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The influence of twine thickness, twine number and netting orientation on codend selectivity

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ABSTRACT

Based on an experimental Baltic trawl fishery, we tested diamond mesh codends with different twine thicknesses, twine numbers (single or double), and netting orientation (T0 or T90) to quantify the effects of the twine characteristics on the size selection of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). For a given twine thickness: going from T0 to T90 increases selectivity of cod; while going from single to double reduce it. Increasing twine thickness reduces selection but the extent depends on whether the twine is single or double and whether the netting orientation is T0 or T90. In general, the results demonstrate the benefit of using a relatively thin single twine netting to ensure the appropriate size selection with round fish and the best results were obtained using netting with a T90 orientation. For a given twine thickness going from T0 to T90 decreases selectivity of plaice. Increasing twine thickness reduces selection for plaice. Our results demonstrate that very different selectivity results can be obtained using the same mesh size, simply by varying the twine thickness, the twine number, and the netting orientation. In some fisheries, the size selectivity could be improved considerably by adjusting these simple design parameters alternatively to produce more advanced and complex designs.

1. Introduction

Because of its simplicity of construction and ease of operation, diamond mesh codends have traditionally been used to fish for round fish such as cod and haddock (*Melanogrammus aeglefinus*), and flatfish species such a plaice, at the aft end of demersal trawls in northern European fisheries (Graham et al., 2007; O'Neill and Herrmann, 2007; Krag et al., 2008). In recent years, the fishing industry has introduced stronger, stiffer, and thicker twines, which are often used as double twine netting, particularly in the designs of diamond mesh cod-ends used by many European trawl fisheries (Herrmann and O'Neill, 2006). Concerns about their effect on codend size selectivity led to restrictions on the maximum twine thickness and twine number allowed onboard EU fishing vessels. EU regulations, such as 850/1998 and 1967/2006, define the maximum twine thickness permitted in codends used in European waters. The maximum thickness of diamond meshes is 6 mm for double twines and 8 mm for single twine in northern European waters while it is 3 mm in the Mediterranean area. For the size selection of haddock, experimental studies (Lowry and Robertson, 1996; Kynoch et al., 1999) and theoretical studies (Herrmann and O'Neill, 2006; O'Neill and Herrmann, 2007) have demonstrated a significant decrease in the 50% retention length (*L*50) with increasing netting twine thickness for double twine diamond mesh codends. In particular, Herrmann and O'Neill (2006) formulated a set of hypotheses, using the simulation tool PRESEMO (Herrmann, 2005a), to investigate mechanisms that might potentially explain and quantify the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends (T0 cod-ends). The authors reported that an increase in twine thickness could lead to a reduction in selectivity, because: (i) the internal lateral mesh opening of meshes made of thicker twine would be smaller with the same knot-center to knot-center lateral mesh opening; (ii) the increased twine bending stiffness of thicker twines would increase the mesh resistance to opening; (iii) it would be more difficult for fish to deform and escape via partly open meshes compared with those made from stiffer twine; and (iv) netting made from thicker twine

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would present a greater visual barrier to fish, which may discourage them from making escape attempts. Thus, the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends have been well described in the scientific literature, based on experimental and theoretical investigations. From a mechanistic perspective, the effect of twine thickness on haddock size selection using double twine diamond mesh codends can probably be extrapolated to predict and understand the size selection of morphologically similar round fish species such as cod. However, this extrapolation is less likely to be applicable to flatfish species such as plaice, which has a very different cross-sectional shape compared with round fish species. In Baltic Sea trawl fisheries that target cod, the codends made solely from traditional diamond mesh netting has been banned in the legislation since 2003, while it is legal to use diamond mesh netting in combination with square meshes in the BACOMA design and codends where the diamond mesh netting direction is turned 90° (T90)(EU Regulation No. 2187/2005). The T90 codend, which for cod, is believed to have better size selectivity properties compared with the traditional T0 cod-end (Dahm, 2004), was introduced as a legal alternative to the BACOMA codend in the Baltic Sea cod trawl fishery during 2005. For a specific type of single twine netting, Wienbeck et al. (2011) have documented improved cod size selective properties when using T90 cod-ends compared with similar T0 cod-ends. However, Wienbeck et al. (2011) cautioned that their results are specific to the type of netting used for the cod-ends in their experiments and they recommended that a systematic study should be conducted to investigate the effects of twine parameters such as thickness and twine number on the size selectivity of T0 and T90 codends. Furthermore, the legislation describing the construction of T90 codends for the Baltic Sea trawl fishery did not define a specific twine thickness, although an upper limit of twine thickness for single and double twine codends was specified (EU Regulation No. 2187/2005 and EU Reg. No. 686/2010). It is unknown to what extent the size selectivity properties of the T90 codend vary within the legal ranges for twine thickness below this maximum thickness and to what extent the twine number in the netting is important.

During trawl fishing, the codend meshes are stretched by hydrodynamic drag forces that act primarily on the accumulated catch in the aft (Herrmann, 2005b; Herrmann et al., 2006). However, difference in mechanical properties of the T0 and T90 codends mean that the shapes of their meshes can be very different during fishing, which can influence their size selectivity properties. According to Herrmann et al. (2007), the bending stiffness of the T0 codends mesh bar, which depends on the twine thickness, tends to keep the meshes closed. By contrast, an increased twine bending stiffness will increase the resistance against mesh closing with the T90 netting. Furthermore, the netting knot size, which increases with twine thickness, may also contribute to the benefit of turning the netting by 90°. These effects seem to favor the use of T90 constructions made of thick twine to achieve high L50 values.

However, some mechanisms that influence the effect of the twine thickness on size selection were described by Herrmann and O'Neill (2006), such as the ability of fish to partly deform the mesh bars during escape attempts and the visual barrier, which favors constructions based on thinner twine netting. These potentially counteracting mechanisms make it difficult to predict the overall effect of changing the twine characteristics (twine thickness and number) on the size selectivity of T0 and T90 cod-ends for round and flatfish species.

Given this lack of knowledge, the main aim of this study was to investigate and quantify the effect of twine thickness, twine number (single or double), and the netting orientation on size selectivity. Therefore, we formulated the following research questions: (i) To what extent does the twine thickness in the codend affect the size selection of round fish (cod) and flatfish (plaice)? (ii) Does it matter whether the codend is made of single or double twine netting? (iii) Do these twine characteristics affect the size selectivity of cod and plaice in different ways with the T0 and T90 codends?

2. Materials and methods

2.1. Experimental design

To investigate the research questions regarding the effect of twine characteristics on codend size selection, we tested a total of 12 different codends made of six different commercial netting types (Fig. 1). All codends were made of polytit COMPACT netting (EuroRed S.L., Callosa de Segura, http://www.eurored.org). A T0 and a T90 codend were made from each netting type, resulting in six pairs of codends. Three pairs of nets were made of double twine netting (nominal twine diameter 3, 4, and 6 mm), and three pairs were made of single twine netting (nominal twine diameter 4, 6, and 8 mm). The actual twine diameter was estimated by scanning sample pieces of the different nets using a high resolution flatbed scanner and the image analysis facilities in the FISHSELECT program (Herrmann et al., 2009).

All codends were constructed with 50 open meshes in the circumference to comply with the current legislation for the Baltic Sea trawl fishery regarding this design parameter for T90 codends. A symmetrical two-panel construction with identical upper and lower panel was used for all codends. All codends had the same number of meshes in the two selvedges (three). We attempted to keep the mesh size identical for all codends (approximately 123 mm), although it differed slightly between the different nettings. The mesh size was measured using an OMEGA-gauge (Fonteyne et al., 2007; Council Regulation (EC) No. 517/2008 of 10 June 2008). Based on their construction and twine characteristics, all of the T90-codends described in Fig. 1 can be used legally in the demersal Baltic Sea trawl fishery.

Each of the 12 codends was fished alternately, one at a time, while attached to the same trawl and the same extension piece. The trawl used was a "Codhopper," which has a circumference of 530 meshes and a 160 mm mesh size in the belly. The trawl was spread using two 3.5 m^2 Bison trawl doors. The extension piece was a T90 construction with 50 open meshes around and 50 meshes in length, made of nominal 120 mm single 5 mm netting using the same polytit COMPACT netting that was used for the codends. The codend was the only change in gear between the individual tows.

The covered codend method (Wileman et al., 1996) was applied. Supporting hoops were applied to keep the cover netting clear of the test codend. The cover was connected to the extension piece two mesh rows before the codend. The cover was 238 meshes long. The 2.6 m diameter of the cover hoops ensured that the diamond shaped cover meshes were almost open like square meshes. The cover was a two panel construction with a total of 264 meshes in circumference. The cover mesh size was 80 mm because previous experience during experimental fisheries in the same region demonstrated that fishing with a smaller cover mesh size was impossible because of the retention of large amounts of herring in the cover (Wienbeck et al., 2011). Compared with the recommendations of Wileman et al. (1996), this cover mesh size was rather large compared with the test codend mesh sizes (Table 1). Therefore, special attention was given in the analysis to remove length classes where the selection of cover and test codend potentially overlapped. The experimental fishing was conducted onboard the German Fishery Research Vessel (FRV) "Solea" (total length = 42 m, 950 kW). To make the conditions as similar as possible for each codend, all hauls were conducted on the same fishing ground.

