, all the flatfish species showed significant differences between 20 cm and 30 cm.

The quantification of size integrated capture efficiencies (Section 2.4) showed that there was a significant difference between the two codends for multiple species (Table 5). The LRSM retained 3 % (CI: 2.39–3.90 %) of the cod entering the codend, which is 31 % (CI: 11.17–48.58 %)fewer than the SMC125. The LRSM had a significantly higher release of plaice and flounder below RS with ~49 % (CI: 6.19–71.74 %) and ~30 % (CI: 18.16–39.91 %), respectively (Table 5). An indication of higher release for dab below RS was found, however not significant. The retention of flatfish above RS was not significantly different between the two codends. Therefore, the LRSM achieves a more favorable exploitation pattern.

Table 6
List of species and species-specific categories (determined by species RS, if applied) obtained during the sea trials. The three flatfish species targeted in the demersal trawl fisheries (plaice, flounder, dab) in catch fractions above their respective RS are placed on top of the list (green). The next three species are listed as bycatch with commercial value (yellow). Cod and catch fractions below RS of the targeted flatfish species are placed at the bottom of the list (red) and referred to as unwanted and concerning bycatch. The species in the middle are the bycatch with no commercial value and no concern from a management perspective.

Index	Species Common Name	Latin
S1	Plaice above RS	*Pleuronectes platessa*
S2	Flounder above RS	*Platichthys flesus*
S3	Dab above RS	*Limanda limanda*
S4	Turbot	*Scophthalmus maximus*
S5	Brill	*Scophthalmus rhombus*
S6	Sole	*Solea solea*
S7	American Plaice	*Hippoglossoides platessoides*
S8	Hering/Sprat	*Clupeidae*
S9	Common mackerel	*Scomber scombrus*
S10	Haddock	*Melanogrammus aeglefinus*
S11	Lumpsucker	*Cyclopterus lumpus*
S12	Twait Shad	*Alosa fallax*
S13	Grey gurnard	*Eutrigla gurnardus*
S14	European eelpout	*Zoarces viviparus*
S15	Hooknose	*Agonus cataphractus*
S16	Scorpius	*Myoxocephalus scorpius*
S17	long-spined sea-scorpion	*Taurulus bubalis*
S18	Four-bearded rockling	*Rhinonemus cimbrius*
S19	Gobiidae	*Gobius spp.*
S20	Common Jellyfish	*Aurelia aurita*
S21	Mussels	*Mytilus spp.*
S22	Starfish	*Asterias sp.*
S23	Common shore crab	*Carcinus maenas*
S24	Swimming crab	*Liocarcinus depurator*
S25	Whiting	*Merlangius merlangus*
S26	Plaice below RS	*Pleuronectes platessa*
S27	Flounder below RS	*Platichthys flesus*
S28	Dab below RS	*Limanda limanda*
S29	Cod	*Gadus morhua*