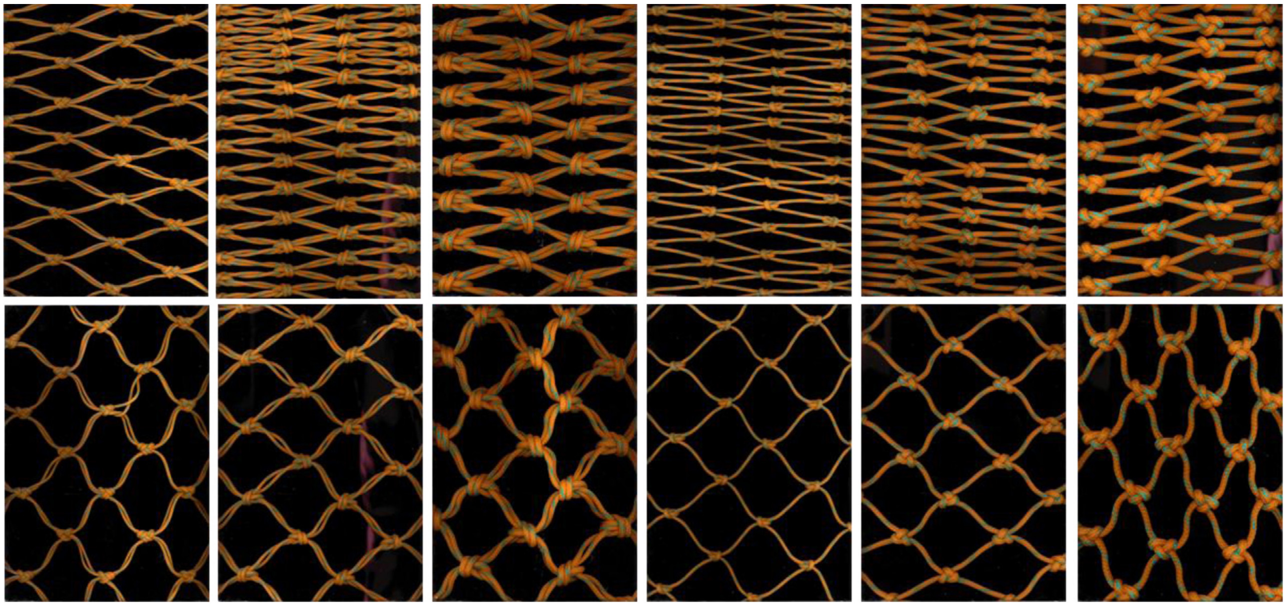

Fig. 1. Nettings used for the 12 codends. Top: the six different nettings stretched in the T0 direction. Bottom: the six different nettings stretched in the T90 direction. From left to right: double twine 3 mm (D3), double twine 4 mm (D4), double twine 6 mm (D6), single twine 4 mm (S4), single twine 6 mm (S6), and single twine 8 mm (S8).

2.2. Data analysis

To model the size selection of cod and plaice for the individual hauls, we used a logistic curve described by the parameters $L50$ and the selection range SR (=$L75-L25$) (Wileman et al., 1996). The capacity of the logistic curve for modeling the data from individual hauls was inspected based on the fit statistics, i.e., the p-value and model deviance versus the degrees of freedom (DOF), following the procedures described by Wileman et al. (1996). In case of a poor fit statistic (p-value < 0.05; deviance $\gg$ DOF), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using the logistic curve or if it was due to the overdispersion of the data. To be able to quantify the strength of the data linked to the amount of binominal noise within it, the R^2-values were also calculated to the ability of the logistic model to describe the experimental data. The R^2-value quantifies the ratio of the variation in the data explained by the model to the total amount of variation in the data. To avoid potential bias in the analysis due to cover selection, the data for length classes below 33 cm were not used for cod, following the procedure described by Wienbeck et al. (2011).

The same method for checking the potential bias due to the cover selection, which as described for cod by Wienbeck et al. (2011), was also applied to plaice prior to the experiments. This found that it is unlikely that any of the available sizes of plaice (>14 cm) would have passed through the cover meshes. Therefore, no plaice length classes were eliminated from the data analysis. To account for the effect of minor differences in mesh sizes between the different codends (Table 1), the analysis was based on the selection factor SF (=$L50/mesh\ size$) and selection ratio SFA (=$SR/mesh\ size$), instead of $L50$ and SR. Therefore, the results from single hauls were transformed from an L50–SR domain to an SF–SFA domain, before the next steps in the analysis (Herrmann and O'Neill, 2006). After the last step in the analysis, the results can be transformed back to the traditional L50–SR domain by multiplying with the specific mesh size. This makes the results directly comparable for the different codends with the different twine characteristics (twine thickness, twine number, and netting orientation).

The data were analyzed using the software tool SELNET. SELNET is a flexible software tool that was developed to acquire and analyze size selectivity and catch data for towed fishing gears, both at the haul level and for a group of hauls. The methods implemented in SELNET comply with the recommendations for the analysis of size selectivity data, which were described by Wileman et al. (1996) and in Fryer (1991). SELNET was developed by the corresponding author of the current study and additional information on SELNET can be obtained directly from him or by consulting the following

Table 1
Specification of the different cod-ends used in this experiment. Each codend name is based on the netting orientation (T0 or T90) and the twine characteristics (see Fig. 1). The parameters TD, DO, T90, and codend category were used in the analysis.

Codend	Mesh size (mm)	*td*: twine diameter (mm)	DO: double twine	T90: netting turned 90°	CC: codend category
T0S4	125.4	3.89	0	0	$T0_{single}$
T0S6	124.2	5.72	0	0	$T0_{single}$
T0S8	124.4	7.40	0	0	$T0_{single}$
T0D3	125.3	3.10	1	0	$T0_{double}$
T0D4	123.4	3.66	1	0	$T0_{double}$
T0D6	123.2	5.49	1	0	$T0_{double}$
T90S4	125.4	3.89	0	1	$T90_{single}$
T90S6	124.2	5.72	0	1	$T90_{single}$
T90S8	124.4	7.40	0	1	$T90_{single}$
T90D3	125.3	3.10	1	1	$T90_{double}$
T90D4	123.4	3.66	1	1	$T90_{double}$
T90D6	123.2	5.49	1	1	$T90_{double}$

references (Sistiaga et al., 2010; Wienbeck et al., 2011; Frandsen et al., 2011; Eigaard et al., 2011; Herrmann et al., 2012).

The analysis applied considered the between-haul variation in the selection process and the effect of codend design parameters, following the procedure described by Fryer (1991). This involves a two-step procedure, as follows. First, analyzing the hauls individually by fitting a logistic curve to the data, as described above. The second step uses the results from all the individual hauls simultaneously for the *SF* and *SFA*, together with their covariance matrix and information on the values of the design parameters *td* (*twine thickness in mm*), *DO* (*double twine:0.0 for single twine netting*; *1.0 for double twine netting*), and *T*90 (T90 orientation: 0.0 for T0 orientation netting; 1.0 for T90 orientation netting) for the codends used in each of the hauls. The data were analyzed species by species, while considering the codend design parameters *td*, *DO*, and *T*90 as potential fixed effects for *SF* and *SFA* (see Table 1). A special model with the following form was constructed and applied in SELNET (see Appendix A for model development and justification).

$$
\begin{aligned}
SF &= f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2 + f_9 \times w \\
SFA &= g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2 + g_9 \times w
\end{aligned}
\tag{1}
$$

Compared with equation (A2) in Appendix A, this Eq. (1) includes additional linear terms ($f_9 \times w$ and $g_9 \times w$) to model the potential general linear effect of the codend catch weight on the codend size selection. W is the total codend catch weight at end of the haul. The codend catch weight is included in the model as a potential fixed effect because it is expected to vary between individual hauls and because some authors have found that it can potentially affect the codend size selection in diamond mesh codends (O'Neill and Kynoch, 1996; Herrmann, 2005b). Thus, Eq. (1) is used to model the effect of the twine characteristics on the *SF* and *SFA* for different codends, while accounting for the potential general effect of the codend catch weight. The species-specific parameters $f_0 \ldots f_9$ and $g_0 \ldots g_9$ have to be estimated while fitting the model to datasets with values for SF and SFA, based on the experimental selectivity results from the individual hauls. Model selection was performed for each species separately based on the AIC value (Akaike, 1974), while considering every possible simpler sub-model following the procedure described in Wienbeck et al. (2011). This resulted in a total of 1,048,576 models that needed to be run and tested for each species in SELNET.

Before making conclusions regarding the effects of twine thickness and twine number for cod and plaice based on the selected models, it was important to check that the models agreed with the results from the individual hauls, on which they were based. Thus, we considered the uncertainty of the individual results and inspected whether the model prediction appeared to reflect the main trends for the effects of twine thickness on the results for each codend category: $T0_{single}$ (DO = 0; T90 = 0), $T0_{double}$ (DO = 1; T90 = 0), $T90_{single}$ (DO = 0; T90 = 1), and $T90_{double}$ (DO = 1; T90 = 1) (see Table 1). The individual codends used in the experiments did not have the same mesh opening. Therefore, it was also necessary to follow the trends in the L50 and SR values for the individual codends to calculate the corresponding *L*50 and *SR* values for a theoretical 120-mm mesh opening simply by multiplying the individual *SF* and *SFA* values by 12. The corresponding confidence limits (CI) for the individual codends were also determined simply by multiplying the lower and upper limit values for the *SF* and *SFA* by 12. The estimates for a mesh size of 120 mm were of particular interest for the Baltic Sea trawl fishery, because this is the minimum legal mesh opening for the T90 codend used in that fishery. After inspecting whether the results from the individual hauls conflicted with the model predictions, it was necessary to consider the estimates of the between-haul variation in the selection process in addition to the uncertainty of the haul results. Therefore, the individual haul results were plotted for the *L*50 and *SR* with 95% CI versus the mean model estimated values and the predicted 95% CI for the between-haul variation. The lower and upper 95% CI for the estimated between-haul variation in the selection parameters (lim L50, lim SR) for a mesh size of 120 mm were calculated by:

$$
\begin{aligned}
\text{lim} \quad L50 &= 12 \times (SF \pm 1.96 \times \sqrt{D_{11}}) \\
\text{lim} \quad SR &= 12 \times (SFA \pm 1.96 \times \sqrt{D_{22}})
\end{aligned}
\tag{2}
$$

where *SF* and *SFA* are the predictions based on the selected submodel based on (1), and D_{11} and D_{22} are the diagonal elements in the estimated between haul-variation matrix for the selected model (for details see Fryer, 1991).

The effect of turning the net orientation by 90° from T0 to T90 with the different codend categories ($T0_{single}$, $T0_{double}$, $T90_{single}$ and $T90_{double}$) was given as a percentage effect (p_T90) for the 120 mm nominal mesh opening. The mean percentage effect for L50 (p_T90_{L50}) was predicted using the resulting submodels (1) with the parameters DO and T90 for a range of twine thickness values *td* to estimate the pairs of *L*50 for the T0 and T90 designs:

$$
p\_T90_{L50} = \frac{L50_{T90} - L50_{T0}}{L50_{T0}} \times 100 \tag{3}
$$

A similar approach was used for *SR*.

3. Results

3.1. Collection of selectivity data

The experimental fishing trials were conducted between 18 March and 7 April 2011 in the Arkona Basin, western Baltic Sea. The water depths varied between 32 and 49 m in the fishing grounds. The average towing speed (GPS speed over ground) was 3.4 knots (range of 3.2–3.6 knots). The haul duration was between 90 and 180 min (mean = 150.2 min). The size selectivity data for cod and plaice were collected from a total of 43 valid hauls. The catch information for each haul is described in Table 2. In addition to cod and plaice, the most abundant catch species in the codend catch was flounder (*Platichthys flesus*) while the cover catch also contained large quantities of herring and sprat. The total catch weight in the codend varied from 180 to 1266 kg. A total of 64,376 cod measuring between 13 and 103 cm were caught and their lengths were measured to the nearest cm. We used 47,276 cod measuring >33 cm and their data in the analysis. For plaice the length span was 14–50 cm and a total of 13,760 were caught and measured. The total number of cod (>33 cm) in the test codend ranged from 130 to 1370 individuals, and from 155 to 2253 in the cover. The number of plaice in the test codend ranged from 42 to 319 and from 52 to 420 in the cover. The high number of target species (cod and plaice) caught in most hauls, combined with no subsampling provided strong data for cod in particular, with very little binominal noise in the size selection data.

3.2. Analysis of the cod data

As described in Section 2.2, a logistic curve was fitted to data from individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values. Table 3 summarizes the results from individual hauls of cod. Inspection of fit statistics indicated that there were no problems with using a logistic curve to describe the selection data for all hauls, except for haul no. 4 (*p*-value = 0.02). The inspection of the residuals for haul 4 did

Table 2
Catch data for individual hauls.

Haul no.	Codend	Total codend catch (kg)	Cod							Plaice						
			Codend catch (kg)	No. length classes	Min length (cm)	Max length (cm)	Total no.	No in codend	No. in cover	Codend catch (kg)	No. length classes	Min length (cm)	Max length (cm)	Total no.	No. in codend	No. in cover
1	T90D4	422	321	34	33.5	80.5	1201	370	831	33	25	16.5	44.5	217	152	65
2	T90D4	844	727	36	33.5	79.5	3057	804	2253	30	24	16.5	39.5	264	152	112
3	T90D4	375	269	33	33.5	102.5	1118	364	754	18	21	16.5	39.5	262	99	163
4	T90D4	251	171	29	33.5	64.5	965	209	756	21	23	17.5	46.5	181	99	82
5	T90S4	427	271	30	33.5	72.5	1362	340	1022	34	25	17.5	46.5	303	159	144
6	T90S4	284	135	23	33.5	62.5	521	188	333	29	24	15.5	40.5	380	125	255
7	T90S4	434	329	32	33.5	74.5	1851	350	1501	21	24	16.5	39.5	209	88	121
8	T90S4	423	300	29	33.5	65.5	1598	358	1240	23	21	15.5	36.5	282	105	177
9	T90D6	572	357	22	33.5	58.5	1053	549	504	53	26	15.5	42.5	423	314	109
10	T90D6	546	424	32	33.5	72.5	1250	571	679	31	23	16.5	46.5	232	172	60
11	T90D6	631	404	29	33.5	74.5	1251	557	694	52	24	15.5	47.5	438	327	111
12	T90D6	461	288	25	33.5	58.5	788	405	383	41	24	16.5	42.5	392	233	159
13	T90S6	595	478	29	33.5	72.5	1909	608	1301	25	26	16.5	45.5	192	134	58
14	T90S6	573	410	30	33.5	71.5	1638	523	1115	48	23	16.5	41.5	475	263	212
15	T90S6	281	153	22	33.5	54.5	503	216	287	33	24	16.5	40.5	343	191	152
16	T90S6	346	284	28	33.5	71.5	1881	384	1497	21	23	16.5	40.5	224	98	126
17	T90D3	430	283	26	33.5	58.5	1460	349	1111	44	26	16.5	43.5	439	222	217
18	T90D3	299	149	24	33.5	79.5	618	205	413	36	22	15.5	37.5	429	188	241
19	T90D3	386	227	30	33.5	80.5	951	264	687	30	25	16.5	42.5	371	135	236
20	T90D3	219	159	27	33.5	66.5	589	185	404	13	23	17.5	42.5	123	52	71
21	T90S8	243	176	26	33.5	61.5	526	209	317	22	28	16.5	44.5	198	90	108
22	T90S8	529	418	31	33.5	63.5	1539	479	1060	41	27	16.5	43.5	290	218	72
23	T90S8	315	160	26	33.5	67.5	672	221	451	44	21	15.5	37.5	474	302	172
24	T90S8	713	147	27	33.5	65.5	512	155	357	23	24	17.5	42.5	177	125	52
25	T0D4	364	305	27	33.5	74.5	874	410	464	20	25	17.5	46.5	199	73	126
26	T0D4	428	348	28	33.5	61.5	965	447	518	23	28	15.5	48.5	213	78	135
27	T0D4	280	224	26	33.5	63.5	567	293	274	16	24	17.5	42.5	157	57	100
28	T0S4	273	233	27	33.5	62.5	488	295	193	12	21	17.5	37.5	137	47	90
29	T0S4	180	123	25	33.5	92.5	516	130	386	11	23	17.5	39.5	113	42	71
30	T0S4	363	245	28	33.5	71.5	1343	273	1070	26	23	16.5	39.5	360	103	257
31	T0S4	302	176	27	33.5	63.5	817	192	625	34	27	14.5	43.5	450	137	313
32	T0D3	272	192	21	33.5	55.5	837	255	582	26	26	16.5	42.5	397	102	295
33	T0D3	234	180	27	33.5	60.5	792	227	565	14	22	16.5	39.5	219	49	170
34	T0D3	326	187	24	33.5	76.5	505	270	235	32	25	14.5	40.5	500	130	370
35	T0S8	798	542	29	33.5	68.5	1055	836	219	28	25	16.5	43.5	457	120	337
36	T0S8	474	384	28	33.5	63.5	862	561	301	16	25	16.5	42.5	214	152	62
37	T0S8	598	401	30	33.5	83.5	792	577	215	35	26	15.5	42.5	339	250	89
38	T0S8	604	423	26	33.5	72.5	975	641	334	24	25	17.5	43.5	365	272	93
39	T0D6	922	717	30	33.5	65.5	1250	1095	155	25	25	15.5	49.5	396	124	272
40	T0D6	1266	937	31	33.5	73.5	1810	1370	440	49	25	16.5	41.5	683	263	420
41	T0D6	1057	788	29	33.5	69.5	1338	1055	283	33	26	14.5	41.5	477	158	319
42	T0S6	586	479	28	33.5	73.5	1618	662	956	27	24	15.5	38.5	413	124	289
43	T0S6	461	360	26	33.5	60.5	1059	552	507	24	24	16.5	46.5	353	110	243

Table 3
Estimation of the selection parameters and fit statistics for individual hauls of cod.

Haul no.	Codend	L50 (cm)	SR (cm)	SF	SFA	p-Value	Deviance	DOF	R^2-value
1	T90D4	41.94	7.21	3.40 (3.35–3.45)	0.58 (0.50–0.67)	0.9709	18.66	32	0.9823
2	T90D4	42.54	5.38	3.45 (3.42–3.47)	0.44 (0.40–0.47)	0.7917	27.15	34	0.9941
3	T90D4	41.22	6.99	3.34 (3.29–3.39)	0.57 (0.48–0.65)	0.5890	28.62	31	0.9759
4	T90D4	43.61	7.43	3.53 (3.44–3.63)	0.60 (0.47–0.73)	0.0202	44.10	27	0.9045
5	T90S4	42.58	7.79	3.40 (3.34–3.46)	0.62 (0.53–0.72)	0.9008	18.91	28	0.9734
6	T90S4	39.86	6.16	3.18 (3.12–3.24)	0.49 (0.39–0.60)	0.9833	9.63	21	0.9646
7	T90S4	45.63	8.31	3.64 (3.57–3.70)	0.66 (0.58–0.75)	0.5403	28.57	30	0.9688
8	T90S4	43.62	6.43	3.48 (3.43–3.52)	0.51 (0.45–0.57)	0.8521	19.47	27	0.9867
9	T90D6	37.21	5.37	3.02 (2.99–3.05)	0.44 (0.37–0.50)	0.7376	15.66	20	0.9834
10	T90D6	38.24	4.43	3.10 (3.08–3.13)	0.36 (0.31–0.40)	0.9999	8.92	30	0.9954
11	T90D6	38.23	5.10	3.10 (3.07–3.13)	0.41 (0.36–0.47)	0.9292	17.08	27	0.9852
12	T90D6	37.45	4.70	3.04 (3.01–3.07)	0.38 (0.32–0.44)	0.9943	9.43	23	0.9873
13	T90S6	41.25	6.69	3.32 (3.29–3.36)	0.54 (0.48–0.60)	0.7697	21.35	27	0.9850
14	T90S6	41.22	6.29	3.32 (3.28–3.35)	0.51 (0.45–0.57)	0.9575	16.52	28	0.9905
15	T90S6	39.09	7.04	3.15 (3.09–3.21)	0.57 (0.44–0.70)	0.1606	26.16	20	0.8517
16	T90S6	41.83	5.19	3.37 (3.33–3.41)	0.42 (0.37–0.47)	0.9397	15.85	26	0.9748
17	T90D3	42.48	7.18	3.39 (3.34–3.44)	0.57 (0.49–0.65)	0.7752	18.56	24	0.9789
18	T90D3	39.71	4.81	3.17 (3.13–3.21)	0.38 (0.31–0.45)	0.5560	20.43	22	0.6846
19	T90D3	41.33	6.03	3.30 (3.25–3.35)	0.48 (0.41–0.56)	0.7348	22.96	28	0.9768
20	T90D3	42.37	7.68	3.38 (3.31–3.46)	0.61 (0.49–0.73)	0.9416	14.99	25	0.9466
21	T90S8	40.36	5.19	3.24 (3.20–3.29)	0.42 (0.34–0.49)	0.9835	11.66	24	0.9892
22	T90S8	41.21	5.92	3.31 (3.28–3.35)	0.48 (0.42–0.53)	0.5791	26.86	29	0.9792
23	T90S8	40.04	7.20	3.22 (3.15–3.28)	0.58 (0.46–0.70)	0.9049	15.51	24	0.9540
24	T90S8	41.82	4.80	3.36 (3.31–3.42)	0.39 (0.31–0.46)	0.9008	16.45	25	0.9835
25	T0D4	38.88	7.96	3.15 (3.10 –3.20)	0.65 (0.53–0.76)	0.9990	8.69	25	0.9816
26	T0D4	39.51	7.25	3.20 (3.16–3.24)	0.59 (0.49–0.68)	0.4697	25.88	26	0.9188
27	T0D4	38.79	7.69	3.14 (3.09–3.20)	0.62 (0.49–0.76)	0.9990	8.09	24	0.9812
28	T0S4	37.91	8.65	3.02 (2.95–3.09)	0.69 (0.52–0.86)	0.3923	26.29	25	0.8903
29	T0S4	43.21	6.21	3.45 (3.37–3.52)	0.50 (0.39–0.60)	0.9967	8.76	23	0.9711
30	T0S4	43.50	6.84	3.47 (3.41–3.53)	0.55 (0.47–0.62)	0.4783	25.72	26	0.9800
31	T0S4	43.03	6.81	3.43 (3.36–3.50)	0.54 (0.45–0.64)	0.7792	19.37	25	0.9518
32	T0D3	40.57	6.46	3.24 (3.18–3.29)	0.52 (0.42–0.61)	0.7316	14.86	19	0.9712
33	T0D3	41.83	7.43	3.34 (3.27–3.41)	0.59 (0.48–0.70)	0.9435	14.91	25	0.9501
34	T0D3	37.32	8.74	2.98 (2.91–3.04)	0.70 (0.51–0.89)	0.7853	16.59	22	0.9255
35	T0S8	29.84	11.08	2.40 (2.22–2.57)	0.89 (0.60–1.18)	0.5030	26.28	27	0.8110
36	T0S8	35.00	8.86	2.81 (2.75–2.88)	0.71 (0.55–0.88)	0.7583	20.68	26	0.9401
37	T0S8	34.33	6.25	2.76 (2.70–2.81)	0.50 (0.39–0.61)	0.9980	11.19	28	0.9713
38	T0S8	34.51	7.44	2.77 (2.73–2.82)	0.60 (0.47–0.72)	0.9822	11.79	24	0.9637
39	T0D6	29.97	7.67	2.43 (2.29–2.57)	0.62 (0.45–0.79)	0.9999	8.35	28	0.9689
40	T0D6	32.06	9.54	2.60 (2.52–2.68)	0.77 (0.62–0.92)	0.9562	17.36	29	0.9628
41	T0D6	30.76	9.98	2.50 (2.38–2.62)	0.81 (0.61–1.01)	0.9713	14.86	27	0.9249
42	T0S6	39.60	8.59	3.19 (3.15–3.23)	0.69 (0.59–0.79)	0.9320	16.17	26	0.9759
43	T0S6	37.07	8.08	2.98 (2.94–3.03)	0.65 (0.53–0.77)	0.3524	26.01	24	0.9414