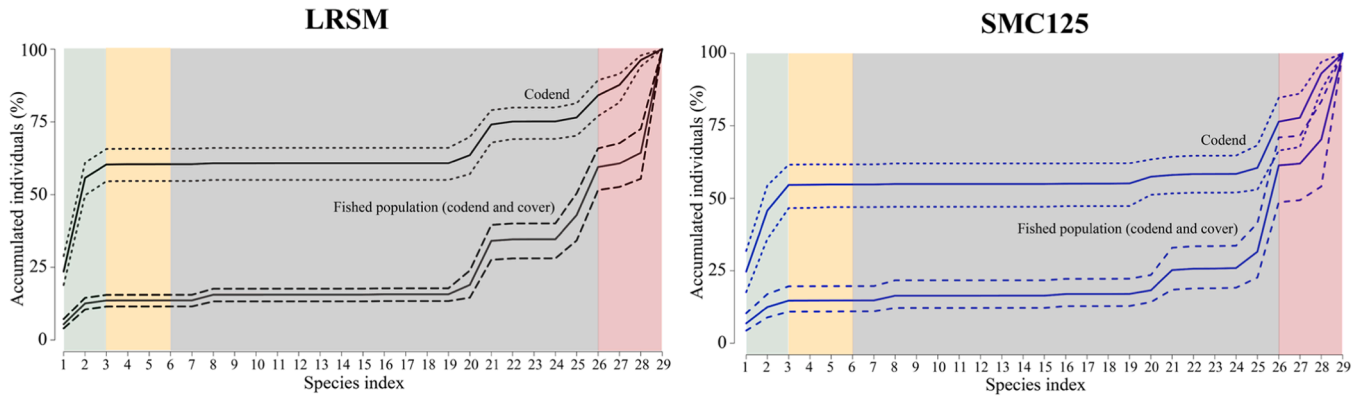

Fig. 4. Species dominance curves for the two tested codends. The species index is related and follows the same order to the list of species in Table 6. In plots the cumulative dominance in % are listed. The solid lines denote the average number in percent for both the catch in codend and the total retained individuals in the codend and cover. The dashed lines denote the CIs for the catch in the codend, and the dotted lines denote the CIs of the total retained individuals in the codend and cover. The target species (green), bycatch with commercial value (yellow), the species that are of no commercial or preservation interest (grey), and the species that are unwanted (red) are color-coded. The values used in the figure can also be accessed in Table S2 in supplementary materials. At the transition from green to yellow, LRSM goes higher than SMC125, representing more relevance of the targeted species relative to the total catch of the LRSM. Also interesting, there is a clear shifting point between species 20 and 21 (mussels and stars) for the LRSM, which is not visible for the SMC (the shifting point happens at the edge of the red zone).

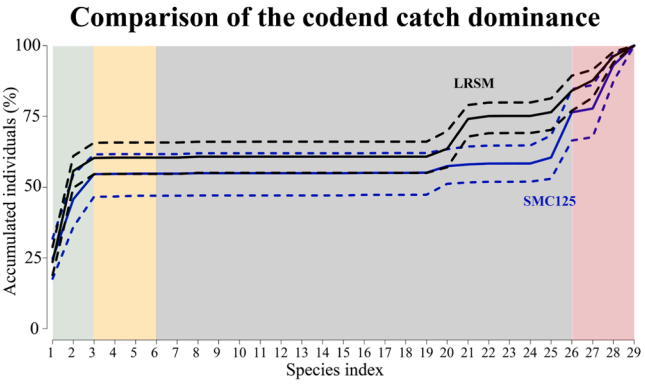

Fig. 5. A comparison of the codend catch dominance curves for the two tested codends; LRSM (black) and SMC125 (blue). The species index is related to the species in Table 6. In the plot the accumulated numbers of species in % are listed. The solid lines denote the average number in percentage. The dashed lines denote the CIs. The target species (green), bycatch with commercial value (yellow), the species that are of no commercial or preservation interest (grey), and the species that are unwanted (red) are color-coded.

3.3. Catch dominance analysis

The list of species caught during the sea trials consists of 26 different species (Table 6). Of these, plaice, flounder and dab above their respective reference sizes (RS) are in this study assumed to be targets for the fishery (S1-S3), while undersized individuals (below RS) of these flatfish species and cod are referred to as unwanted and concerning bycatch (S26-S28). Some species have commercial interest but appear only in low numbers and are therefore listed as bycatch of commercial value (S4-S6). The species listed S7 to S25 are bycatch species with no commercial value and no concern from a management perspective.