not indicate any structural problems with using the logistic curve to model the experimental data. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about applying the logistic curve to model the size selection of cod in all hauls. In general, high R^2-values were obtained, i.e., all but one was >0.8 and only 4/43 were <0.90 (Table 3). In addition to the capacity of the model for describing the data, these high R^2-values also highlighted the low binominal noise in the data as a consequence of strong data acquisition because many cod were measured and no subsampling was applied.

The values for L50 ranged from 29.84 cm to 45.63 cm, which did correspond to the SF values of 2.40 and 3.64. The highest values were obtained for hauls 7 (T90S4), 1–4 (T90D4), 8 (T90S4), 17 (T90D3), and 29–31 (T0S4) (Table 3). By contrast, low L50 and SF values were determined for haul 35 (T0S8) and hauls 39–41 (T0D6). The range of values for SR and SFA were 4.43 cm to 11.08 cm and 0.36–0.89, respectively. Thus except for codend T0D6 the data included in the analysis covered most of the selective range from zero retention ($r(l) = 0.0$) to full retention ($r(l) = 1.0$). For T0D6 detail inspection of results showed the data coverage at the lowest length class (33 cm) varied from $r = 0.55$ to $r = 0.70$. This increase the uncertainty when evaluating the validity of the logit curve to model the size selection of the full selection curve for this codend design and increase confidence limits for the estimated SF and SFA values (Tables 2 and 3). But given the fact that none of the results for the other codends indicated problems by applying the logit curve to model the size selection in individuals we assume that is this also valid for the T0D6 design even if the SF and SFA values are based on extrapolation of the estimated logit curve. Therefore despite of the poor coverage of the selective range for the hauls with the T0D6 codend we have chosen also to use the results for this codend in the further analysis. This is further defended by that in the further step of the analysis is the uncertainties in the individual hauls accounted for. Specifically is the uncertainty in the individual haul *SF* and *SFA* values modeled as within haul variation and therefore automatically accounted for in the analysis (see Fryer (1991) for further details on this).

To estimate the general effects of the design parameters *td*, DO, and T90 on the codend size selection of cod, we analyzed model (1) and each simpler submodel that could be derived from this model, before comparing them. This evaluation was based on the results for the SF and SFA for all 43 hauls, as described in Section 2.2. For cod, this resulted in the following model (model (4)).

$$SF = f_0 + (f_2 + f_6 \times T90 + f_7 \times DO) \times td^2$$
$$SFA = g_0 + g_3 \times T90 \times td \tag{4}$$

Model (4) shows that all three design parameters, i.e., *td*, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between

Table 4
Results for combined model (4) with fixed and random effects using the method described in Fryer (1991). D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the SF and SFA (for details see Fryer (1991)).

	Multiplier	Value	SE	95% confidence limits	*p*-Value
SF					
f_0	Intercept	3.5228	0.0453	3.4326–3.6129	3.8074e−77
f_2	td^2	−0.0149	1.4441e−3	−0.0178 to −0.0121	2.0449e−16
f_6	T90 × td^2	0.0106	1.3343e−3	0.0079–0.0132	1.2046e−11
f_7	DO × td^2	−0.0133	1.8633e−3	−0.0170 to −0.0096	4.1584e−10
SFA					
g_0	Intercept	0.6116	0.0199	0.5720–0.6513	5.2094e−46
g_3	T90 × td	−0.0242	4.8565e−3	−0.0339 to −0.0146	3.4547e−6
Between-haul variation					
D_{11}	1.7361e−2				
D_{12}	−2.4980e−3				
D_{22}	4.6925e−3				
Model statistics					
Log-likelihood					−303.57
AIC-value					661.14
Delta log-likelihood for the estimate					7.5773e−15
Number of hauls					43

using single and double twine netting, was absent from the best model. Table 4 lists the details of model (4).

Because f_2 was significantly less than zero (see Table 4), an increase in the twine thickness resulted in a decrease in SF, and thus L50. This effect was much stronger for double twine nettings because the parameter f_7 was close to the value of f_2 and it was also significantly less than zero. Based on the estimated f_6 value, which was significantly larger than zero, turning the netting by 90° would reduce the negative effects of the twine thickness and twine number on the SF and L50. Nevertheless, this T90 effect was not sufficiently strong to fully compensate for both negative effects. Consequently, the overall effect would be a slight decrease in the SF with an increase in the twine thickness.

However, inspecting the confidence intervals for f_2 and f_6 showed that the predicted decrease in SF with an increase in twine thickness for single twined T90 codends was not significant because the upper limit for f_6 was more than the limit for f_2, which was closest to zero. By contrast, for double twine codends, the confidence interval for f_6 did not overlap with the confidence interval for the combined negative effect of f_2 and f_7. Thus, for double twine T90 codends, we estimated that there was a significant decrease in SF with an increase in twine thickness. Because the sum of f_6 and f_7 is also negative, the model predicts a lower SF for a double twine T90 codend compared with a similar T0 single twine with the same twine thickness. This effect was not statistically significant according to Table 4.

For SFA and thus also SR, model (4) predicted no effect of twine thickness for T0 codends ($T0_{single}$ and $T0_{double}$) and no difference in the values for single and double twined T0 codends. For T90 codends, there was a significant decrease in SFA with an increase in twine thickness. The model predicted that this effect would be identical for single and double twine T90 codends. Fig. 2 shows the predicted mean effect on the L50 and SR, depending on the twine thickness for cod in a codend with a 120-mm mesh size based on model (4). Table 4 shows the four different codend categories based on the predicted values for SF and SFA with corresponding rescaling to the L50–SR domain for a mesh size of 120 mm (see Section 2.2).

Fig. 3 shows the L50 and SR values (rescaled to 120 mm) for the individual hauls for the four different codend categories, depending on the codend twine thickness. The CI for the individual haul parameters are indicated, as well as the predicted between-haul variation in the selection process (see model (2) and Table 4).

For all four codend categories, model (4) could reproduce the main trends of the effect of the twine thickness on L50 and SR, which was found in the experimental results (Fig. 3). None of the results for any of the 43 hauls were found to be in direct conflict with the models for either L50 or SR after inspecting the CI for the estimated values in the individual hauls and for the predicted between-haul variation in the selection process. Thus, we were confident when applying the model to make predictions.

Model (4) was used to predict the effect of an increase in twine thickness on the mean values for L50 and SR with a 120-mm codend mesh size (Table 5). In addition, the percentage effect of turning the netting by 90° from (T0 to T90) was estimated for different twine thicknesses (see formulae (3)).

The percentage effect on L50 by going from T0 to T90 orientation increased with the twine thickness. This was found to have a more profound effect with double twine netting compared with single twine netting. For twine thickness at 2 mm the effect is predicted to be 1.22% for single twine and 1.24% for double twine. For

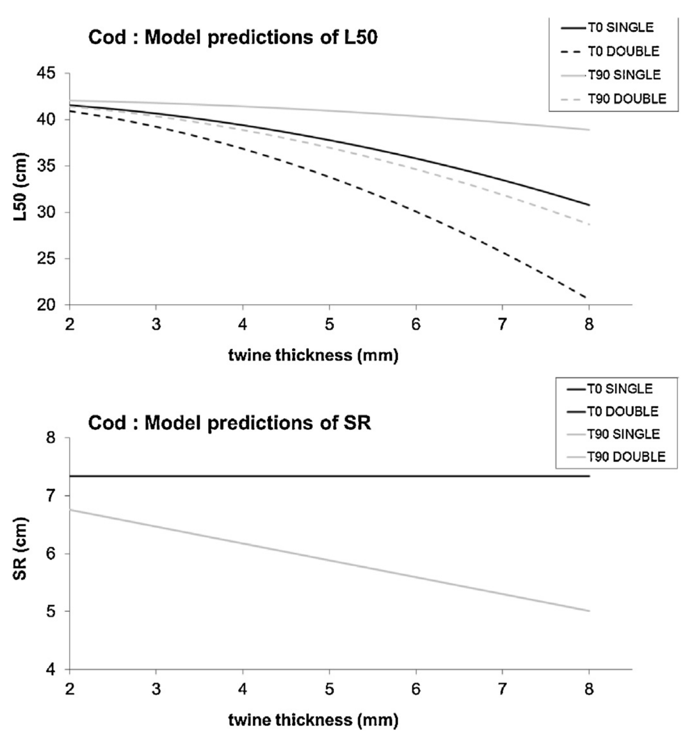

Fig. 2. Predicted mean L50 and SR values for cod, depending on the twine thickness. The SF and SFA values were rescaled for a 120-mm mesh size, according to the procedure described in Section 2.2. For SR, both T0 and both T90 curves (single and double) are identical according to the model predictions.

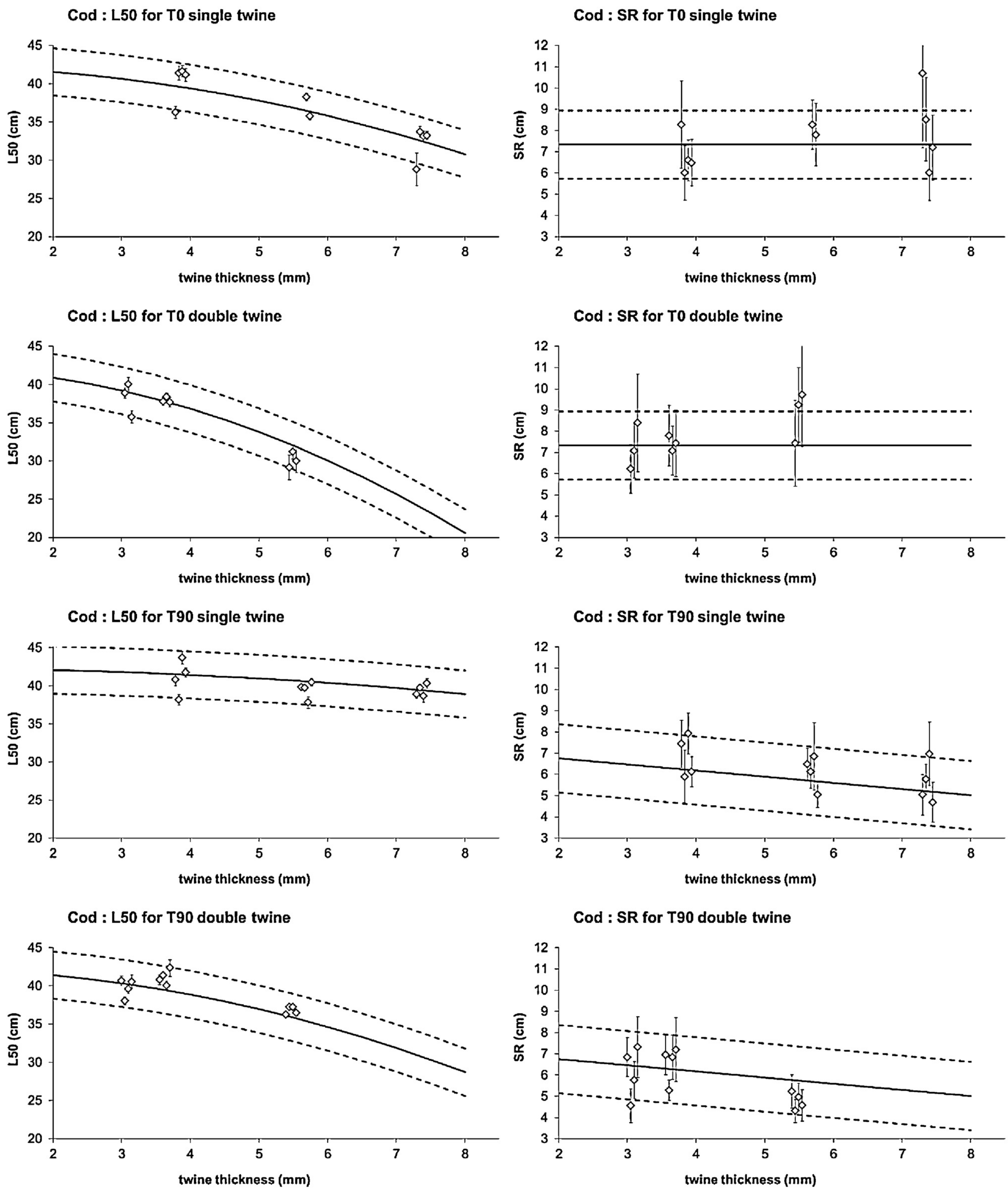

Fig. 3. L50 and SR values for cod from single hauls with the different cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which have been rescaled to a 120-mm mesh size.

twine thickness at 8 mm the effected is predicted to be 26.33% for single twine and 39.34% for double twine. According to the model, however, this positive effect could not compensate for the negative effect that the increased twine thickness had on the T0 baseline value. For cod, therefore, the model predicted a decrease in the L50 with an increase in the codend twine thickness for T0 and T90 codends. Nevertheless, this effect was not significant for the T90 single twine codends. For the codend category T0 with a single twine, the effect of increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 41.56 cm to 30.80 cm. This was a drop of 10.76 cm, which corresponded to >25%. This effect was more profound with double twine T0 codends, where

Table 5
Model predictions for the influence of twine thickness on the size selection of cod in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

td (mm)	L50 single twine			L50 double twine			SR single twine			SR double twine		
	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2.0	41.56 (40.57–42.54)	42.06 (41.07–43.05)	1.22	40.92 (40.02–41.82)	41.43 (40.52–42.33)	1.24	7.34 (6.86–7.82)	6.76 (6.23–7.29)	−7.92	7.34 (6.86–7.82)	6.76 (6.23–7.29)	−7.92
2.5	41.15 (40.21–42.09)	41.94 (40.99–42.90)	1.92	40.16 (39.35–40.97)	40.95 (40.12–41.77)	1.97	7.34 (6.86–7.82)	6.61 (6.06–7.17)	−9.91	7.34 (6.86–7.82)	6.61 (6.06–7.17)	−9.91
3.0	40.66 (39.77–41.55)	41.80 (40.88–42.72)	2.80	39.23 (38.51–39.94)	40.37 (39.61–41.12)	2.91	7.34 (6.86–7.82)	6.47 (5.88–7.06)	−11.89	7.34 (6.86–7.82)	6.47 (5.88–7.06)	−11.89
3.5	40.08 (39.24–40.91)	41.63 (40.72–42.53)	3.87	38.13 (37.49–38.76)	39.68 (38.96–40.40)	4.07	7.34 (6.86–7.82)	6.32 (5.70–6.95)	−13.87	7.34 (6.86–7.82)	6.32 (5.70–6.95)	−13.87
4.0	39.40 (38.61–40.20)	41.43 (40.52–42.35)	5.14	36.86 (36.26–37.45)	38.88 (38.13–39.64)	5.50	7.34 (6.86–7.82)	6.18 (5.51–6.84)	−15.85	7.34 (6.86–7.82)	6.18 (5.51–6.84)	−15.85
4.5	38.64 (37.88–39.41)	41.21 (40.23–42.18)	6.64	35.42 (34.78–36.06)	37.98 (37.10–38.86)	7.24	7.34 (6.86–7.82)	6.03 (5.32–6.74)	−17.83	7.34 (6.86–7.82)	6.03 (5.32–6.74)	−17.83
5.0	37.79 (37.02–38.56)	40.96 (39.88–42.03)	8.38	33.81 (33.03–34.59)	36.98 (35.89–38.06)	9.37	7.34 (6.86–7.82)	5.89 (5.13–6.64)	−19.81	7.34 (6.86–7.82)	5.89 (5.13–6.64)	−19.81
5.5	36.85 (36.04–37.66)	40.68 (39.45–41.91)	10.40	32.03 (31.04–33.03)	35.86 (34.51–37.22)	11.96	7.34 (6.86–7.82)	5.74 (4.94–6.54)	−21.79	7.34 (6.86–7.82)	5.74 (4.94–6.54)	−21.79
6.0	35.82 (34.92–36.72)	40.38 (38.96–41.80)	12.73	30.09 (28.82–31.36)	34.65 (32.96–36.33)	15.16	7.34 (6.86–7.82)	5.59 (4.75–6.44)	−23.77	7.34 (6.86–7.82)	5.59 (4.75–6.44)	−23.77
6.5	34.70 (33.67–35.73)	40.05 (38.39–41.71)	15.43	27.97 (26.38–29.56)	33.32 (31.27–35.38)	19.14	7.34 (6.86–7.82)	5.45 (4.56–6.34)	−25.75	7.34 (6.86–7.82)	5.45 (4.56–6.34)	−25.75
7.0	33.49 (32.29–34.68)	39.69 (37.76–41.63)	18.54	25.69 (23.74–27.63)	31.89 (29.42–34.36)	24.17	7.34 (6.86–7.82)	5.30 (4.36–6.24)	−27.73	7.34 (6.86–7.82)	5.30 (4.36–6.24)	−27.73
7.5	32.19 (30.79–33.59)	39.31 (37.07–41.55)	22.14	23.23 (20.89–25.57)	30.36 (27.44–33.28)	30.67	7.34 (6.86–7.82)	5.16 (4.17–6.15)	−29.72	7.34 (6.86–7.82)	5.16 (4.17–6.15)	−29.72
8.0	30.80 (29.17–32.43)	38.90 (36.33–41.48)	26.33	20.61 (17.84–23.37)	28.72 (25.31–32.12)	39.34	7.34 (6.86–7.82)	5.01 (3.97–6.06)	−31.70	7.34 (6.86–7.82)	5.01 (3.97–6.06)	−31.70

increasing the twine thickness from 2 mm to 6 mm reduced the L50 by >26%.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 5). Thus, using a thicker twine tended to decrease the SR with T90 codends.

3.3. Analysis of the plaice data

As with cod, a logistic curve was fitted to the size selection data for plaice captured in individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values for individual hauls. Table 6 summarizes results for individual hauls of plaice. An inspection of the fit statistics indicated that there was no problem with using a logistic curve to describe the selection data for all hauls, except for hauls no. 14 and no. 40 with *p*-values of 0.0029 and 0.0035, respectively. An inspection of the residuals for hauls 14 and 40 did not indicate any structural problems with using the logistic curve to model the experimental data in either of these hauls. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about using the logistic curve to model the size selection of plaice in all individual hauls. Furthermore, the high R^2-values, where the lowest value was 0.74 and only 3/43 values were <0.91, highlighted the power of the data based on the very low binominal noise.

To estimate the general effect of the design parameters *td*, DO, and T90 on the codend size selection of plaice, model (1) and all simpler submodels were analyzed and compared. This evaluation was based on the results for the SF and SFA for all 43 hauls we conducted (see Section 2.2). For plaice, this resulted in the following model (model (5)).

$$SF = f_0 + f_1 \times td + f_3 \times T90 \times td + f_5 \times T90 \times DO \times td$$
$$SFA = g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td \qquad (5)$$

Model (5) shows that all three design parameters, i.e., *td*, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between using single and double twine netting, was absent from the best model. Table 7 shows the details for model (5).