Only 14 % (CI: 12–16 %) of the fish population that entered the LRSM codend and 15 % (CI: 11–20 %) that entered the SMC125 were considered wanted catch (green and yellow areas in Table 6 and Fig. 4). However, the wanted catches accounted for 60 % (CI: 55; 66 %) and 55 % (CI: 47; 62 %) of the catches retained in the codend in the LRSM and SMC125, respectively (Fig. 5). This demonstrates the ability for both codends to sort the fished populations into a more desired exploitation pattern. This is further supported by the cumulative contribution of the unwanted and concerning bycatch (red shaded area Fig. 4), representing 16 % (CI: 11; 23 %) and 24 % (CI: 16; 34 %) of the total catch observed in the LRSM and SMC125, respectively (Fig. 5). Thereby the LRSM have a less retention of unwanted catch than the SMC125. The difference can be attributed to less retention of target flatfish fish below RS. For the species 21, mussels, there is a large increase for the LRSM compared to the SMC125 (Fig. 5). However, the abundance of mussels also constitutes a larger share of the fished population in the LRSM. Consequently, this increase could possibly be a result of differences in population composition fished on.

3.4. Release size limits

To assess to what extent cod and the targeted flatfish species utilize the release potential offered by the LRSM codend, the size selection curves obtained from the fishing trials were compared to predicted curves based on fall through experiments. For cod, this fall through size selectivity curve was obtained by conducting fall throughs directly for the LRSM codend meshes (Section 2.6). A total of 183 cod individuals ranging from 20 to 70 cm in length (Distribution is shown in supplementary materials in Figure S1) were used during this *ad-hoc* fall through experiment. The size selection curves for the flatfish species obtained during the fishing trials with the LRSM where compared to predictions for the LRSM mesh size based on the models established in Bak-Georgsen et al. (2025) for optimal escape.

The high degree of correspondence between the predicted retention curves and the experimental curves obtained from catch data reveals that both plaice and dab fully utilize the escape opportunities provided by the LRSM codend (Fig. 6). However, the comparison of the theoretical quantified maximum size selectivity and experimental size selectivity curves obtained for cod and flounder shows a large unutilized potential for escape (Fig. 6). The maximum size selectivity based on optimal escape situation had a lower retention of smaller sized cod and flounder than compared to the experimental, which implies that some of the retained cod and flounder would be able to physically pass through the meshes but did not utilize the opportunity to escape during the fishing trials.

4. Discussion

This study investigated if a codend with large rigid square-meshes (LRSM) could provide the desired exploitation pattern for flatfish species targeted in demersal trawl fisheries in the Baltic Sea, and simultaneously maximizing the capabilities of a codend to avoid catches of the