Table 7 shows that an increase in the twine thickness (TD) tended to decrease the SF, and thus the L50, for all four categories of codends, because parameter f_1 was significant less than zero. For the T0 types of codends ($T0_{single}$ and $T0_{double}$), the effect was predicted to be identical. For T90 codends, the decrease in SF with an increase in the twine thickness would be even bigger because f_3 and f_5 were significantly less than zero. Thus, the biggest decrease in SF with an increase in the twine thickness was found with the codend type $T90_{double}$ whereas the lowest was with the two T0 codend types.

For visualization purposes, the predicted SF values were transformed to L50 values for the 120 mm nominal mesh size, as for cod. The increase in the L50 with increasing twine thickness is shown in Fig. 4 for the four different codend categories. The L50 tended to decrease monotonically for all four codend categories with a twine thickness in the range of 2–8 mm (Fig. 4).

For the SFA model (5) containing first order and second order terms for the effect of twine thickness (g1 and g2) with opposite signs, this relationship was more complex and it need to be inspected for specific values of twine thickness. However, turning the netting orientation to a T90 orientation tended to decrease the SFA and this effect increased with the twine thickness because g_3 was significantly less than zero (Table 7). Fig. 4 plots the predicted effect of the twine thickness on SR with a 120-mm codend mesh size.

Fig. 5 shows the rescaled (for a 120-mm mesh size) L50 and SR values for plaice in the individual hauls for the four different

Table 6
Estimation of the selectivity parameters and the fit statistics for individual hauls of plaice.

Haul no.	Codend	L50 (cm)	SR (cm)	SF	SFA	p-Value	Deviance	DOF	R^2-value
1	T90D4	21.17	1.20	1.72 (1.69–1.74)	0.10 (0.06–0.13)	0.9999	5.56	23	0.9929
2	T90D4	22.97	1.56	1.86 (1.83–1.89)	0.13 (0.08–0.17)	0.9999	5.28	22	0.9928
3	T90D4	23.22	2.56	1.88 (1.84–1.93)	0.21 (0.15–0.27)	0.9994	4.99	19	0.9941
4	T90D4	21.97	1.96	1.78 (1.74–1.82)	0.16 (0.10–0.22)	1.0000	1.61	21	0.9971
5	T90S4	22.92	2.91	1.83 (1.79–1.87)	0.23 (0.18–0.29)	0.2811	26.43	23	0.9614
6	T90S4	23.91	2.63	1.91 (1.86–1.95)	0.21 (0.16–0.26)	0.9846	10.18	22	0.9841
7	T90S4	24.30	1.99	1.94 (1.89–1.98)	0.16 (0.11–0.21)	0.9978	7.74	22	0.9917
8	T90S4	24.68	2.80	1.97 (1.92–2.02)	0.22 (0.17–0.28)	0.798	13.75	19	0.9899
9	T90D6	20.21	3.62	1.64 (1.60–1.68)	0.29 (0.22–0.37)	1.0000	4.33	24	0.9928
10	T90D6	20.54	2.60	1.67 (1.63–1.71)	0.21 (0.13–0.29)	0.9831	9.65	21	0.9748
11	T90D6	20.49	2.30	1.66 (1.64–1.69)	0.19 (0.14–0.23)	1.0000	4.61	22	0.9965
12	T90D6	21.12	2.46	1.71 (1.69–1.74)	0.20 (0.15–0.25)	0.6758	18.5	22	0.9710
13	T90S6	20.41	2.66	1.64 (1.60–1.69)	0.21 (0.14–0.29)	0.9967	9.37	24	0.9658
14	T90S6	22.21	3.56	1.79 (1.74–1.84)	0.29 (0.20–0.37)	0.0029	43.3	21	0.9373
15	T90S6	22.15	2.30	1.78 (1.75–1.81)	0.18 (0.14–0.23)	0.9698	11.33	22	0.9914
16	T90S6	22.24	2.35	1.79 (1.75–1.83)	0.19 (0.13–0.25)	0.2676	24.54	21	0.9472
17	T90D3	22.66	2.47	1.81 (1.78–1.84)	0.20 (0.16–0.24)	0.9996	7.34	24	0.9916
18	T90D3	23.39	3.00	1.87 (1.83–1.90)	0.24 (0.19–0.29)	0.6152	17.58	20	0.9813
19	T90D3	23.94	2.97	1.91 (1.87–1.95)	0.24 (0.18–0.29)	1.0000	3.18	23	0.9963
20	T90D3	23.29	1.75	1.86 (1.81–1.91)	0.14 (0.08–0.20)	0.9978	7.17	21	0.9682
21	T90S8	22.77	2.86	1.83 (1.77–1.89)	0.23 (0.15–0.31)	0.9953	11.07	26	0.9706
22	T90S8	20.39	1.96	1.64 (1.61–1.67)	0.16 (0.11–0.21)	1.0000	5.02	25	0.9624
23	T90S8	20.83	2.52	1.67 (1.65–1.70)	0.20 (0.16–0.25)	0.9235	11.01	19	0.9879
24	T90S8	20.05	3.71	1.61 (1.55–1.67)	0.30 (0.17–0.43)	0.9570	12.02	22	0.8886
25	T0D4	25.35	3.34	2.05 (1.99–2.12)	0.27 (0.19–0.35)	0.9987	7.77	23	0.9747
26	T0D4	25.25	3.47	2.05 (1.98–2.12)	0.28 (0.20–0.36)	0.0657	37.61	26	0.7384
27	T0D4	24.93	3.11	2.02 (1.94–2.10)	0.25 (0.17–0.34)	0.7760	16.77	22	0.9369
28	T0S4	24.60	2.16	1.96 (1.89–2.03)	0.17 (0.10–0.24)	0.9957	6.70	19	0.9756
29	T0S4	25.82	2.73	2.06 (1.97–2.15)	0.22 (0.13–0.30)	0.9758	10.23	21	0.9177
30	T0S4	26.58	2.95	2.12 (2.07–2.17)	0.24 (0.18–0.29)	0.9803	9.89	21	0.9894
31	T0S4	26.52	3.04	2.11 (2.08–2.15)	0.24 (0.19–0.29)	0.5398	23.65	25	0.9838
32	T0D3	26.75	3.14	2.14 (2.09–2.18)	0.25 (0.20–0.30)	0.4914	23.48	24	0.9846
33	T0D3	26.63	2.42	2.13 (2.07–2.18)	0.19 (0.12–0.26)	0.6289	17.37	20	0.9675
34	T0D3	26.65	3.76	2.13 (2.08–2.17)	0.30 (0.24–0.36)	0.2007	28.41	23	0.9778
35	T0S8	25.96	3.69	2.09 (2.04–2.14)	0.30 (0.24–0.35)	0.2664	26.76	23	0.9825
36	T0S8	24.17	3.26	1.94 (1.89–2.00)	0.26 (0.18–0.34)	0.9852	10.79	23	0.9783
37	T0S8	23.31	4.24	1.87 (1.82–1.93)	0.34 (0.25–0.43)	0.8855	16.07	24	0.9663
38	T0S8	23.71	4.25	1.91 (1.85–1.96)	0.34 (0.26–0.42)	0.7351	18.41	23	0.9131
39	T0D6	24.81	5.09	2.01 (1.95–2.08)	0.41 (0.32–0.51)	0.1542	29.84	23	0.9142
40	T0D6	24.71	4.69	2.01 (1.95–2.06)	0.38 (0.30–0.47)	0.0035	45.41	23	0.9649
41	T0D6	25.13	3.88	2.04 (2.00–2.08)	0.32 (0.26–0.37)	0.1031	33.05	24	0.7546
42	T0S6	25.10	2.81	2.02 (1.98–2.07)	0.23 (0.18–0.27)	0.9930	9.06	22	0.9840
43	T0S6	25.95	4.65	2.09 (2.03–2.15)	0.37 (0.29–0.46)	0.1314	29.49	22	0.9392

codend categories, which depended on the codend twine thickness. The CI for the individual haul parameters are shown, as well as the predicted between-haul variation in the selection process (see formula (2) and Table 7).

For all four codend categories, model (5) reproduced the main trends of the effect of twine thickness on the L50 and SR, which were found in the experimental results (Fig. 5). For plaice, none of the results for any of the 43 hauls were in direct conflict with the model

Table 7
Results for combined model (5) with fixed and random effects using the method described in Fryer (1991) where D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the size selection process.

	Multiplier	Value	SE	95% CI	p-Value
SF					
f_0	Intercept	2.1575	0.0343	2.0893–2.2257	2.9273e−69
f_1	td	−0.0247	6.8768e−3	−0.0384 to −0.0110	5.6158
f_3	T90 × td	−0.0412	4.0824e−3	−0.0493 to −0.0331	7.1936e−16
f_5	T90 × DO × td	−0.0253	5.417e−3	−0.0361 to −0.0145	1.2313e−5
SFA					
g_1	td	0.0941	6.2664e−3	0.0816–0.1065	7.4037e−25
g_2	td^2	−7.0250e−3	9.9873e−4	−0.0090 to −0.0050	6.4346e−10
g_3	T90 × td	−0.0163	3.048e−3	−0.0223 to −0.0102	8.7512e−7
Between haul variation					
D_{11}			3.1507e−3		
D_{12}			3.1263e−4		
D_{22}			1.5233e−3		
Model statistics					
Log-likelihood					−246.78
AIC-value					563.55
Delta log-likelihood for the estimate					4.2050e−15
Number of hauls					43

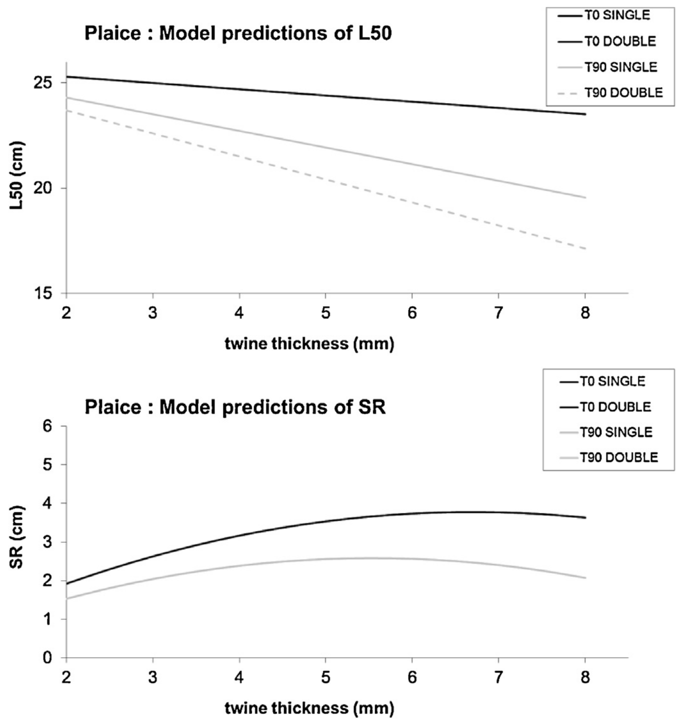

Fig. 4. Predicted mean L50 and SR values for plaice, depending on the twine thickness. The SF and SFA values were rescaled to a 120-mm mesh size, according to the procedure described in Section 2.2, for the different codend categories. The model-predicted L50 curves for T0 single and T0 double are identical. This also applies to both T0 and both T90 curves for the SR predictions.

for either the L50 and SR, after inspecting the CI of the estimated values in the individual hauls and the predicted between-haul variation in the selection process. Thus, we can be confident when applying the model for plaice predictions.

Model (5) was used to predict the effect of an increase in the twine thickness on the mean value for L50 and SR with a 120-mm codend mesh size (Table 8). In addition, the percentage effect of turning the netting by 90° (from T0 to T90) was estimated for different twine thickness (see formulae (3), Section 2.2).

In contrast to cod, the percentage effect of changing the netting orientation to T90 decreased with the increasing twine thickness for plaice. In addition, the effect was more profound for double twine netting compared with single twine netting. The effect with 2 mm twine was predicted to be −3.91% and −6.31% for single and double netting, respectively, but this effect increased to −16.83% and −27.15%, respectively, after increasing the twine thickness to 8 mm. For both T0 codend categories, increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 25.30 cm to 23.52 cm, which corresponded to a drop of 7%. The effect was more pronounced with T90 codends.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 8). This was based on the increase of the SR with thicker twine when applied in T0 codends. By contrast, the SR tended to be less dependent on the twine thickness with T90 codends.

4. Discussion

This research addresses the effects of codend twine thickness and twine number on the size selectivity for round fish and flat fish species when using traditional T0 codends and T90 codends. This investigation is based on a case study of cod and plaice with experimental fishing in the Baltic Sea where both species are important

Table 8
Model predictions for the influence of twine thickness on the size selection of plaice in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

td (mm)	L50 single twine			L50 double twine			SR single twine			SR double twine		
	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2	25.30 (24.76–25.83)	24.31 (23.70–24.92)	−3.91	25.30 (24.76–25.83)	23.70 (23.18–24.22)	−6.31	1.92 (1.61–2.23)	1.53 (1.18–1.88)	−20.33	1.92 (1.61–2.23)	1.53 (1.18–1.88)	−20.33
2.5	25.15 (24.68–25.62)	23.91 (23.33–24.50)	−4.92	25.15 (24.68–25.62)	23.15 (22.67–23.64)	−7.93	2.29 (1.89–2.70)	1.81 (1.36–2.25)	−21.26	2.29 (1.89–2.70)	1.81 (1.36–2.25)	−21.26
3	25.00 (24.58–25.42)	23.52 (22.94–24.09)	−5.93	25.00 (24.58–25.42)	22.61 (22.13–23.08)	−9.57	2.63 (2.13–3.12)	2.04 (1.50–2.58)	−22.28	2.63 (2.13–3.12)	2.04 (1.50–2.58)	−22.28
3.5	24.85 (24.48–25.22)	23.12 (22.54–23.70)	−6.97	24.85 (24.48–25.22)	22.06 (21.56–22.55)	−11.24	2.92 (2.32–3.52)	2.23 (1.58–2.89)	−23.42	2.92 (2.32–3.52)	2.23 (1.58–2.89)	−23.42
4	24.70 (24.36–25.04)	22.72 (22.12–23.33)	−8.01	24.70 (24.36–25.04)	21.51 (20.97–22.05)	−12.92	3.17 (2.46–3.88)	2.38 (1.62–3.15)	−24.67	3.17 (2.46–3.88)	2.38 (1.62–3.15)	−24.67
4.5	24.55 (24.23–24.88)	22.33 (21.69–22.97)	−9.06	24.55 (24.23–24.88)	20.96 (20.36–21.57)	−14.62	3.37 (2.54–4.20)	2.49 (1.60–3.38)	−26.06	3.37 (2.54–4.20)	2.49 (1.60–3.38)	−26.06
5	24.41 (24.07–24.74)	21.93 (21.25–22.62)	−10.13	24.41 (24.07–24.74)	20.42 (19.74–21.10)	−16.35	3.54 (2.58–4.49)	2.56 (1.54–3.58)	−27.61	3.54 (2.58–4.49)	2.56 (1.54–3.58)	−27.61
5.5	24.26 (23.90–24.62)	21.54 (20.80–22.28)	−11.21	24.26 (23.90–24.62)	19.87 (19.10–20.64)	−18.09	3.66 (2.56–4.75)	2.58 (1.42–3.75)	−29.36	3.66 (2.56–4.75)	2.58 (1.42–3.75)	−29.36
6	24.11 (23.71–24.51)	21.14 (20.34–21.95)	−12.31	24.11 (23.71–24.51)	19.32 (18.46–20.18)	−19.86	3.74 (2.50–4.98)	2.57 (1.25–3.88)	−31.35	3.74 (2.50–4.98)	2.57 (1.25–3.88)	−31.35
6.5	23.96 (23.50–24.42)	20.75 (19.87–21.62)	−13.42	23.96 (23.50–24.42)	18.77 (17.82–19.73)	−21.65	3.77 (2.37–5.18)	2.51 (1.03–3.98)	−33.63	3.77 (2.37–5.18)	2.51 (1.03–3.98)	−33.63
7	23.81 (23.30–24.33)	20.35 (19.40–21.30)	−14.54	23.81 (23.30–24.33)	18.23 (17.17–19.29)	−23.46	3.77 (2.20–5.34)	2.40 (0.75–4.05)	−36.26	3.77 (2.20–5.34)	2.40 (0.75–4.05)	−36.26
7.5	23.66 (23.08–24.25)	19.96 (18.93–20.98)	−15.67	23.66 (23.08–24.25)	17.68 (16.52–18.84)	−25.29	3.72 (1.97–5.47)	2.26 (0.43–4.09)	−39.34	3.72 (1.97–5.47)	2.26 (0.43–4.09)	−39.34
8	23.52 (22.86–24.17)	19.56 (18.45–20.67)	−16.83	23.52 (22.86–24.17)	17.13 (15.86–18.40)	−27.15	3.63 (1.69–5.57)	2.07 (0.05–4.10)	−42.99	3.63 (1.69–5.57)	2.07 (0.05–4.10)	−42.99

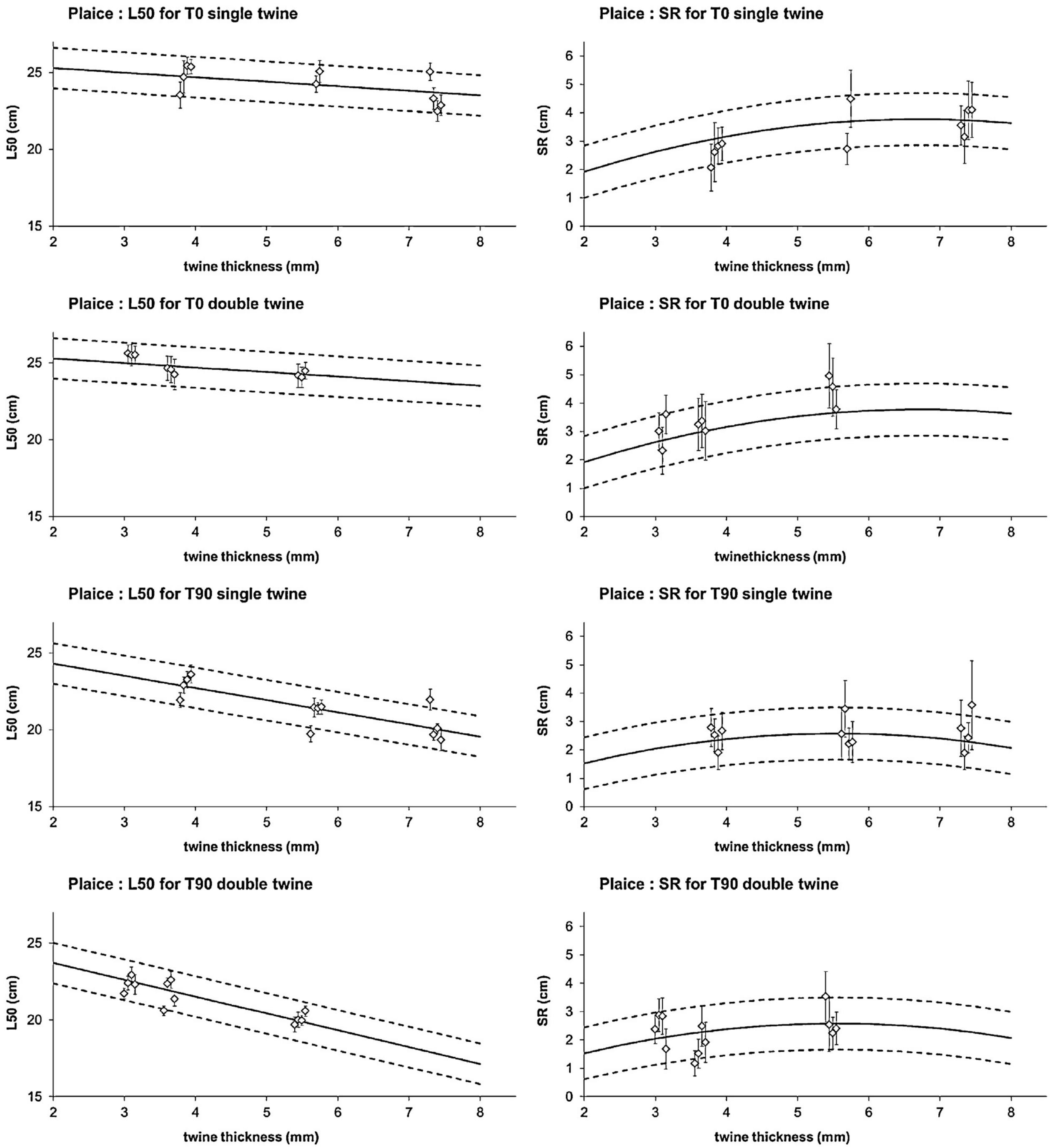

Fig. 5. The L50 and SR values for plaice from single hauls using the four cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which were rescaled to a 120-mm mesh size.

for trawl fisheries (Probst et al., 2011). Based on an assumption that the fish morphology has a major role in the codend size selection process (Herrmann et al., 2009, 2012; Frandsen et al., 2010; Krag et al., 2011), we expected that the trends in the results obtained for cod could be extrapolated to other round fish such as haddock due to similarities in their morphology (Sistiaga et al., 2011). Similarly, we expected that the trends in the results for plaice could be extrapolated to other flat fish species. This extrapolation relies on morphological similarities and it might be affected by differences in fish behavior.