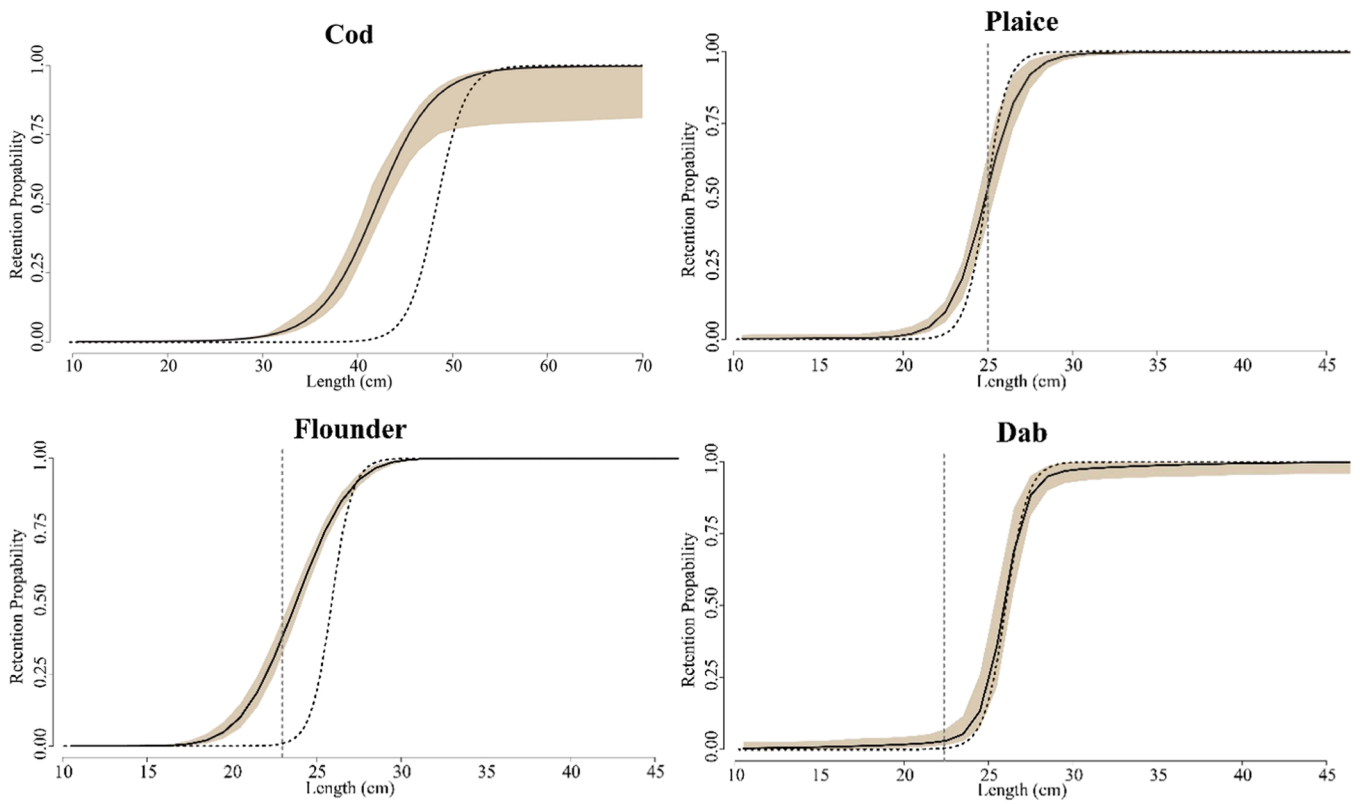

Fig. 6. Visual comparison of the retention curves obtained experimentally for LRSM (solid black line and shaded area denotes CIs), and the predicted curve based on fall throughs experiments (black dashed line). Note the x-axis has been cut to fit the fall through data (for full catch data see Fig. 3). For all Three flatfish species the predicted curves are made based on fall through from an earlier sea trial (see Bak-Georgsen et al., 2025 for more details). The dashed vertical lines represent the RS for the species.

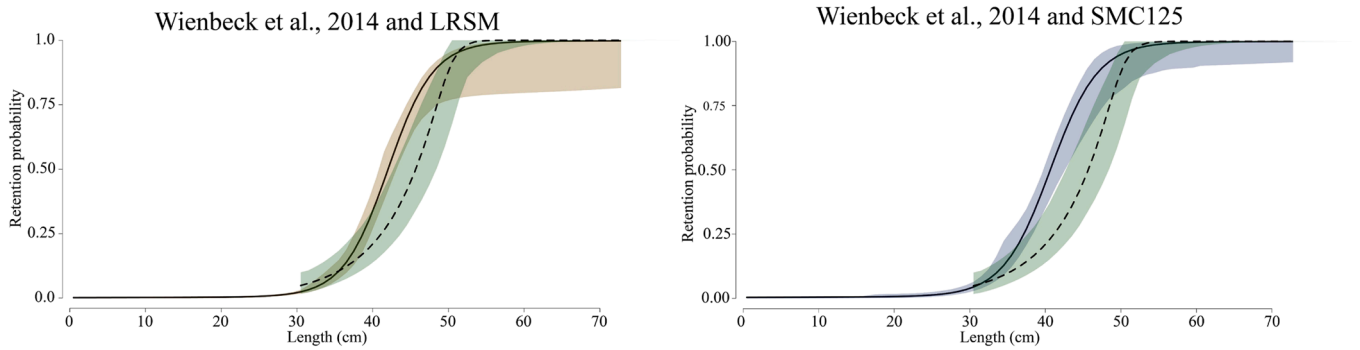

Fig. 7. Retention curves for cod estimated in Wienbeck et al., (2014) for a square mesh codend with and mesh size ~127 mm (dashed lines), compared to the retention curves obtained in this study for the LRSM (left) and the SMC125 (right). CIs associated with the curves are shown as shaded polygons.