For cod, the results for single and double twine T0 codends documented that the L50 decreased with increases in the twine thickness. This effect was more pronounced for double twine T0 codends. These results are in agreement with previously reported results for haddock (Lowry and Robertson, 1996; Kynoch et al., 1999; Herrmann and O'Neill, 2006; O'Neill and Herrmann, 2007) and they follow the same pattern as that observed in a Mediterranean study of other species (Sala et al., 2007). Our results for cod show that turning the netting orientation from T0 to T90, both for single and double twine netting, provided a significant increase in the L50 values and this effect increased with the twine thickness. These findings are logical when we consider the mechanical-based explanation given by Herrmann et al. (2007) to account for the effect of turning a diamond mesh netting by 90° (T90). For the double twine T90 codends, however, this positive effect was more than compensated for by the negative effect that an increase in the twine thickness had on the baseline T0 codend. Consequently, the L50 values decreased significantly with increasing twine thickness for double twine T90 codends. Thus, despite the positive effect of turning the netting, there was a decrease in the L50 values for cod with an increase in the twine thickness for double twined T90 codends.

In addition to the positive effect of increasing the twine thickness on the size selectivity with a T90 construction, this result highlights the importance of considering the other, and potentially counteracting, mechanisms described by Herrmann and O'Neill (2006). For the T90 single twine codends, our results indicate that these counteracting mechanisms can almost compensate for each other, resulting in only a slight decrease in the predicted L50 for cod with an increase in the twine thickness. Furthermore, the predicted decrease was not significant. Therefore, it cannot be ruled out that the counteracting mechanisms completely compensated for each other with this type of codend, resulting in a size selection process that did not depend on the twine thickness for cod. For cod, and potentially other round fish in general, the results obtained using double twine codends showed there was a significantly reduced size selection with T0 and T90 codend constructions. Therefore, improved size selectivity could be obtained by simply changing from double twine, which is the current commercial practice, to single twine codend netting. In general, our results demonstrated that using nets with a thinner twine in a single twine codend construction provided the highest L50 values. In the current experiments, the best results were obtained with a single twine T90 codend construction. Furthermore, the performance of this codend type appeared to be highly insensitive to the choice of twine thickness.

In addition to improved selectivity based on L50 estimates, the T90 constructions were predicted to allow a more acute size selection with smaller SR values. This appears to favor this type of codend for size selection with round fish. This effect may be because the meshes in the T90 codends are predicted to open more uniformly further ahead of where the catch accumulates compared with the T0 codends. The mesh opening was also less dependent on the size of the catch (Herrmann et al., 2007). One effect of a more uniform mesh opening could be a reduction in the SR in individual hauls (Herrmann, 2005b; Herrmann and O'Neill, 2005; Herrmann et al., 2009).

Initially, it was questioned whether the codend twine characteristics would affect the size selection of round fish and flat fish in the same direction and to the same extent. After we compared the results for cod and plaice, we concluded that there were some similarities but also major differences in the effects of the twine characteristics on size selection in both species. An increase in the twine thickness tended to decrease the L50 for cod and for plaice, whereas this effect was far less pronounced for plaice with T0 constructions. For example, we predicted that increasing the twine thickness from 2 mm to 8 mm for a single twine L50 would lead to decreases of 7% and 25% for plaice and cod, respectively. In contrast to cod, we found no evidence of any difference in performance between single and double twine T0 codends for plaice. Changing the netting orientation from T0 to T90 was predicted to affect the size selection for plaice in the opposite direction compared with cod. The percentage T90 effect for plaice significantly decreased with increasing twine thickness and the lowest values were obtained for the double twine T90 codend. It is possible that the differences in the effects on cod and plaice may be linked to differences in their morphology because the shape of plaice would require a diamond mesh with a relative small opening angle to pass though, whereas the shape of cod would benefit from a more open diamond mesh. This mechanism could potentially explain the different effects of increasing the twine thickness and turning the netting orientation

Our results were based on sea trials conducted using codends with a nominal mesh size of 120 mm. Thus, the results are most relevant to codend constructions with similar mesh sizes, which are used widely in North East Atlantic commercial fisheries. Based on the mechanisms described in Herrmann and O'Neill (2006) and Herrmann et al. (2007), we expect larger effects with smaller mesh sizes, because of the greater influence of a shorter mesh bar with increasing twine thickness. This mechanism also influences the T90-effect, so we also expect a larger T90 effect with smaller mesh sizes. By contrast, we would expect a very small T90 effect when using a relatively big mesh compared with the twine thickness and, therefore, the knot size in a T90 configuration. As a consequence, it may be possible to obtain stronger effects than the trends we observed based on the effects of the twine characteristics on codend size selection with smaller mesh sizes, and lower effects with bigger mesh sizes.

It is commercial practice in some fisheries to use different codend attachments such as chafers, round straps, or protective bags. The results presented here are based on codends with no such attachments. It is known that attachments such as round straps affect the codend shape (Herrmann et al., 2006) and devices that cover some of the codend meshes will affect the size selectivity of the codend (Kynoch et al., 2004). Consequently, these attachments might also influence the degree of the effects of the twine thickness and netting orientation.

We used the method described by Fryer (1991) to model size selection in the codends based on the effects of the codend netting design parameters (Table 1) and we assumed that the between-haul variation in the selection process could be modeled in a similar way for all of the codends we investigated. This is a usual approximation for this type of model, but it neglects potential differences in the between-haul characteristics of the different codends investigated (Wienbeck et al., 2011). However, to account for this would require far more hauls for each codend design. Additionally, the potential effect of codend catch weight on size selection (O'Neill and Kynoch, 1996; Herrmann, 2005b) is taken into account in model (1) by linear terms and by such approximated to affect the codend size selection independent of twine characteristics. This was omitted for SF and SFA in the resulting models (4) and (5) for cod and plaice, respectively. Thus, the results did not indicate any general trend in the effect of catch weight on the size selection of cod and plaice and we are confident in applying models (4) and (5) because a potential non-general effect of the codend catch weight is explicitly included in the between-haul variation modeling.

For the "T90 effect," it is important to note that our results are based on using new netting materials and we do not know if the effect of turning the codend netting orientation to T90 would disappear with the material relaxation caused by tension during fishing operations over some time (Herrmann et al., 2007). This would require a special experimental study to analyze any potential material-aging effect.

The results presented in this study have some potential implications for fisheries management in different areas. The current legislation often permits the use of a relatively wide range of twine characteristics for codend constructions in many management areas. The current study showed that this has a potentially dramatic effect on the size selectivity of codends. Further, it is possible that the increasing trend to use thicker and double twined netting for T0 and T90 codends has created an artificial need for more sophisticated selective devices. These devices often include square mesh panels such as the BACOMA design (Madsen et al., 2002; Wienbeck et al., 2011) and other square mesh panel designs, such as those described by Madsen et al. (2010). The use of such constructions is often aimed at releasing juvenile round fish, such as cod. Based on the results obtained in the research reported here, we may question whether a simpler alternative could be used by some fisheries such as the deployment of diamond mesh codends (in T0 or T90 configuration) made of thinner single twine netting.

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Appendix A. Model development

In this section, we describe the development of the model that was used to quantify the effect of twine thickness *td* in the netting used for codend construction on the size selection of a specific species. A general model for each of SF and SFA to order td^2 can be expressed on the form (shown only for *SF*):

$$SF \sim 1 + T90 + DO + DO \times T90 + (1 + T90 + DO + DO \times T90) \times td + (1 + T90 + DO + DO \times T90) \times td^2 \quad \text{(A1)}$$

One way to argue for the model (A1) is that it can be derived by the following steps: (i) first formulating individual models for *SF* and *SFA* for each of the four codend categories ($T0_{single}$, $T0_{double}$, $T90_{single}$, and $T90_{double}$; Table 1) as functions of *td*; (ii) then approximating each of these functions by second order Taylor-expansions (see Bers and Karal (1976) for details on this kind of expansions) with *td* = 0.0 as the expansion point; (iii) then arguing that the same coefficients belonging to the models for the different codend categories can be expressed by the same function in *T*90 and *DO* since it is the values of these parameters which makes the codend categories different; (iv) then using a simple linear model in *T*90 and *DO*, including an interaction term, to approximate the relationship between the values of the coefficients in models for the four different codend categories, which finally enable aggregating the codend models into to one having the form of model (A1).

We will require that our model for the selective characteristics (*SF* and *SFA*) should be independent of *T*90 and *DO* as *td* goes to 0. Since this can only be achieved if the coefficients of *T*90, *DO* and *DO* × *T*90 in model (A1) are 0, we constrain the model to fulfill this asymptotic condition. The arguments for the asymptotic constraint are based on a mechanical point of view. The following argument can be used: according to Herrmann et al. (2007), the knot size and the mesh bar bending stiffness potentially leads to differences in the SF and SFA values for the T0 and T90 codends made of the same netting material while the other design parameters remained identical. Based on simple geometrical consideration can it be expected that the knot size would increase approximately linearly with increase in twine diameter. Therefore, a gradual decrease in twine thickness toward zero should result in a gradual decrease in the knot size toward zero. A gradual degrease in the mesh bars bending stiffness toward zero with gradual degrease in twine thickness toward zero is also expected since this is well known from the thin beam theory (Timoshenko and Goodier, 1982). As a consequence of the above argumentation, a gradual decrease in twine thickness toward zero, should lead to a gradual decrease in the differences in the *SF* and *SFA* values for T0 and T90 codends toward zero. A similar type of argument can be applied to the asymptotic differences in the *SF* and *SFA* values for single or double twine codends, because their bending stiffness will affect the inner mesh aperture geometry, through which the fish try to attempt, which decreases with the twine thickness. Based on the above argument, it was assumed that it was a reasonably good approximation to eliminate coefficients for *T*90, *DO* and *DO* × *T*90 in model (A1). This then enable us to write the models for SF and SFA on the form (A2).

$$\begin{aligned} SF &= f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2 \\ SFA &= g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2 \end{aligned} \quad \text{(A2)}$$

Model (A2) was used to model the influence of the twine thickness on the SF and SFA for codends with different designs. As described in Section 2.2 was model (A2) and all submodels which could be derived from it by leaving of one or more terms at the time tested against each other. The model resulting in the lowest AIC value was then chosen to model the influence of twine characteristics on the size selection.

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