endangered cod. Considering the differences in morphology and somatic growth between these flatfish species and cod, the design of the LRSM involved the optimization of the codend mesh size and mesh shape to achieve the intended performance. The LRSM was compared to a square-mesh codend design (SMC125) implemented in the fishery as a technological measure for the protection of cod stocks in flatfish fisheries.

Overall, the LRSM demonstrated a more desirable exploitation pattern than the SMC125 on flatfish species. For the most important flatfish species, plaice, the desired exploitation pattern was achieved, where 85 % of the target sizes were retained and 92 % of the unwanted sizes were released (Table 5). From a multispecies perspective, both codends demonstrated the ability to discriminate between sizes and species in the marine population that were abundant in the fished area, where wanted catches constituted 60 % and 55 % retained in the codend contrary to the 14 % and 15 % of what entered the codend in the LRSM and SMC125, respectively (Fig. 4). Despite the LRSM providing a more desired exploitation pattern than SMC125, its performance is still not as good as sought-after since the unwanted catch constitutes 24 % of the total (red zone in Figs. 4 and 5).

In terms of cod bycatch, the results show that both codends performed very efficiently in releasing cod out of the trawl, as only 3 % and 4 % of all cod that entered the codend were caught in the LRSM and SMC125, respectively. The LRSM showed a higher release-efficiency of cod compared to the SMC125. This improved release efficiency can be explained by the larger mesh size in the LRSM, mesh geometry, or the combined effect of both design aspects. The population structure for cod might be decisive for the positive result for the LRSM, where the high number of small cod led to the high number of releases being high. However, catching mostly smaller-sized cod is no longer a rare event; it has become the new reality in the Baltic Sea (Santos, 2021). Therefore,

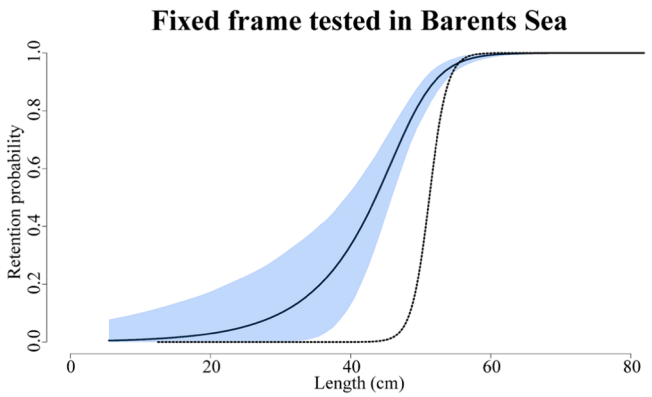

Fig. 8. Comparison of the fall troughs model (black dashed line) (Sistiaga et al., 2011) and catch data for cod in the Barents Sea caught with a similar codend concept (solid black line and shaded area denotes CIs) (for full catch data see (Herrmann et al., 2024)).

these are the conditions under which the LRSM must perform, and therefore the results obtained are promising.

Catching other species than the intended target can have impact on the sustainability of the fishery (Petetta et al., 2023). However, the flatfish directed fishery in the Baltic Sea in general catches few species other than the intended (Fig. 4). Mussels, jellyfish, starfish, herring/-sprat and whiting were the only species with more than 10 individuals combined during the sea trials caught in the one of the codends. These few species are all listed as species with no commercial or preservation concerns in this specific fishery.

Wienbeck et al., (2014) investigated a 5 mm knotless square-mesh codend with a mesh size of 127.9 mm which is comparable to the SMC125 tested here. Wienbeck et al., (2014) found a *L50* for cod of 45.6 cm (CI: 43.2; 47.8 cm), which compared to our finding for both codends are higher (Fig. 7). Thereby the codend used by Wienbeck et al., (2014) seem to have better release of larger cod than the two tested codends. As the technical measures of the SMC125 and the Wienbeck et al., (2014) codend is similar, they were expected to be approximately the same.

Fig. 6 showed that cod and flounder, contrary to plaice and dab, do not utilize the full escape potential provided by the LRSM codend. This could partly explain why the LRSM did not fulfill the initial zero-cod bycatch expectations, especially considering that the cod population encountered during the experimental trials was mostly composed of small individuals.

The same tendency of cod not exploiting theoretical full escape possibilities offered by the meshes has also been observed in the Norwegian cod fishery in the Barents Sea (Fig. 8). In that fishery, Herrmann et al. (2024) tested a rigid codend similar to the LRSM. In particular, the LRSM and the design tested in Herrmann et al. (2024) differed in dimensions and mesh size. Looking at the retention curve in Fig. 7, the curve seems to have the same tendency to have a flatter slope towards the smaller sizes. This means that there is a retention of small cod, which should be able to escape if fully open meshes were available. It could be speculated that cod and flounder, while in the codend, are less active in attempting escape during most of the fishing process compared to plaice and dab. It could also be due to the fact that the release potential is based on optimal contact (perpendicular to meshes) and that requires a swimming maneuver that cod and flounder are less able or willing to undertake. Further, it could be speculated that the very short towing time in these experiments could have influenced the selectivity for flounder and cod. A longer towing time or a short period of buffer towing during haul back might be beneficial for size selection for the LRSM, as this has previously been shown to improve selectivity (Brinkhof et al., 2018). However, further research is needed to investigate this which could also include direct observation of the behavior during the fishing process. Future work should investigate how to improve the selectivity of species that are more passive in the codend, either by making their escape as easy as possible or by introducing devices that stimulate mesh contact. An example of a measure that might activate the escape efforts for more passive species could be a shaking codend (Nguyen et al., 2023). Alternatively, it could be speculated that utilizing the hydrodynamic flow in the codend to maximize the mesh contact might improve selectivity or ensuring escape gaps are placed optimal for escape.

In the experiment, the haul duration was shorter than what would typically occur in commercial fishing operations and consequently the catch size was smaller. When scaling up to commercial conditions, with longer towing times and larger catches, it is expected that the LRSM would maintain its desirable exploitation pattern and continue to exhibit low variability in mesh openness. This consistency is due to the proof-of-concept design, which helps preserve mesh geometry even under increased catch pressure.

In contrast, the SMC125 is likely to show higher variability in mesh openness during longer tows. As the catch accumulates, the mesh openings just in front of the build-up increases, causing the mesh openings to variate. This variation leads to inconsistent mesh openings, meaning that fish encountering the mesh at different times during the tow may experience different escape opportunities. Such variability could negatively impact the selectivity and overall performance of the gear under commercial conditions.

Besides the need for stimulating some species to fully utilize the escape opportunities provided by the LRSM, this codend concept demonstrated the potential to improve the harvesting pattern in a multispecies fishery aiming at size selecting flatfish while avoiding capture of cod. However, for use in commercial fisheries, another design that provides the same mesh properties as the currently tested proof of concept model of the LRSM needs to be developed.

CRediT authorship contribution statement

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

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jordan P. Feekings reports financial support was provided by Danish Maritime, Fisheries and Aquaculture Program. Zita Bak-Georgsen reports financial support was provided by Danish Maritime, Fisheries and Aquaculture Program. Bent Herrmann reports financial support was provided by Danish Maritime, Fisheries and Aquaculture Program. Valentina Melli reports financial support was provided by Danish Maritime, Fisheries and Aquaculture Program. If there are other authors, they declare that they have no known competing financial interests or

personal relationships that could have appeared to influence the work reported in this paper.

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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.rsma.2025.104544.

Data availability

Data will be made available on request.

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